TECHNICAL SESSION PROCEEDINGS

Irrigation Show 2005

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Field Performance of Subsurface Drip Irrigation (SDI) in Kansas

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Introduction: Drip irrigation has proven to be an effective irrigation method for water saving and better return for high dollar cash crops, however, as a surface drip system it does not lend to the field cropping system practiced in the Central Great Plains. Kansas State University's research on suitability of using drip method as subsurface drip irrigation (SDI) has shown that it is a feasible technology for irrigating field crops like corn (Lamm, Manges, Stone, Khan, & Rogers, 1995). More than 2 million acres out of 3 million irrigated in Kansas depends on groundwater from the Ogallala aquifer. The producers are experiencing decline in water level and the pumping cost is rising due to greater depth of pumping and increasing fuel cost. Economic comparison of systems indicated that a well managed SDI system with a promise of fifteen or more years of life is economically competitive (O'Brien, Rogers, Lamm, & Clark, 1998), although it requires a high investment at the start. Extension demonstration in producer field has helped a steady increase in the acreage irrigated by subsurface drip irrigation starting in 1997. Initially many of these systems were installed in small farms with limited water where a part of the water supply was diverted from existing flood or center pivot sprinkler irrigation systems. Lately, producers with large acreage under flood irrigation have started switching to SDI. The state wide SDI acreage is estimated at 20,000 acres, most of which is in western Kansas represents about 1% of irrigated crop land. Although no major concern regarding failure of system has surfaced, it was felt necessary to evaluate the present operational condition of these systems to provide field performance information to farmers intending to adopt SDI in their irrigation operation. The objective of the study was to assess the operational condition of the existing subsurface drip irrigation (SDI) systems and the level of satisfaction of the producers. Information would help address clientele needs and keep the service providers informed.

Methods: A survey questionnaire was sent out to producers using SDI system. The sample questionnaire is shown in Appendix A. The mailing list of producers was prepared from sign up lists of farmers attending educational meetings conducted by cooperative extension on use of SDI and a list obtained from Kansas State Division of Water Resources that show producers reporting use of microirrigation. The recipients of survey forms were requested to return the survey form even if they were not SDI users. Survey forms numbering 297 were mailed out.

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Results: The return rate of survey was 31% (returned 92) out of which 53% (49 responses) were from actual SDI users. The others either heard of SDI and wanted to comment or are using some other form of microirrigation. The response from surface drip users amounted to five percent (5 responses).
SDI acreage totaled from responses received amounts to 8,022 acres out of 323,260 acres irrigated (about 2.5%) by the responding farmers.

Although some started using surface drip for trees and orchards in small acreage as early as 1975, the subsurface drip for field crop was installed in 1994. There was no appreciable installation until 1998. The peak number of system installation according to the survey response was in 2000 and continued steadily at a somewhat reduced number to the present. The numbers from the survey response are shown in Table 1.

Table 1. Yearly installation of SDI systems starting in 1994 according to survey response from producers in western Kansas.

1994	1997	1998	1999	2000	2001	2002	2003
1	3	9	4	10	7	5	7

All of these systems are currently in use, except for one self-installed system of 2001. This system of 22 acres was used for alfalfa and the producer was unable to keep up with the rodents and field gophers. More detailed information is necessary to determine present status.

Majority of the SDI systems were installed jointly by producers and contractors (54%) according to survey response. Contractors installed systems account for 19% and the remainders - 27% were self-installed by the producers.

When asked about if the producers received an “as-built” drawing or diagram of the system from the contractors, thirty four responses were in the affirmative and fourteen were in the negative. The response on receiving operational and maintenance instructions or procedures for the SDI system was similar, thirty three received and fifteen did not receive operational procedures. Names of eight contractors were mentioned as installers and one of them located in Garden City, Kansas, came up as an installer of maximum number of systems.

Crops irrigated by SDI systems were corn (43 responses), soybeans (24 responses), cotton and alfalfa (5 responses each), and sorghum (3 responses). Besides these the systems were also used for wheat, oats, and sorghum silage.

In response to the level of satisfaction with the system performance in a scale of 1 to 5; where 1 indicates as very satisfied and 5 being unsatisfied, the majority of the responses were between 1 and 2. The responses are shown in Table 2.

Table 2. Responses indicating the level of satisfaction with the performance of the SDI system being used by the producers in a scale of 1 to 5.

1	2	3	4	5
Very satisfied	Satisfied	Almost satisfied	Somewhat satisfied	Unsatisfied
17	19	4	4	2

Survey response to a question on whether the SDI users are planning to expand acreage under SDI was that the majority plan to do so (30 responses), however a good number (19) responded in the negative. The overwhelming concern was about rodent damages and filtration. The major concerns were,

- Rodents, gophers, and other vermin damages requiring many hours of repair. (37)
- Filtration is a concern, but with a good system and maintenance there was no problem. Some asked if there were better filtration systems. Should one oversize to avoid frequent cleaning. (15)
- Clogging due to iron bacteria and calcium precipitation is a concern. Some reported clogging concern from drip oil used in pump. Clogging from drip oil is more evident in pumps with low capacity or fluctuating water levels. (15)
- Cost of the system, especially worried about the life of the system. (8)
- Wetting up of the top soil for germination. (3)
- Hard to visualize soil water condition.

Finally, answering to what are information needs that Kansas State Research and Extension might be able to address, the responses from the producers were as follows:

- Rodent control – how and what to use.
- Fertilizer use through SDI including micro-nutrients.
- More educational meetings, seminars on management - both pre and post season included. Field tour to visit systems and exchange information with other operators.
- Drip tape spacing for crops other than corn. More research for alternative crops under SDI.
- More information about planting alfalfa under SDI.
- How to germinate seed in dry soil. Conserving moisture in surface soil for planting.
- How to unclog drip lines. How to keep system clean with different water supplies.
- System capacity, how much water to use, and limited water issues.
- Comparisons of crop yield advantage from SDI over sprinkler.
- Any improvement to cut down cost, better filtration, less maintenance system for this area.
- Property Taxation classification for SDI needs to be developed to avoid over taxation where currently the producers are being penalized for conserving water.
- Why assistances are unavailable to conservation conscious farmers who want to install SDI, whereas it is available to non-conservative circle irrigation?

Discussion: A closer look of the survey response reveals that the owners of systems installed earlier than 1994 are experiencing some difficulties. K-State Research and Extension was still in the process of researching SDI and was not promoting the method. Most of these systems were installed by producers themselves or inexperienced contractors, some of these contractors are probably not in business currently. It is evident that more research and extension education program are necessary. Individual owners will be contacted for further evaluation.

Acknowledgement: The authors acknowledge partial funding support of the USDA-Ogallala Initiative Program.

Literature Cited:

1. Lamm, F. R., Manges, H. L., Stone, L. R., Khan, A. H., & Rogers, D. H. (1995). Water requirement of subsurface drip-irrigated corn in northwest Kansas. *Transactions of the ASAE.* 38 (2): 441-448. ASAE, St. Joseph, MI 49085.
2. O'Brien, D., Rogers, D. H., Lamm, F. R., & Clark, G. A. (1998). An economic comparison of subsurface drip and center pivot sprinkler irrigation systems. *Applied Engineering in Agriculture.* 14 (4): 391-398. ASAE, St. Joseph, MI 49085.

Appendix A

Subsurface Drip Irrigation (SDI) Field Survey

The individual information collected will be kept confidential. The compiled information is for Kansas State University Research and Extension educational purposes only.

County_________________

1. Do you have a buried subsurface drip irrigation (SDI) system? ____ Yes. ____ No. **Please return survey even if you do not have an SDI system.**
2. Number of acres in SDI. _______________Number of total irrigated acres.___________
3. Year of installation of oldest system. __________
4. Is the oldest system in use? ______ Yes ______ No
5. Who installed your SDI system? ______ Self-installed_____ Contractor _______ Both
6. Name of the contractor ______________________
7. If the contractor designed or installed your SDI system:
   a. Did you receive an "as-built" drawing or diagram of your system? ____ Yes. ____ No.
   b. Did you receive an operational and maintenance instructions or procedures for your SDI system? ____ Yes. ____ No.

8. Crops grown with SDI: corn ______ soybeans _______ cotton _____
   other _______________________________, please list.
9. Please indicate your level of satisfaction with the system performance in a scale of 1 to 5; where 1 indicates as very satisfied and 5 being unsatisfied.
   Please circle a number: 1 2 3 4 5
10. Are you planning to expand SDI acreage? ____ Yes. ____ No.
11. What are your concerns about the system (such as filtration, clogging of drip lines, rodent damage, etc.)? Please list and comment.
    ____
    ____
    ____
12. What are information needs that Kansas State Research and Extension might be able to
    address?____
    ____
    ____

If you would like to participate in an evaluation of your system (provided funding is available from the university) please indicate so by signing below.

____

If the system is operated by someone else on your behalf, please provide the name and address of that person below.
Name: ______________________________ Phone Number:__________________

Address: ____

City, State and ZIP ____________________________________

Thank you for your time and input. The survey is complete. Please return using the envelope provided. If you have any questions about this survey, please contact Dan Rogers at 785-532-5813 or drogers@ksu.edu. Or Mahbub Alam at 620-275-9164 or malam@ksu.edu SDI survey 2005-100a.

Tapered Lateral Design for Subsurface Drip Irrigation [1]

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Abstract

A stepwise tapered lateral design was evaluated for drip tape laterals that are used in High Plains subsurface drip irrigation systems. Spreadsheet models were developed to simulation drip irrigation lateral hydraulics to determine flow requirements, emission uniformity, and chemical travel times for tapered and non-tapered laterals. Models were run for a straight 11/8-inch lateral, a 11/8-inch to 7/8-inch tapered lateral, and a 11/8-inch to 9/8-inch tapered lateral. Each of these lateral combinations were simulated for nominal flow rates of 0.20, 0.25, and 0.25 gpm/100ft, and slopes of 0%, -0.5%, and –1.0.

Tapered laterals reduced the travel time of injected chemicals and reduced required flow rates during the flushing process. The 11/8-inch to 7/8-inch combination was generally not desirable due to low emission uniformities. However, the 11/8 to 9/8-inch combination was acceptable for most simulation scenarios. . Reduced fitting costs associated with smaller laterals, also reduced system costs for the tapered lateral design.

Introduction

Subsurface drip irrigation (SDI) systems are increasing in acceptance and use throughout the Great Plains. However, these production systems are concentrated with field crops (i.e. corn, soybean, alfalfa) that need to maintain low production costs. As these SDI systems have evolved, longer lateral run lengths result in the most economical designs. Because many of the agricultural production fields were divided into quarter sections and flood irrigated with runs of 2640 ft, larger diameter drip laterals have been developed to accommodate these long runs by maintaining acceptable emission uniformities.

System maintenance is essential to ensure longevity and continued performance of the irrigation system. This generally requires injection of chlorine, acid, and/or other water treatment chemicals to treat the laterals. In addition liquid fertilizers can be injected to provide essential crop nutrients on an as needed basis. While some dispersion can occur, these injected chemicals travel with the water and are thus dependant upon the flow velocity of the water in the lateral and pipe network. Flow velocities in drip laterals are typically very low, starting at 1 to 2 ft/s at the inlet end and decreasing to zero at the distal end. Therefore, injected chemicals will move very slowly in the lower sections of a drip lateral. When lateral diameter is increased, but the emitter spacing and discharge remain the same, flow velocities are even lower. Some chemical travel time analyses will not consider the last 10, 20 or 30 feet of the lateral because the water is moving so slow and that section represents less than1-2% of the lateral length. For example, in a plug flow analysis of a 0.875-inch diameter lateral that is 1320 feet long with an average flow rate of 0.25 gpm/100ft, the

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[1] Contribution No. 06-55-A of the Kansas Agricultural Experiment Station, Manhattan. This project was funded in part through Regional Project W-1128, "Reducing Barriers to Adoption of Microirrigation"
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travel times for injected chemical to get to the end of the lateral and within 10 feet of the end are 103 and 64 minutes, respectively. In a similar analysis for a 1.375-inch diameter lateral that is 2640 feet long, the travel times are 274 and 179 minutes, respectively, while for a 1.375-inch diameter lateral that is 1320 feet long the times are 241 and 150 minutes. Thus, it can take almost 90 minutes for chemical to travel the last 10 feet in a 1.375-inch diameter lateral. Therefore, it is evident that lateral diameter is a significant factor that influences chemical travel times and that the analysis position is also very important.

Flushing of drip laterals is an essential maintenance practice. In order to properly flush a lateral, it is recommended to have a minimum flush velocity of 1 ft/s. The required volumetric flow rate during a flushing cycle will be dependant upon the size of the laterals, the emitter discharge characteristics, the number of laterals in a flushing zone, and the average lateral pressure during the flushing cycle. larger diameter laterals require greater volumetric flow rates. For example, a 1 ft/s flow velocity in a 0.875-inch diameter lateral corresponds to a flow velocity of 1.9 gpm while that same flow velocity in a 1.375-inch diameter lateral requires 4.6 gpm.

A tapered lateral that steps from a larger diameter lateral to a smaller diameter lateral could improve chemical travel times and reduce required flush cycle flow rates. However, the appropriate location of the taper split needs to be analyzed. In addition, the hydraulic performance of the resultant lateral needs to be assessed for uniformity of emitter discharge. Thus, the objectives of this work were to design and analyze tapered laterals that use a discrete size change.

Methods and Materials

A spreadsheet model was developed to conduct a hydraulic analysis for a microirrigation lateral. The model analysis was designed to first determine the optimal taper step position on a microirrigation lateral based upon minimum flow velocity criteria during a flushing event. The model analysis was designed to determine normal flow hydraulic characteristics and chemical travel times using a plug flow analysis.

The lateral model hydraulics were based upon a Bernoulli energy head balance

$$h_1 + \frac{v_1^2}{2g} + z_1 = h_2 + \frac{v_2^2}{2g} + z_2 + h_f \qquad (1)$$

where h_1 and h_2 represent the pressure head (ft) at two positions in the lateral, v_1 and v_2 are the flow velocities (ft/s) at those locations ($v^2/2g$ is the velocity head), z_1 and z_2 are the elevation heads (ft) at those locations, and h_f is the friction head (ft) between locations 1 and 2. This analysis was conducted between adjacent emitters in a stepwise manner from the last (distal) emitter on a lateral to the first (inlet) emitter on that lateral. Because the flow velocities in a microirrigation lateral are low and the differences between flow velocities (and associated velocity heads) are very small, the velocity head terms were negligible and were removed from Eq. 1.

The friction head, h_f, was determined using the Darcy-Weisbach equation

$$h_f = 1000(F_f)\frac{L}{D}\left(\frac{v^2}{2g}\right) \tag{2}$$

where L is the length (in.) of the lateral section that is being analyzed (in this case the distance between emitters), D is the inside diameter (in.) of the lateral, and F_f is the friction factor. The friction factor was determined using the following relationship for Reynold's numbers (R_y) below 2000

$$F_f = \frac{64}{R_y} \tag{3}$$

The Blasius equation was used for Reynold's numbers that exceeded 2000

$$F_f = 0.316 \bullet \left(R_y^{-0.25}\right) \tag{4}$$

The Reynold's number was determined from

$$R_y = (3214)\left(\frac{Q}{D}\right) \tag{5}$$

where Q is the flow rate (gpm) and D is the inside diameter of the lateral (in.). Emitter discharge was determined using the emitter equation

$$q_e = k\,p^x \tag{6}$$

where q_e is the emitter discharge (gph), k is the emitter flow constant, p is the emitter pressure (psi) and x is the emitter discharge exponent. An emitter discharge exponent of 0.5 was used in all calculations.

Lateral emission uniformity (EU) and emitter flow variation (q_{var}) were used to quantify the "quality" of a design. Emission uniformity was calculated as:

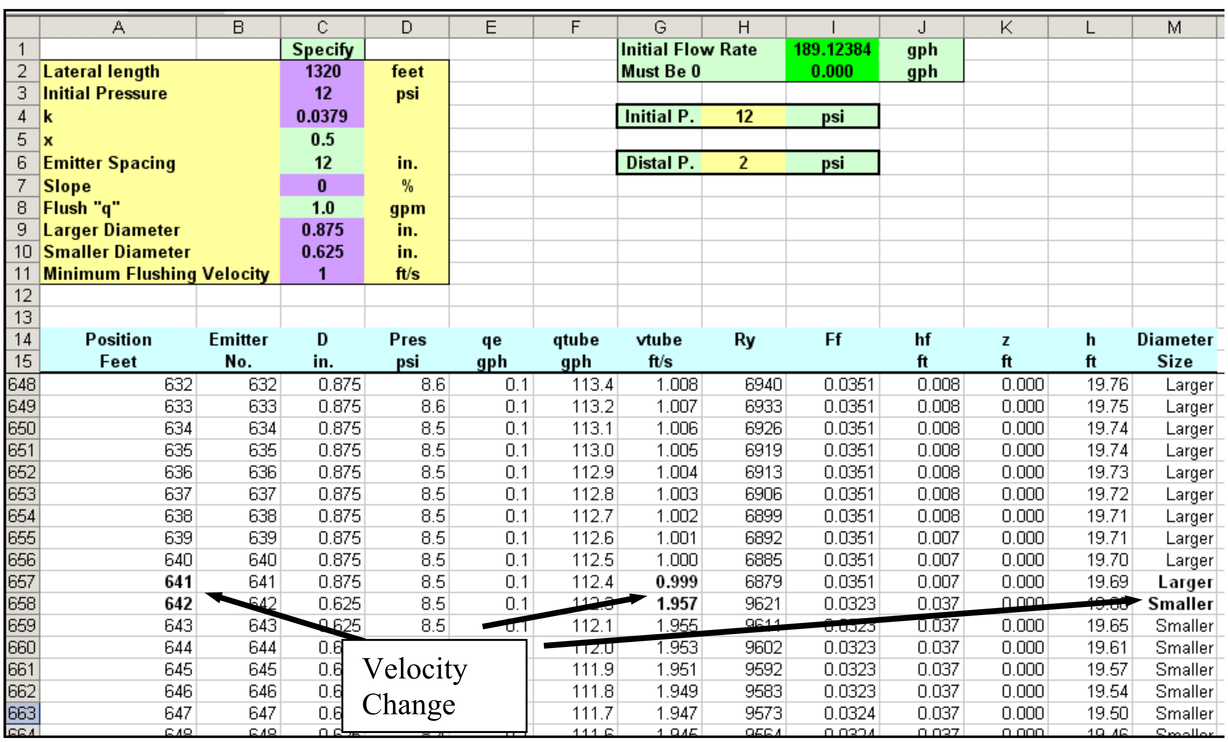
$$EU = 100\left(1.0 - 1.27\frac{C_v}{\sqrt{n_p}}\right)\frac{q_{\min}}{q_a} \tag{7}$$

where C_v is the manufacturers coefficient of variation (a value of 0.03 was used in all analyses), n_p is the number of emitter per plant (1 for these analyses), q_{min} is the minimum emitter discharge on the lateral, and q_a is the average emitter discharge for the lateral. The emitter flow variation (q_{var}) was calculated as

$$q_{var} = \left(\frac{q_{max} - q_{min}}{q_{max}} \right) (100) \qquad (8)$$

where q_{max} is the maximum emitter discharge along the lateral and q_{min} is the minimum emitter discharge along the lateral.

The previously described relationships were programmed into a spreadsheet model (fig. 1). That model and a companion model were used to determine the optimal location of the split junction from larger to smaller lateral based upon maintaining a minimum flow velocity of 1 ft/s in all portions of the lateral during a "flushing" operation. Flushing operation criteria used a distal pressure of 3 psi with nominal tubing flow rates of 0.20, 0.25, and 0.25 gpm/100 ft (based on a nominal pressure of 8 psi), and slopes of 0, –0.5%, and –1%. While the "optimal " junction location varied with the three lateral design flow rates and distal pressure, most were close to the midpoint of the lateral. Thus, subsequent design runs were conducted using a midpoint junction position. Flushing operation simulations generated values for inlet pressure, lateral flow rate, and time to completely flush the lateral.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1			Specify				Initial Flow Rate		189.12384	gph			
2	Lateral length		1320	feet			Must Be 0		0.000	gph			
3	Initial Pressure		12	psi									
4	k		0.0379				Initial P.	12	psi				
5	x		0.5										
6	Emitter Spacing		12	in.			Distal P.	2	psi				
7	Slope		0	%									
8	Flush "q"		1.0	gpm									
9	Larger Diameter		0.875	in.									
10	Smaller Diameter		0.625	in.									
11	Minimum Flushing Velocity		1	ft/s									
12													
13													
14	Position	Emitter	D	Pres	qe	qtube	vtube	Ry	Ff	hf	z	h	Diameter
15	Feet	No.	in.	psi	gph	gph	ft/s			ft	ft	ft	Size
648	632	632	0.875	8.6	0.1	113.4	1.008	6940	0.0351	0.008	0.000	19.76	Larger
649	633	633	0.875	8.6	0.1	113.2	1.007	6933	0.0351	0.008	0.000	19.75	Larger
650	634	634	0.875	8.5	0.1	113.1	1.006	6926	0.0351	0.008	0.000	19.74	Larger
651	635	635	0.875	8.5	0.1	113.0	1.005	6919	0.0351	0.008	0.000	19.74	Larger
652	636	636	0.875	8.5	0.1	112.9	1.004	6913	0.0351	0.008	0.000	19.73	Larger
653	637	637	0.875	8.5	0.1	112.8	1.003	6906	0.0351	0.008	0.000	19.72	Larger
654	638	638	0.875	8.5	0.1	112.7	1.002	6899	0.0351	0.008	0.000	19.71	Larger
655	639	639	0.875	8.5	0.1	112.6	1.001	6892	0.0351	0.007	0.000	19.71	Larger
656	640	640	0.875	8.5	0.1	112.5	1.000	6885	0.0351	0.007	0.000	19.70	Larger
657	**641**	641	0.875	8.5	0.1	112.4	**0.999**	6879	0.0351	0.007	0.000	19.69	**Larger**
658	**642**	642	0.625	8.5	0.1	[illegible]	**1.957**	9621	0.0323	0.037	0.000	[illegible]	**Smaller**
659	643	643	0.625	8.5	0.1	112.1	1.955	9611	[illegible]	0.037	0.000	19.65	Smaller
660	644	644	0.6			112.0	1.953	9602	0.0323	0.037	0.000	19.61	Smaller
661	645	645	0.6			111.9	1.951	9592	0.0323	0.037	0.000	19.57	Smaller
662	646	646	0.6			111.8	1.949	9583	0.0323	0.037	0.000	19.54	Smaller
663	647	647	0.6			111.7	1.947	9573	0.0324	0.037	0.000	19.50	Smaller

Figure 1. Display of the "Split" spreadsheet that was used to determine the split junction between larger and smaller diameter laterals.

Simulations were next conducted on those laterals for "normal" operation. Under the normal operation simulations, the inlet pressure was set at 10 psi for each of the design lateral flow rates and lateral slopes. These simulation runs provided data on distal pressure, actual lateral flow rate

(q_{lat}), emission uniformity (EU), emitter flow variation (q_{var}), and time for an injected chemical to travel to the end of the tube ($Time_{end}$) and to 10 ft from the end of the tube ($Time_{end-10}$). Both models were run for a straight 11/8-inch lateral, a 11/8-inch to 7/8-inch tapered lateral, and a 11/8-inch to 9/8-inch tapered lateral.

Results

Example emitter discharge profiles on a level (05) slope for all three lateral combinations are shown in fig. 2. The 11/8 to 7/8 combination has a more substantial emitter discharge variation due to friction losses than the 11/8 to 9/8 combination. The 11/8 to 7/8 combination would not be acceptable for a zero slope condition.

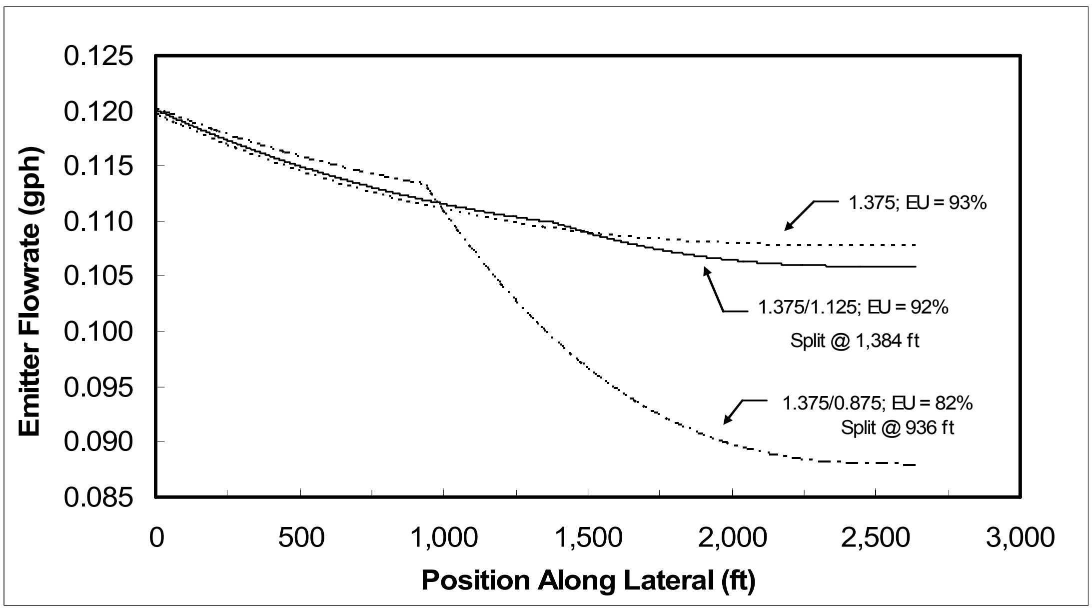


Figure 2. Emitter discharge along the length of a 2,640-ft-long lateral under normal operating conditions for a standard 1.375-in. lateral, a tapered 1.375 – 1.125-in. lateral, and a 1.375 - 0.875-in. lateral.

Summary tables of the hydraulic performance of all lateral and nominal flow combinations are shown in tables 1, 2, and 3. The non-tapered 11/8-inch lateral with a nominal flow of 0.20 gpm/100 ft (tab. 1a) resulted in distal pressures of 7.8, 12.8, and 17.8 psi for slopes of 0, -0.5%, and –1%, respectively. Associated emission uniformities were 93, 92, and 84%. Thus the steeper slope reduced the performance level of the lateral. Travel times to the end of the lateral ranged from 223 to 330 minutes while travel times to a position 10 feet upstream from the lateral ranged from 147 to 215 minutes. It is probably more realistic to use the $Time_{end-10}$ data which substantially reduces the travel time. However, the travel times can average 3 hours or more. Similar results exist for the other nominal flowrates of 0.25 and 0.30 gpm/100 ft (tab. 1b and 1c).

Tapering of the laterals from 11/8-inch to 7/8-inch (tables 2a, 2b, and 2c) and from 11/8-inch to 9/8-inch (tables 3a, 3b, and 3c) reduced both distal pressures and travel times for injected chemicals. In general the 11/8 to 7/8 inch combination was not desirable due to low (<90) emission uniformities. However, the 11/8 to 9/8 inch combination had acceptable (>90) or near acceptable emission uniformities for most nominal flow rates and slopes. This lateral combination reduced the end-10 chemical travel time ($Time_{end-10}$) times by 40 to 60 minutes for the 0.20 gpm/100 ft laterals. This situation can enhance the discharge and application uniformity of injected chemicals. This tapered lateral combination also reduced the required flowrate during flushing by 1.0 to over 1.5 gpm per lateral while maintaining similar lateral inlet pressures during the flushing operation. The times to purge the lateral during flushing were minimally increased. These are desirable design and operational conditions.

Summary and Conclusions

Spreadsheet models were developed to simulation drip irrigation lateral hydraulics to determine flow requirements, emission uniformity, and chemical travel times for tapered and non-tapered laterals. Models were run for a straight 11/8-inch lateral, a 11/8-inch to 7/8-inch tapered lateral, and a 11/8-inch to 9/8-inch tapered lateral. Each of these lateral combinations were simulated for nominal flow rates of 0.20, 0.25, and 0.25 gpm/100ft, and slopes of 0%, -0.5%, and –1.0%.

Tapered laterals reduced the travel time of injected chemicals and reduced required flow rates during the flushing process. The 11/8-inch to 7/8-inch combination was generally not desirable due to low emission uniformities. However, the 11/8 to 9/8-inch combination was acceptable for most simulation scenarios.

Table 1. Normal and flushing operation data for an 11/8-inch diameter, 2,640 ft lateral at nominal flowrates of (a) 0.20, (b) 0.25, and (c) 0.30 gpm/100 ft.

a. 11/8-inch --- 0.20 gpm/100ft			**Slopes (%)**		
Operation	**Parameter**	**Unit**	**0%**	**-0.50%**	**-1.00%**
Normal	Distal P	psi	7.8	12.8	17.8
	q_{lat}	gpm	5.40	6.11	6.73
	EU	%	93	92	84
	qvar	%	12	12	25
	$Time_{end}$	min	330	261	223
	$Time_{end-10}$	min	215	172	147
Flushing	Inlet P	psi	12.6	5.8	3.6
	q_{lat}	gpm	9.41	8.20	9.27
	Time	min	32	33	27

b. 11/8-inch --- 0.25 gpm/100ft			**Slopes (%)**		
Operation	**Parameter**	**Unit**	**0%**	**-0.50%**	**-1.00%**
Normal	Distal P	psi	7.0	11.7	16.4
	q_{lat}	gpm	6.48	7.35	8.08
	EU	%	91	93	87
	qvar	%	17	11	22
	$Time_{end}$	min	279	219	186
	$Time_{end-10}$	min	182	144	123
Flushing	Inlet P	psi	14.2	7.0	3.1
	q_{lat}	gpm	10.77	9.28	9.33
	Time	min	30	31	27

c. 11/8-inch --- 0.30 gpm/100ft			**Slopes (%)**		
Operation	**Parameter**	**Unit**	**0%**	**-0.50%**	**-1.00%**
Normal	Distal P	psi	6.2	10.6	15.1
	q_{lat}	gpm	7.46	8.45	9.32
	EU	%	90	93	89
	qvar	%	22	11	21
	$Time_{end}$	min	247	192	162
	$Time_{end-10}$	min	161	126	107
Flushing	Inlet P	psi	16.0	8.3	3.5
	q_{lat}	gpm	12.21	10.44	9.80
	Time	min	28	30	27

Table 2. Normal and flushing operation data for a tapered 11/8-inch to 7/8-inch diameter, 2,640 ft lateral at nominal flowrates of (a) 0.20, (b) 0.25, and (c) 0.30 gpm/100 ft.

a. 11/8 -7/8 inch --- 0.20 gpm/100ft			**Slopes (%)**		
Operation	**Parameter**	**Unit**	**0%**	**-0.50%**	**-1.00%**
Normal	Distal P	psi	6.0	10.2	14.4
	q_{lat}	gpm	5.19	5.85	6.45
	EU	%	85	93	88
	qvar	%	23	7	17
	$Time_{end}$	min	168	133	113
	$Time_{end-10}$	min	115	92	79
Flushing	Inlet P	psi	16.5	9.4	3.9
	q_{lat}	gpm	7.75	6.76	6.04
	Time	min	33	35	35

b. 11/8 -7/8 inch --- 0.25 gpm/100ft			**Slopes (%)**		
Operation	**Parameter**	**Unit**	**0%**	**-0.50%**	**-1.00%**
Normal	Distal P	psi	4.9	8.5	12.3
	q_{lat}	gpm	6.18	6.95	7.65
	EU	%	80	90	93
	qvar	%	31	12	10
	$Time_{end}$	min	148	116	98
	$Time_{end-10}$	min	101	80	68
Flushing	Inlet P	psi	19.9	12.4	4.6
	q_{lat}	gpm	9.68	8.47	6.90
	Time	min	29	30	33

c. 11/8 -7/8 inch --- 0.30 gpm/100ft			**Slopes (%)**		
Operation	**Parameter**	**Unit**	**0%**	**-0.50%**	**-1.00%**
Normal	Distal P	psi	3.9	7.1	10.4
	q_{lat}	gpm	7.04	7.94	8.72
	EU	%	75	86	90
	qvar	%	38	20	13
	$Time_{end}$	min	138	105	88
	$Time_{end-10}$	min	94	73	61
Flushing	Inlet P	psi	24.0	15.9	7.5
	q_{lat}	gpm	11.83	10.40	8.61
	Time	min	25	27	30

Table 3. Normal and flushing operation data for a tapered 11/8-inch to 9/8-inch diameter, 2,640 ft lateral at nominal flowrates of (a) 0.20, (b) 0.25, and (c) 0.30 gpm/100 ft.

a. 11/8 -9/8 inch --- 0.20 gpm/100ft			**Slopes (%)**		
Operation	**Parameter**	**Unit**	**0%**	**-0.50%**	**-1.00%**
Normal	Distal P	psi	7.3	12.1	17.0
	q_{lat}	gpm	5.33	6.04	6.66
	EU	%	91	93	85
	qvar	%	14	10	23
	$Time_{end}$	min	237	187	160
	$Time_{end-10}$	min	158	126	108
Flushing	Inlet P	psi	12.7	5.9	3.0
	q_{lat}	gpm	8.16	7.02	7.42
	Time	min	33	35	30

b. 11/8 -9/8 inch --- 0.25 gpm/100ft			**Slopes (%)**		
Operation	**Parameter**	**Unit**	**0%**	**-0.50%**	**-1.00%**
Normal	Distal P	psi	6.4	10.9	15.4
	q_{lat}	gpm	6.41	7.24	8.00
	EU	%	89	94	89
	qvar	%	20	8	19
	$Time_{end}$	min	202	158	134
	$Time_{end-10}$	min	134	106	91
Flushing	Inlet P	psi	14.6	7.4	3.7
	q_{lat}	gpm	9.66	8.26	8.22
	Time	min	30	32	29

c. 11/8 -9/8 inch --- 0.30 gpm/100ft			**Slopes (%)**		
Operation	**Parameter**	**Unit**	**0%**	**-0.50%**	**-1.00%**
Normal	Distal P	psi	5.5	9.7	13.8
	q_{lat}	gpm	7.34	8.32	9.15
	EU	%	86	94	91
	qvar	%	26	9	17
	$Time_{end}$	min	181	140	118
	$Time_{end-10}$	min	120	94	80
Flushing	Inlet P	psi	16.8	9.2	3.7
	q_{lat}	gpm	11.26	9.62	8.61
	Time	min	28	30	29

Cotton production with SDI, LEPA, and spray irrigation in a thermally-limited climate[1]

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Abstract

Producers in the Northern Texas Panhandle and Southwestern Kansas are considering cotton as an alternative crop to corn because cotton has a similar profit potential for about one-half the irrigation requirement. However, limited growing degree days pose some risk for cotton production. We hypothesized that cotton under subsurface drip irrigation (SDI) would undergo less evaporative cooling following an irrigation event compared with low energy precision applicators (LEPA) or spray irrigation and, therefore, would increase growing degree day accumulation and lead to earlier maturation. Cotton maturity was more related to irrigation rate than irrigation method, with dryland and minimal irrigation rates reaching maturity earliest. However, fiber quality, as indicated by total discount, was usually better with SDI. Lint yield and water use efficiency were greatest with SDI at low irrigation rates in 2003, and lint yield and gross returns were greatest with SDI regardless of irrigation rate in 2004.

Introduction

The Southern High Plains of Texas, centered at approximately Lubbock, is one of the major cotton-producing areas in the United States, contributing approximately 10-20 percent of the average 20 million bales of upland cotton produced in the nation (USDA-NASS, 2005; TDA-TASS, 2005). In recent years, cotton production has expanded northward toward the Northern Texas Panhandle and Southwestern Kansas as an alternative to corn because cotton has only one-half the irrigation requirement but has a similar revenue potential as corn (Howell et al., 1997; 2004). The primary limitation to cotton production where corn has traditionally been produced is the lack of growing degree days (heat units) (Peng et al., 1989; Morrow and Krieg, 1990) and the lack of an industry infrastructure (gins, custom harvesters, etc.). The other main limitation is of course water, specifically the declining availability of irrigation water from the Ogallala aquifer, insufficient and sporadic in-season rainfall, and high evaporative demand. Despite these limitations, Howell et al. (2004) showed that cotton production in this area is feasible, with lint yields and water use efficiencies comparable to those in more ideal climates (Zwart and Bastiaanssen, 2004).

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Pressurized irrigation systems such as mechanically moved and microirrigation can enhance cotton lint yield and water use efficiency compared to furrow (gravity) irrigation or dryland regimes, provided the pressurized system is properly designed and managed. Mechanically moved systems have numerous variants of applicator packages, with the more common configurations being mid- and low-elevation spray application (MESA and LESA, respectively) and LEPA (Low Energy Precision Applicator; Lyle and Bordovsky, 1983; Bordovsky et al., 1992). Microirrigation, usually in the form of subsurface drip irrigation (SDI), has been widely adopted by commercial cotton producers throughout the South Plains and Trans Pecos regions of Texas beginning in the early 1980s (Henggeler, 1995; 1997; Enciso et al., 2003; 2005). Although SDI has significantly greater initial costs than spray or LEPA systems (O'Brien et al., 1998; Segarra et al., 1999), it has been documented to slightly outperform LEPA and spray in terms of lint yield, lint quality (as reflected by loan prices), and water use efficiency (Segarra et al., 1999; Bordovsky and Porter, 2003). Similar trends have been reported for surface drip where laterals were placed in alternate furrows (Yazar et al., 2002) and each planted row (Cetin and Bilgel, 2002). Nonetheless, Segarra et al. (1999), analyzing four years of continuous monoculture cotton data at Halfway, Texas, concluded that SDI may not always provide economic returns as large as LEPA does; but this largely depended on system life, installation costs, pumping lift requirements, and hail damage that commonly occurs in West Texas. Also, Howell et al. (1987) found no differences in lint yield of narrow row (0.5 m) cotton between surface drip and furrow irrigation systems that were designed and managed to minimize soil water deficits, although soil water evaporative losses were less for surface drip.

There is a general perception by some cotton producers that SDI enhances seedling emergence and plant maturity due to reduced evaporative cooling compared to LEPA or spray, which is a critical consideration in a thermally limited environment and is seldom considered in economic analyses. There is, however, limited data in direct support of this view. Next to air temperature, soil water depletion in the root zone appears most responsible for inducing earliness for cotton (Guinn et al., 1981; Mateos et al., 1991; Orgaz et al., 1992) as well as for other crops (Wang, 1960; Idso et al., 1978). Nonetheless, a few studies may indirectly support the premise that SDI can enhance cotton maturity. Wang et al. (2000) reported that mean soil temperatures were 4.4 °C greater for plots irrigated with surface drip laterals than stationary rotating sprinklers, and they observed greater emergence rates and seedling development of soybeans. They noted, however, that their results may have been influenced by the solar heating of water as it passed through the black plastic drip laterals rather than the greater evaporating surface area of the sprinkler plots. Tolk et al. (1995) showed that corn transpiration rates, canopy temperature, and vapor pressure deficits were significantly reduced for several hours following irrigation by overhead impact sprinklers, but not greatly changed following irrigation by LEPA in alternate furrows. The reduced evaporative cooling thought to be associated with SDI, on the other hand, may be countered by the greater cooling effect of increased irrigation frequency (Wanjura et al., 1996). Constable and Hodgson (1990) reported that cotton under SDI matured several days later than cotton under furrow irrigation.

The objectives of this study are to evaluate cotton yield, fiber quality, and maturity rates for spray, LEPA, and SDI under full and deficit irrigation in the Northern Texas Panhandle, which is a marginal climate for cotton production. This paper presents the results of the 2003 and 2004 growing seasons.

Procedure

An experiment was conducted during the 2003 and 2004 growing seasons using MESA, LESA, LEPA, and SDI to irrigate cotton at the USDA Conservation and Production Research Laboratory in Bushland, Texas (35° 11′ N lat., 102° 06′ W long., 1070 m elevation MSL). The climate is semi-arid with a high evaporative demand of about 2,600 mm per year (Class A pan evaporation) and low precipitation averaging 470 mm per year. Most of the evaporative demand and precipitation occur during the growing season (May to October) and average 1,550 mm and 320 mm, respectively. Cumulative growing degree days (heat units) for cotton average 1,050 °C-days during the growing season (mean daily air temperature minus base temperature of 15.6 °C); however, Peng et al. (1989) state that about 1,450°C is required for full maturity cotton in the region to our south centered around Lubbock, TX. The climate is also characterized by strong regional advection from the south and southwest, with average daily wind runs at 2 m height exceeding 460 km, especially during the early part of the growing season. The soil is a Pullman clay loam (fine, superactive, mixed, thermic torrertic Paleustoll; USDA-NRCS, 2005), with slow permeability due to a dense B21t layer that is 0.15- to 0.40-m below the surface. A calcic horizon begins about 1.2 m below the surface.

Agronomic practices were similar to those practiced for high lint yield in the High Plains region of Texas (Table 1). Cotton (*Gossypium hirsutum* L., Paymaster[3] 2280 BG RR) was planted on 21 May 2003, and disked and replanted on 10 June 2003 (following severe hail damage to seedlings) at 17.3 plants m^{-2}, on east-west oriented raised beds spaced 0.76 m. The same variety was planted on 20 May 2004 at 19.0 plants m^{-2}. In 2004 only, this variety was also planted in an adjacent, non-irrigated field at 12.5 plants m^{-2}, where every third row was not planted (known regionally as "skip row" planting). Furrow dikes were installed in the irrigated field after crop establishment both years to control runoff (Schneider and Howell, 2000). In 2003, preplant fertilizer containing nitrogen (N) and phosphorous (P) (10-34-0) was incorporated into the raised beds, at rates resulting in 31 and 107 kg ha^{-1} of N and P, respectively, which were based on a soil fertility analysis. In 2004, similar rates of preplant fertilizer were applied (34 and 114 kg ha^{-1} of N and P, respectively). Additional N (32-0-0) was injected into the irrigation water from first square to early bloom, resulting in a total N application of 48 and 50 kg ha^{-1} in 2003 and 2004, respectively, for the full irrigation treatment. Deficit irrigation treatments received proportionately less N in irrigation water. Treflan was applied at one time before planting at 2.3 L ha^{-1} to control broadleaf weeds in both seasons. No other in-season or post-harvest chemical inputs were required in either year.

The experimental design consisted of four irrigation methods (MESA, LESA, LEPA, SDI, described in more detail shortly), and five irrigation rates (I_0, I_{25}, I_{50}, I_{75}, and I_{100}). The I_{100} rate was sufficient to prevent yield-limiting soil water deficits from developing, and the subscripts are the percentage of irrigation applied relative to the full (I_{100}) irrigation rate. The I_{100} rate was based on soil water measurements with neutron scattering to 2.4-m depth. Early in the season, irrigation water was applied when soil water measurements indicated a deficit of 25 mm

[3] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

below field capacity in the I_{100} treatment. From first square to termination of irrigations, the appropriate irrigation amount was applied on a weekly basis. The different irrigation rates were used to estimate production functions, and to simulate the range of irrigation capacities one might encounter in the region. The I_0 rate received sufficient irrigation for emergence only and to settle and firm the furrow dikes and represents dryland production. In 2004, the adjacent non-irrigated field ("skip row," designated I_{sr}) was actually a true dryland treatment; however, available resources limited soil water and plant measurements to the irrigated field (I_0 through I_{100} treatments) so that only final lint yield and fiber quality were obtained for the I_{sr} treatment. The statistical design was a variant of the split-block design (Little and Hills, 1978), where irrigation methods were in the direction of travel of a three-span lateral move system, and irrigation rates were perpendicular to the direction of travel. This sacrificed the power of comparing different irrigation rates, but was necessary to facilitate operation of the lateral-move system using applicators common in the Southern High Plains. Each span of the linear move system constituted a complete block (i.e., replicated three times), and irrigation methods were randomized within each block. Plots were 25 m long by 9 m wide with 12 rows each, and 5 m planted borders separated irrigation rate strips.

Spray and LEPA irrigations were applied with a hose-fed Valmont (Valmont Irrigation, Valley, NE) Model 6000 lateral move irrigation system. Drop hoses were located over every other furrow at 1.52-m spacing. Applicators were manufactured by Senninger (Senninger Irrigation Inc., Orlando, FL) and were equipped with 69-kPa pressure regulators and #17 plastic nozzles, giving a flow rate of 0.41 L s^{-1}. The MESA and LESA spray heads were positioned 1.5 and 0.3 m above the furrow, respectively. A double-ended drag sock (A. E. Quest and Sons, Lubbock, TX) was used with LEPA. The SDI consisted of Netafim (Netafim USA, Fresno, CA) Typhoon dripline that was shank injected in 1999 under alternate furrows at 0.3 m depth below the surface (before bedding). Irrigation treatment levels were controlled by varying the speed of the lateral-move system for the spray and LEPA methods, and by different emitter flow and spacing for the SDI method. All treatments were irrigated uniformly with MESA at the I_{100} level until furrow dikes were installed to ensure crop establishment.

Soil water was measured gravimetrically near the center of each plot prior to planting and just after harvest to 1.8-m depth in 0.3-m increments, oven dried, and converted to volumetric contents using known soil bulk densities by profile layer. During the season, soil water was measured volumetrically near the center of each plot on a weekly basis by neutron attenuation to 2.4-m depth in 0.2-m increments according to procedures described in Evett and Steiner (1995) and Evett et al. (2003). The gravimetric samples were used to compute seasonal water use (irrigation + rainfall + change in soil water), and the neutron measurements were used to verify that irrigation was sufficient so that no water deficits developed in the I_{100} treatment.

Plants were mapped both seasons in all plots on a weekly basis beginning with 1st square, which included data on height, width, nodes, and number and position of fruit forms. Hand samples of bolls were collected from each plot on 19 Nov 2003 and 14 Dec 2004 from a 10 m^2 area that was sequestered from other activity during the season. Samples were weighed, ginned, and analyzed for micronaire, strength, color grade, and uniformity at the International Textile Center, Lubbock, Texas. Seed cotton was harvested following hand sampling with a commercial cotton stripper, and stalks were shredded and rotary-tilled into the beds.

Lint yield, seasonal water use (estimated from total irrigation + in season rainfall + change in soil water content to the 1.8-m depth), micronaire, strength, uniformity, water use efficiency (WUE), and irrigation water use efficiency (IWUE), total discount, and total return were tested for differences for each irrigation method using the SAS mixed model (PROC MIXED, Littell et al., 1996). In PROC MIXED, fixed and random effects are specified separately. Random effects were block replicates, block by irrigation rate, and block by irrigation method, and the fixed effect was irrigation method. Differences of fixed effects were tested using least square means ($\alpha \leq 0.05$) within each irrigation rate. Here, WUE was defined as the ratio of economic yield (i.e., lint yield, LY) to seasonal water use (WU) or $WUE = LY\ WU^{-1}$. Seasonal water use includes evapotranspiration, deep percolation (if any), and runoff minus run on (if any). IWUE was defined as the increase in irrigated yield (Y_i) over dryland yield (Y_d) due to irrigation (IR), or $IWUE = (Y_i - Y_d)\ IR^{-1}$ (Bos, 1980). Further details of experimental design, procedures, and equipment can be found in Colaizzi et al. (2004).

Results and Discussion

Rainfall, Irrigation, and Growing Degree Days

The 2003 and 2004 growing seasons contrasted in that 2003 had below average rainfall and above-average air temperatures (Figure 1) and *vice-versa* for 2004 (Figure 2). In 2003, in-season rainfall was near the 66-year average until around 30 June, which allowed in-season irrigations to be delayed until 8 July as there was sufficient water stored in the soil profile (Figure 1a). No significant rainfall occurred again until 29 August, and the last irrigation was on 20 August. Irrigations plus rainfall (since planting only; does not include preplant irrigation) for the I_{100} treatment tracked crop water use (measured by gravimetric samples and neutron scattering in the 1.8-m profile, I_{100} treatment average) fairly well until irrigations were terminated just after maximum bloom, indicating irrigation timing and amounts were appropriate. Additional water for consumptive use after 20 August was provided by water stored in the soil profile.

Cumulative growing degree days (15.6 ˚C base temperature; Fry, 1983; Peng et al., 1989) from replanting (10 June) to harvest (21 November) in 2003 totaled 1076 °C-days (Figure 1b). This was above the 17-year average of 893 °C-days for this period, and record high air temperatures from 16 September to 23 October were no doubt fortuitous in compensating for a late start following replanting due to hail damage. The first open boll in the I_{100} treatment was not observed until 22 September (900 °C-days), but nearly all bolls were open by 20 October, and the first frost occurred on 26 October. Additional frost events defoliated all remaining vegetative matter so that chemical defoliant was not required by harvest (21 November).

In 2004, in-season rainfall was unusually frequent but remained slightly below the 66-year average until late September, after which precipitation was above average for the remainder of the year (Figure 2a). Precipitation frequency continued to be unusually high for the remainder of the season, and the crop could not be harvested until 14 December. Numerous freeze events beginning 14 Oct (including 36 cm of snow on 2 Nov) defoliated all vegetative material and hastened boll opening by harvest so that no chemical defoliant was required. The period up to the first neutron scattering measurement (23 June) indicated only 5 mm of water use on average for the I_{100} irrigation rate (Figure 2a). This was unlikely because there were two 25-mm irrigation events and numerous rainfall events (totaling 38 mm). Furthermore, evaporation from bare soil plus a very small amount of transpiration from young plants was estimated at 53 mm using the Food and Agriculture Organization Paper No. 56 (FAO 56) dual crop coefficient approach (Allen et al., 1998). It is possible that unaccounted water entered the soil profile control volume from field run-on following a series of rainfall events 3-6 June that totaled 21 mm before the furrow dikes were installed (16 June).

Cumulative growing degree days for 2004 were near the 17-year average from planting (20 May) until around 9 August, and below average thereafter, only reaching 865 °C-days by harvest (Figure 2b). This is considerably below the 17-year average of 1000 °C-days for the same period. Cumulative growing degree days for both the 2003 and 2004 seasons were considerably less than the 1450 °C-days thought to be required for full maturity cotton in the Southern High Plains (Peng et al., 1989). The 2003 season (1076 °C-days) was slightly less than that reported by Howell et al. (2004) for the 2000 and 2001 cotton seasons at our location, and was at the minimal range of growing degree days reported by Wanjura et al. (2002) for 12 years of data at Lubbock, TX. The 2004 season (865 °C-days) represents the least amount of growing degrees documented for full maturity cotton that we are aware of.

Crop Response to Irrigation Methods and Rates

No differences in maturity rates (open harvestable bolls) were noted for any irrigation method (MESA, LESA, LEPA, or SDI) in both the 2003 and 2004 seasons. Differences in maturity rates appeared to vary primarily with irrigation rates, beginning with I_0 and I_{sr}, which had the greatest soil water depletion, and proceeding through each subsequent level, in agreement with Guinn et al. (1981), Mateos et al. (1991), and Orgaz et al. (1992).

Crop response in terms of lint yield, seasonal water use, water use efficiency (WUE), irrigation water use efficiency (IWUE), fiber quality parameters, discount or premium, and gross return were evaluated for irrigation rates and methods for 2003 (Table 2) and 2004 (Table 3). In 2003, crop response with SDI was most favorable at the I_{25} and I_{50} irrigation rates, followed by LEPA. At I_{75}, LEPA outperformed the other methods, and at I_{100}, MESA performed best. For a given irrigation rate, seasonal water use was greatest for SDI at I_{25} and I_{75}, nearly the same as LEPA at I_{50}, but smallest at I_{100}. Total discount or premium reflects fiber quality from a base loan value of \$1.1352 kg^{-1}, and SDI had the highest premiums at all irrigation rates except for I_{100}, which suggests SDI generally results in higher fiber quality. This is an important consideration given the greater emphasis placed on fiber quality by the textile industry in recent years. Fully irrigated MESA (I_{100}) had the highest lint yield (1,229 kg ha^{-1}), premium (\$0.0950 kg^{-1}), and gross return (\$1,515.96 ha^{-1}) of all treatments in this study, but these were not always significantly greater than other irrigation methods at I_{100}. Most parameter differences within a given irrigation rate were not significant, including seasonal water use, and crop response varied more by irrigation rate than method. Among irrigation methods, I_{100} resulted in the greatest values of lint yield, seasonal water use, WUE, premium, and gross return. However, I_{75} resulted in the greatest IWUE and most optimal fiber quality parameters (except fiber length). Note that WUE at I_{50} and I_{100} were more than doubled and almost quadrupled, respectively, over I_0.

Similar trends were observed with grain sorghum yield in a previous study using the same experimental design (Colaizzi et al., 2004).

The cooler and wetter conditions of 2004 (Table 3) resulted in less seasonal water use, IWUE, micronaire, fiber strength, and greater discounts compared to 2003 (Table 2). Micronaire values were especially poor (the greatest was only 3.37 for I_0), and all treatments resulted in discounts below the base loan value. The greater precipitation also reduced the response to irrigation rates for lint yield, seasonal water use, WUE, IWUE, and gross return. Nonetheless, crop response parameters, including fiber quality, were significantly greater with SDI at all irrigation rates except for I_{25}, as well as among irrigation rates. Fiber quality, however, was best for the skip row treatment (I_{sr}), which reflects true dryland cotton production in the region, and I_{sr} had the smallest loan value discount (-\$0.0422 kg^{-1}) of all treatments in 2004, and the second highest gross return (\$649.25 kg^{-1}). From a commercial production standpoint, net returns would have been greatest for I_{sr} in 2004 because there were no costs associated with irrigation, but probably negative in 2003 because drought conditions would have resulted in near nonexistent lint yield.

The 2003 and 2004 lint yield, seasonal water use, and WUE were within the range of values reported by Howell et al. (2004) for the 2000 and 2001 cotton seasons under MESA irrigation at our location, and 2003 lint yields were almost as high as those reported by Wanjura et al. (2002) for their 1992 season, which only had 1092 °C-days. They found that lint yield was more correlated to growing degree days than irrigation applied over their 12 years of data.

<u>Production Functions and Water Use Efficiency</u>

The relationships between lint yield and seasonal water use were significant ($P < 0.001$) following linear regression for each year (Figure 3). These relationships were not significantly different from those for individual irrigation methods, not surprising since lint yield showed greater variability with irrigation levels than for irrigation methods (Tables 2 and 3). The different responses should be expected for different years due to interactions between seasonal water use, growing degree days, and other environmental factors (Wanjura et al., 2002; Howell et al., 2004). The X-axis intercept was significantly different from zero in 2003 ($P < 0.001$) but not in 2004 ($P = 0.234$). In 2003, 400 mm of water was required for minimum lint yield, which was double reported by Howell et al. (2004) for the 2000 and 2001 seasons at our location.

Conclusion

Cotton maturity was influenced by soil water depletion (reflected by irrigation rate) rather than irrigation method. Fiber quality was usually better with SDI in both years, which is becoming increasingly important in the global market. For a given irrigation rate, seasonal water use differences were not always significant or consistent between irrigation methods, with seasonal water use sometimes being greater with SDI, possibly due to enhanced plant vigor. In 2003, SDI outperformed (either numerically or significantly) other irrigation methods at low irrigation rates (I_{25} and I_{50}). However, MESA and LESA outperformed both LEPA and SDI at the I_{100} rate, but only on a numerical basis. At the I_{75} rate, LEPA numerically outperformed SDI, and SDI numerically outperformed MESA and LESA. In 2004, SDI outperformed (often significantly) all other methods at the I_{50}, I_{75}, and I_{100} rates, as well as among irrigation rates. In both years, significant (but different) relationships were observed between lint yield and seasonal water use.

In order to further investigate crop response to irrigation methods, this study has been expanded to include detailed studies of near-surface soil temperature and volumetric moisture content, where arrays of permanent thermocouple and time-domain reflectometry (TDR) probes were installed in the raised beds beginning with the 2005 season. Large hail on 10-11 June 2005 destroyed the third cotton crop, and the field was replanted in soybeans, but it appears we have obtained quality soil temperature and moisture data for several irrigation events. Plans are to plant cotton again in 2006.

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References

Allen, R. G., L. S. Periera, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. Irrig. and Drain. Paper No. 56. United Nations, Food and Agric. Org.: Rome, Italy.

Bordovsky, J. P., and D. Porter. 2003. Cotton response to pre-plant irrigation level and irrigation capacity using spray, LEPA, and subsurface drip irrigation. Presented at the 2003 ASAE International Meeting, Las Vegas, NV, 27-30 July. ASAE Paper No. 032008.

Bordovsky, J. P., W. M. Lyle, R. J. Lascano, and D. R. Upchurch. 1992. Cotton irrigation management with LEPA systems. *Trans. ASAE.* 35(3): 879-884.

Bos, M. G. 1980. Irrigation efficiencies at crop production level. *ICID Bull.* 29: 18-25, 60.

Cetin, O., and L. Bilgel. 2002. Effects of different irrigation methods on shedding and yield of cotton. *Agric. Water Manage.* 54(1): 1-15.

Colaizzi, P. D., A. D. Schneider, S. R. Evett, T. A. Howell. 2004. Comparison of SDI, LEPA, and spray irrigation performance for grain sorghum. *Trans. ASAE.* 47(5): 1477-1492.

Constable, G. A. and A. S. Hodgson. 1990. A comparison of drip and furrow irrigated cotton on a cracking clay soil. 3. Yield and quality of four cultivars. *Irrig. Sci.* 11(3): 149-153.

Enciso, J. M., P. D. Colaizzi, and W. L. Multer. 2005. Economic analysis of subsurface drip irrigation lateral spacing and installation depth for cotton. *Trans ASAE.* 48(1): 197-204.

Enciso, J., B.L. Unruh, P.D. Colaizzi, and W.L. Multer. 2003. Cotton Response to Subsurface Drip Irrigation Frequency under Deficit Irrigation. *Applied Engr. Agric.* 19(5): 555-558.

Evett, S. R., and J. L. Steiner. 1995. Precision of neutron scattering and capacitance type soil water content gauges from field calibration. *Soil Sci. Soc. Am. J.* 59(4): 961-968.

Evett, S.R., J.A. Tolk, and T.A. Howell. 2003. A depth control stand for improved accuracy with the neutron probe. *Vadose Zone J.* 2(4): 642-649. Available at: http://www.cprl.ars.usda.gov/wmru/wmpubs.htm#2003 (accessed 22 September 2004).

Fry, K. E. 1983. Heat-unit calculations in cotton crop and insect models. *Advances in Agricultural Techniques, A AT-W-23*, U.S. Dept. of Agriculture, Agricultural Research Service, Cotton Research Center, Phoenix, AZ.

Guinn, G., Mauney, J. R., and Fry, K. E. 1981. Irrigation scheduling and plant population effects on growth, bloom rates, boll abscission, and yield of cotton. *Agron. J.* 63(3): 529-534.

Henggeler, J. C. 1995. A history of drip-irrigated cotton in Texas. In *Microirrigation for a Changing World: Conserving Resources/Preserving the Environment. Proc. Fifth International*

Microirrigation Congress. F. R. Lamm (ed.). pp. 669-674. Am. Soc. Agric. Engr., St. Joseph, MI.

Henggeler, J. C. 1997. Irrigation economics of drip-irrigated cotton under deficit irrigation. In *Proceedings Irrigation Association Technical Conference*, 125-132.

Howell, T. A., S. R. Evett, J. A. Tolk, and A. D. Schneider. 2004. Evapotranspiration of full-, deficit-irrigation, and dryland cotton on the Northern Texas High Plains. *J. Irrig. Drain. Engrg., Am. Soc. Civil Engrgs.* 130(4): 277-285.

Howell, T. A., M. Meron, K. R. Davis, C. J. Phene, and H. Yamada. 1987. Water management of trickle and furrow irrigated narrow row cotton in the San Joaquin Valley. *Applied Engr. Agric.* 3(2): 222-227.

Howell, T. A., A. D. Schneider, and S. R. Evett. 1997. Subsurface and surface microirrigation of corn—Southern High Plains. *Trans. ASAE* 40(3): 635-641.

Idso, S. B., R. D. Jackson, and R. J. Reginato. 1978. Extending the "degree day" concept of plant phenological development to include water stress effects. *Ecology*, 59(3): 431-433.

Littell, R. C., G. A. Milliken, W. W. Stroup, and R. D. Wolfinger. 1996. *SAS System for Mixed Models.* Cary, N.C.: SAS Institute, Inc.

Little, T. M., and F. J. Hills. 1978. *Agricultural Experimentation: Design and Analysis.* New York, N.Y.: John Wiley and Sons.

Lyle, W. M., and J. P. Bordovsky. 1983. LEPA irrigation system evaluation. *Trans. ASAE* 26(3): 776-781.

Mateos, L., J. Berengena, F. Orgaz, J. Diz, and E. Fereres. 1991. A comparison between drip and furrow irrigation at two levels of water supply. *Agric. Water Manage.* 19(4): 313-324.

Morrow, M. R., and D. R. Krieg. 1990. Cotton management strategies for s short growing season environment: water-nitrogen considerations. *Agron. J.* 82(1): 52-56.

O'Brien, D. M., D. H. Rogers, F. R. Lamm, and G. A. Clark. 1998. An economic comparison of subsurface drip and center pivot irrigation systems. *Appl. Engrg. Agric.* 14(4): 391-398.

Orgaz, F., L. Mateos, and E. Fereres. 1992. Season length and cultivar determine the optimum evapotranspiration deficit in cotton. *Agron. J.* 84(4): 700-706.

Peng, S., D. R. Krieg, and S. K. Hicks. 1989. Cotton response to accumulated heat units and soil water supply. *Field Crops Res.* 19:253-262.

Schneider, A. D., and T. A. Howell. 2000. Surface runoff due to LEPA and spray irrigation of a slowly permeable soil. *Trans. ASAE* 43(5): 1089-1095.

Segarra, E., L. Almas, and J. P. Bordovsky. 1999. Adoption of advanced irrigation technology: LEPA vs. drip in the Texas High Plains. In *Proc. Beltwide Cotton Conf.,* 1:324-328. Memphis, Tenn.: National Cotton Council.

TDA- Texas Agricultural Statistics Service. 2005. Texas Agricultural Facts. Bulletin SM-02-05. Austin, Texas: Texas Department of Agriculture. Available at: http://www.nass.usda.gov/tx/magfact.htm. (accessed 25 July 2005).

Tolk, J. A., T. A. Howell, J. L. Steiner, D. R. Krieg, and A. D. Schneider. 1995. Role of transpiration suppression by evaporation of intercepted water in improving irrigation efficiency. *Irrig. Sci.* 16(2): 89-95.

USDA-National Agricultural Statistics Service. 2005. Statistical Highlights of U.S. Agriculture, 2004 and 2005. National Agricultural Statistics Service, Statistical Bulletin 1003. Available at: http://www.usda.gov/nass/pubs/stathigh/content.htm. (accessed 25 July 2005).

USDA-Natural Resources Conservation Service. 2005. Web Soil Survey, Soil Survey TX375, Potter County, Texas. Available at: http://websoilsurvey.nrcs.usda.gov. (accessed 25 August 2005).

Wang, D., M. C. Shannon, C. M. Grieve, and S. R. Yates. 2000. Soil water and temperature regimes in drip and sprinkler irrigation, and implications to soybeans emergence. *Agric. Water Manage.* 43(1): 15-28.

Wang., J. Y. 1960. A critique of the heat unit approach to plant response studies. *Ecology*, 41: 785-790.

Wanjura, D. F., J. R. Mahan, and D. R. Upchurch. 1996. Irrigation starting time effects on cotton under high-frequency irrigation. *Agron. J*. 88(4): 561-566.

Wanjura, D. F., D. R. Upchurch, J. R. Mahan, and J. R. Burke. 2002. Cotton yield and applied water relationships under drip irrigation. *Agric. Water Manage.* 55(3): 217-237.

Yazar, A., S. M. Sezen, and S. Sesveren. 2002. LEPA and trickle irrigation of cotton in the Southeast Anatolia Project (GAP) area in Turkey. *Agric. Water Manage.* 54(3): 189-203.

Zwart, S. J., and W. G. M. Bastiaanssen. 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton, and maize. *Agric. Water Manage.* 69(2): 115-133.

Table 1. Agronomic and irrigation data for 2003 and 2004.

Variable	2003	2004
Fertilizer applied	31 kg ha^{-1} preplant N	34 kg ha^{-1} preplant N
	107 kg ha^{-1} preplant P	114 kg ha^{-1} preplant P
	48 kg ha^{-1} irr N (I_{100}) [a]	50 kg ha^{-1} irr N (I_{100}) [a]
Herbicide applied	2.3 L ha^{-1} Treflan	2.3 L ha^{-1} Treflan
Insecticide applied	NONE	NONE
Gravimetric soil water samples	20-May	17-May
	24-Nov	20-Dec
Cotton variety	Paymaster 2280 BG, RR	Paymaster 2280 BG, RR
Plant density	17 plants m^{-2}	19 plants m^{-2}
Planting date	10-Jun [b]	20-May
Harvest date	21-Nov	14-Dec
I_0 preplant irrigation	200 mm	25 mm
I_{25} preplant irrigation	200 mm	25 mm
I_{50} preplant irrigation	175 mm	25 mm
I_{75} preplant irrigation	125 mm	25 mm
I_{100} preplant irrigation	100 mm	25 mm
Irrigations to set furrow dikes	9-Jul	18-Jun
First treatment irrigation	21-Jul	14-Jul
Last irrigation	20-Aug	8-Aug
I_0 in-season irrigation	25 mm	50 mm
I_{25} in-season irrigation	71 mm	72 mm
I_{50} in-season irrigation	117 mm	94 mm
I_{75} in-season irrigation	165 mm	115 mm
I_{100} in-season irrigation	211 mm	137 mm
Precipitation	230 mm [c]	495 mm

[a] Liquid urea 32-0-0 injected into irrigation water; deficit irrigation treatments received proportionately less.
[b] The first planting on 21 May sustained severe hail damage on 3 June.
[c] Includes all rainfall between gravimetric sampling; 167 mm occurred between replant and harvest.

Table 2. 2003 season yield, water use, fiber quality, and return parameters as affected by irrigation levels and methods. Numbers followed by the same letter are not significantly different ($\alpha \leq 0.05$).

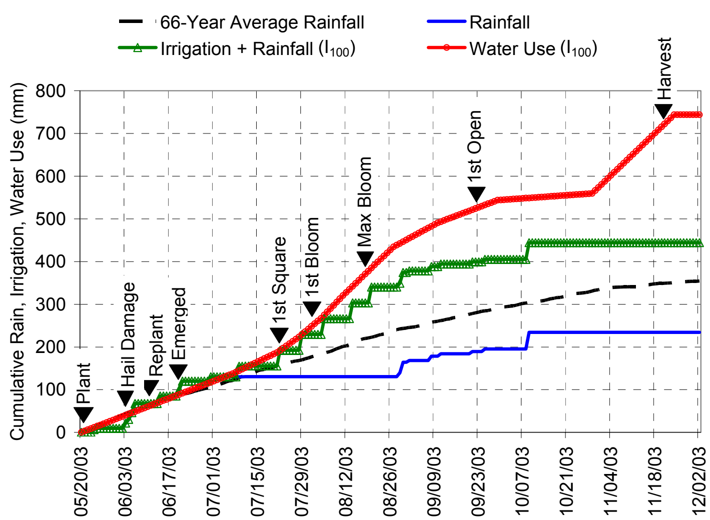
Irrigation Rate [a]	Irrigation Method	Lint Yield (kg ha^{-1})	Seasonal Water Use (mm)	WUE (kg m^{-3})	IWUE (kg m^{-3})	Micronaire value	Fiber strength (g tex^{-1})	Fiber length (mm)	Fiber Uniformity (%)	Total Discount or Premium [b] ($ kg^{-1})	Gross Return ($ ha^{-1})
I_{25} (71 mm)	MESA	213b	477b	0.045b	0.024c	5.20a	28.4b	0.75b	78.9b	$-0.1646b	$208.19b
	LESA	288ab	495ab	0.058b	0.130bc	5.13a	29.4ab	0.79a	80.2ab	$-0.1386b	$288.55ab
	LEPA	362ab	494ab	0.072ab	0.234ab	4.50b	30.1a	0.79a	80.4a	$-0.0810a	$379.56ab
	SDI	491a	530a	0.092a	0.416a	4.70b	29.9a	0.80a	80.9a	$-0.0396a	$540.88a
I_{50} (117 mm)	MESA	536b	604ab	0.089b	0.288b	5.07a	30.2ab	0.83ab	81.3a	$-0.0810b	$567.16b
	LESA	575b	582b	0.098b	0.321b	5.07a	29.2b	0.81b	81.2a	$-0.1111b	$591.89b
	LEPA	685ab	629a	0.109ab	0.415ab	4.77ab	31.3a	0.84ab	81.8a	$0.0150a	$797.32ab
	SDI	844a	627a	0.135a	0.549a	4.40b	30.3ab	0.85a	82.2a	$0.0587a	$1010.08a
I_{75} (165 mm)	MESA	1001a	705a	0.142a	0.491a	4.53a	31.3a	0.86a	82.3a	$0.0623a	$1201.93a
	LESA	984a	685a	0.143a	0.480a	4.40ab	30.8a	0.86a	82.3a	$0.0605a	$1179.55a
	LEPA	1149a	701a	0.164a	0.581a	4.07bc	31.1a	0.87a	81.7a	$0.0500a	$1368.85a
	SDI	1082a	714a	0.152a	0.540a	3.80c	31.6a	0.87a	82.4a	$0.0829a	$1322.12a
I_{100} (211 mm)	MESA	1229a	752a	0.164a	0.492a	4.07a	31.4a	0.88a	82.5a	$0.0950a	$1515.96a
	LESA	1208a	754a	0.160a	0.482a	3.57b	30.9a	0.87a	81.7a	$0.0466b	$1429.41a
	LEPA	1153a	727a	0.158a	0.456a	3.53b	30.9a	0.88a	82.2a	$0.0557ab	$1375.79a
	SDI	1150a	725a	0.159a	0.454a	3.67b	30.4a	0.88a	81.9a	$0.0818ab	$1402.89a
Irrigation Rate Averages											
I_0 (25 mm)	---	196d	437e	0.046c	---	5.17a	28.8c	0.76c	79.1b	$-0.1575c	$192.71d
I_{25} (71 mm)	---	339d	499d	0.067c	0.201c	4.88a	29.4c	0.79c	80.1b	$-0.1060c	$354.3d
I_{50} (117 mm)	---	660c	610c	0.108b	0.393b	4.83a	30.2b	0.83b	81.6a	$-0.0300b	$741.62c
I_{75} (165 mm)	---	1054b	701b	0.150a	0.523a	4.20b	31.2a	0.87a	82.2a	$0.0638a	$1268.12b
I_{100} (211 mm)	---	1185a	739a	0.160a	0.471ab	3.71c	30.9a	0.88a	82.0a	$0.0697a	$1431.02a
Irrigation Method Averages											
---	MESA	745a	635a	0.110a	0.324a	4.72a	30.3ab	0.83a	81.3a	$-0.0220bc	$873.29a
---	LESA	764a	629a	0.115a	0.353a	4.54a	30.0b	0.83a	81.4a	$-0.0356c	$872.35a
---	LEPA	837a	638a	0.126a	0.421a	4.22b	30.8a	0.85a	81.5a	$0.0100ab	$980.39a
---	SDI	892a	649a	0.134a	0.490a	4.14b	30.6ab	0.85a	81.8a	$0.0460a	$1068.99a

[a] Numbers in parentheses are in-season (planting to harvest) irrigation totals and do not include 100 to 200 mm of preplant irrigation.
[b] Based on a base loan value of $1.1352 kg^{-1}(average of all treatments for both years), from International Textile Center, Lubbock, Texas.

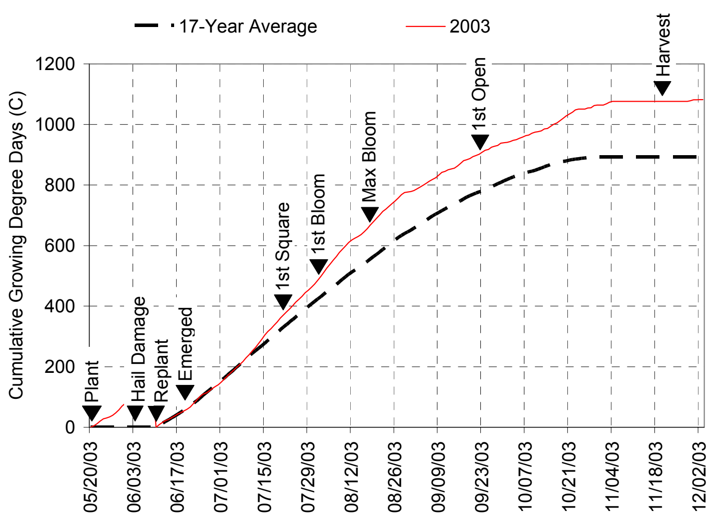
Table 3. 2004 season yield, water use, fiber quality, and return parameters as affected by irrigation levels and methods. Numbers followed by the same letter are not significantly different ($\alpha \leq 0.05$).

Irrigation Rate [a]	Irrigation Method	Lint Yield (kg ha^{-1})	Seasonal Water Use (mm)	WUE (kg m^{-3})	IWUE (kg m^{-3})	Micronaire value	Fiber strength (g tex^{-1})	Fiber length (mm)	Fiber Uniformity (%)	Total Discount or Premium [b] ($ kg^{-1})	Gross Return ($ ha^{-1})
I_{25} (72 mm)	MESA	622a	355c	0.176a	0.124ab	2.83a	26.9b	0.82b	79.9a	$-0.1910a	$587.68a
	LESA	579a	390bc	0.148bc	0.064b	2.70a	28.3a	0.85a	79.8a	$-0.1797a	$553.01a
	LEPA	586a	428a	0.137c	0.074b	2.70a	27.8ab	0.84a	80.3a	$-0.1921a	$555.60a
	SDI	648a	404ab	0.161ab	0.160a	2.77a	27.8ab	0.83ab	79.6a	$-0.1723a	$623.62a
I_{50} (94 mm)	MESA	594b	402b	0.148a	0.065b	2.73a	26.8ab	0.84a	79.8a	$-0.1731a	$571.63ab
	LESA	563b	411b	0.137a	0.032b	2.70a	26.9ab	0.83a	80.6a	$-0.227ab	$510.32b
	LEPA	592b	406b	0.146a	0.063b	2.63a	26.1b	0.82a	80.5a	$-0.2431b	$528.20b
	SDI	681a	452a	0.151a	0.158a	2.77a	27.2a	0.84a	80.3a	$-0.1683a	$658.41a
I_{75} (115 mm)	MESA	644b	434ab	0.148b	0.096b	2.63a	26.9a	0.84a	80.5a	$-0.1954a	$604.78b
	LESA	637b	448a	0.142b	0.091b	2.73a	26.7a	0.83a	80.5a	$-0.1881a	$603.54b
	LEPA	673b	437ab	0.154b	0.122b	2.70a	27.3a	0.83a	80.4a	$-0.2057a	$625.20b
	SDI	779a	410b	0.191a	0.214a	2.80a	27.2a	0.84a	80.9a	$-0.1665a	$755.62a
I_{100} (137 mm)	MESA	684b	461a	0.148b	0.110b	2.70b	27.0b	0.83b	80.7b	$-0.2009b	$640.29b
	LESA	675b	489a	0.139b	0.104b	2.77b	27.2ab	0.82b	80.3b	$-0.1885b	$639.49b
	LEPA	733b	462a	0.159b	0.147b	2.80b	26.8b	0.83b	80.7b	$-0.187b	$695.54b
	SDI	879a	455a	0.194a	0.253a	3.03a	28.3a	0.85a	81.9a	$-0.0854a	$923.80a
Irrigation Rate Averages											
I_{sr} (0 mm)	---	594bc	---	---	---	3.30a	30.0a	0.87a	82.1a	$-0.0422a	$649.25ab
I_0 (50 mm)	---	533c	367c	0.145a	---	3.37a	27.9bc	0.81c	80.1bcd	$-0.0956a	$553.46b
I_{25} (72 mm)	---	609c	394c	0.155a	0.106a	2.75bc	27.7b	0.84b	79.9d	$-0.1838bc	$579.97b
I_{50} (94 mm)	---	607c	418b	0.146a	0.080a	2.71c	26.8d	0.83b	80.3cd	$-0.2029c	$567.14b
I_{75} (115 mm)	---	683ab	432b	0.159a	0.131a	2.72c	27.0cd	0.84b	80.6bc	$-0.1889bc	$647.29ab
I_{100} (137 mm)	---	743a	467a	0.160a	0.154a	2.83b	27.3bc	0.83b	80.9b	$-0.1655b	$724.78a
Irrigation Method Averages											
---	MESA	636b	413a	0.155b	0.099b	2.73ab	26.9b	0.83b	80.2a	$-0.1901b	$601.09b
---	LESA	614b	434a	0.142b	0.073b	2.73ab	27.3ab	0.83ab	80.3a	$-0.1958b	$576.59b
---	LEPA	646b	433a	0.149b	0.101b	2.71b	27.0b	0.83b	80.5a	$-0.2070b	$601.13b
---	SDI	747a	430a	0.174a	0.196a	2.84a	27.6a	0.84a	80.7a	$-0.1481a	$740.36a

[a] Numbers in parentheses are in-season (planting to harvest) irrigation totals and do not include 25 mm of preplant irrigation.
[b] Based on a base loan value of $1.1352 kg^{-1} (average of all treatments for both years), from International Textile Center, Lubbock, Texas.

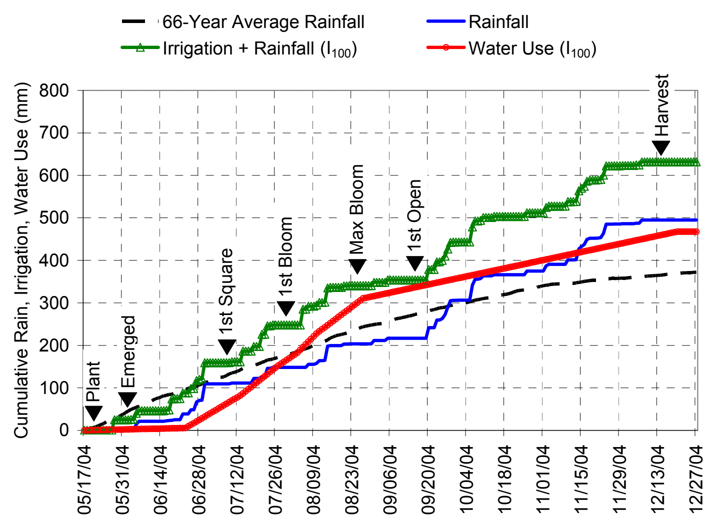


a.

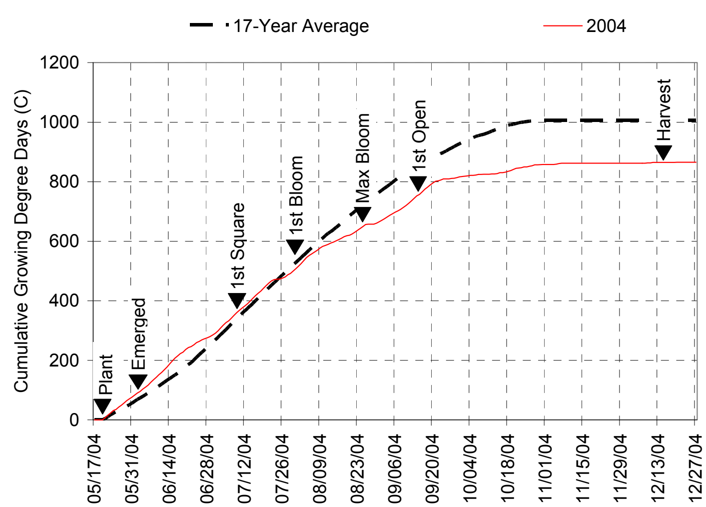


b.

Figure 1. 2003 cotton season for full irrigation (I_{100}) rate.



a.



b.

Figure 2. 2004 cotton season for full irrigation (I_{100}) rate.

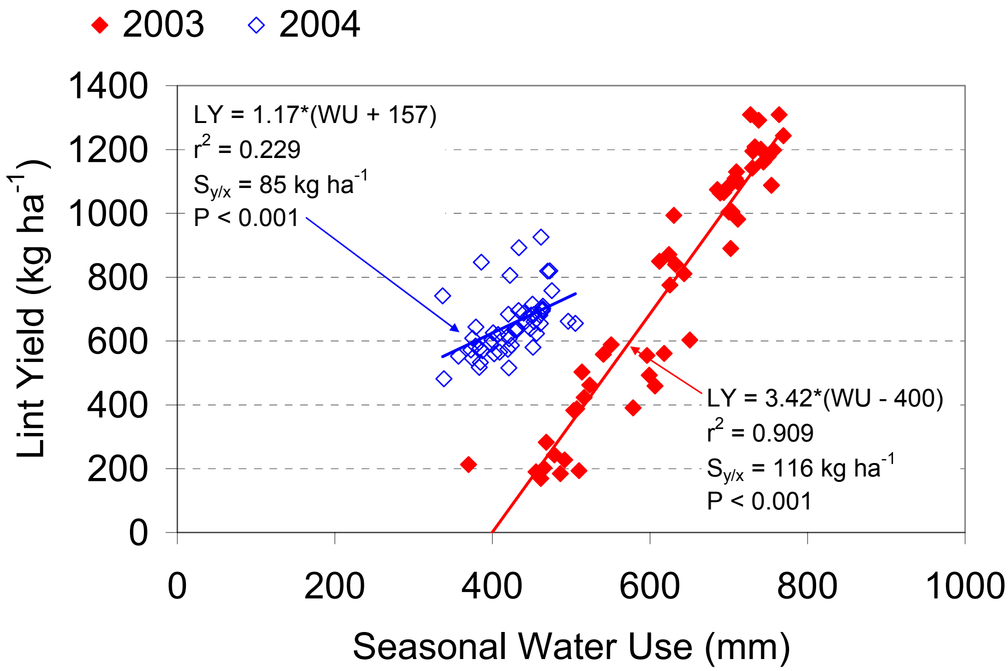


Figure 3. Production functions for the 2003 and 2004 cotton seasons.

Research Using Automated Irrigation Systems

Clinton C. Shock, Erik B. G Feibert, Cedric A. Shock, Andre B. Pereira, and Eric P. Eldredge

Abstract. Starting in 1995, we initiated the use of automatic drip irrigation, based on soil moisture feedback, to address research problems. Soil moisture data to be used for feedback control of drip irrigation has been measured as soil water tension or soil water content. A datalogger checks plots several times a day for soil moisture and irrigates them according to pre-established soil moisture criteria. Using this system, the optimal soil water tension for initiating irrigation for onion and potato were determined. This automation strategy has also been successfully used to determine ideal N fertilizer requirements for drip irrigated onion, to evaluate irrigation intensity and frequency for drip irrigated onion, and to study the effect of the timing of short water stress on onion quality. Starting in 2004, radio telemetry systems were also used to automate irrigations.

Introduction. Soil moisture measurement can provide timely and accurate information to schedule irrigations. Soil moisture can be measured as soil water tension or volumetric soil water content. In the late 1980's the Malheur Experiment Station chose soil water tension as the preferred unit of measurement. Soil water tension can be more closely related to crop productivity than volumetric soil water content, because soil water tension is a direct measurement of the force that plant roots need to exert to exctract water from the soil. Also, soil water tension varies less with minor soil type changes and specific field soil conditions than volumetric soil water content.

Granular matrix sensors (GMS, Watermark Soil Moisture Sensor, Irrometer Co., Riverside, CA) are used in our studies to measure soil water tension. Data from a calibration study was used to modify the equation that converts the electrical resistance reading of the GMS to soil water tension (Shock et al., 1998a). In this study, the GMS electrical resistance was compared to soil water tension readings from tensiometers and to gravimetric soil moisture data in a weighing lysimeter with silt loam soil.

Optimum soil water tension for onion irrigation. Prior to the automation of irrigation systems the optimum soil water tension for furrow irrigated onion was determined testing a range of soil water tensions as setpoints for manually initiating irrigations. The results showed that onion requires frequent irrigations at a soil water tension of 25 cb for maximizing yield and grade (Shock et al., 1998b). Furrow irrigation at 25 cb results in the soil water tension reaching values close to 0 cb (extremely wet, Figure 1).

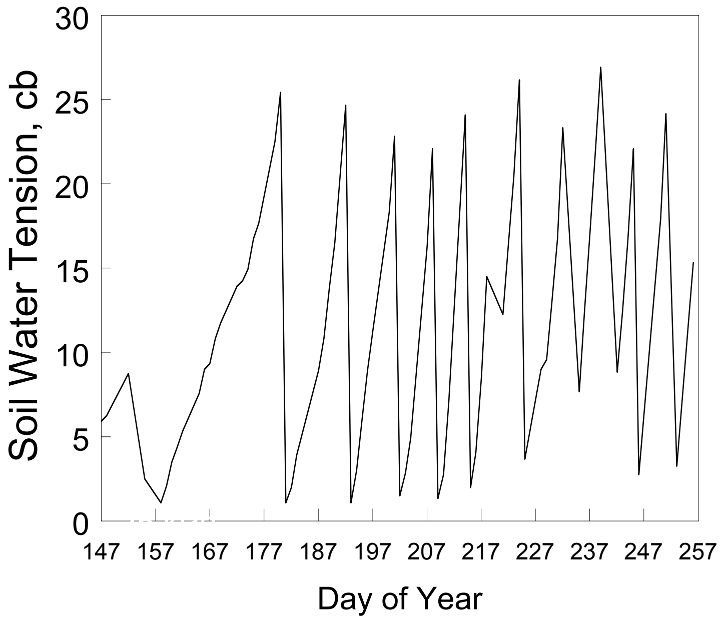


Figure 1. Soil water tension over time for onion furrow irrigated manually at 25 cb.

Frequent furrow irrigations result in nitrate leaching and soil erosion. Drip irrigation can reduce the negative environmental consequences of frequent furrow irrigation and thus has increased in usage. With drip irrigation, the application of small quantities of water at a higher frequency is feasible, thus making irrigation automation feasible and necessary.

In 1997 and 1998, irrigation automation was used to determine the optimum soil water tension for drip-irrigated onion (Shock et al., 2000). Onions were submitted to 5 soil water tension thresholds for automatically initiating drip irrigations (10, 20, 30, 50, and 70 cb). Soil water tension was measured at 8-inch depth below the onion row using GMS. The drip tape was buried at 4-inch depth between the onion rows. The soil water tension was checked by a datalogger reading GMS and the onions were irrigated automatically up to eight times per day if the soil water tension was equal to or exceeded the respective treatment threshold. At each irrigation 0.06 inch of water was applied. The GMS were connected to a datalogger (CR 10 datalogger, Campbell Scientific, Logan, Utah) via multiplexers (AM 416 multiplexer, Campbell Scientific). The irrigations to each plot were controlled by the datalogger through a controller (SDM16 controller, Campbell Scientific) using a solenoid valve. Data was downloaded from the datalogger with a laptop computer or with a SM192 Storage Module (Campbell Scientific) and a CR10KD keyboard display (Campbell Scientific). The datalogger was powered by a solar panel and the controller was powered by 24 V AC. With high frequency automated drip irrigation at 20 cb, the soil water tension remains more constant and does not reach the extremely wet values as with furrow irrigation (Figure 2). With high frequency automated drip irrigation, the amount of water applied over time tracked ET_c (Figure 3). In 1997, the highest marketable yield was achieved at a soil water tension of 21 cb. Marketable yield was lower with higher soil water tension due to increased storage decomposition. In 1998, onion marketable yield was highest with a soil water tension of 10 cb. Storage decomposition was not significant in 1998. Based on this research, a soil water tension threshold of 20 cb is recomended for drip irrigated onion.

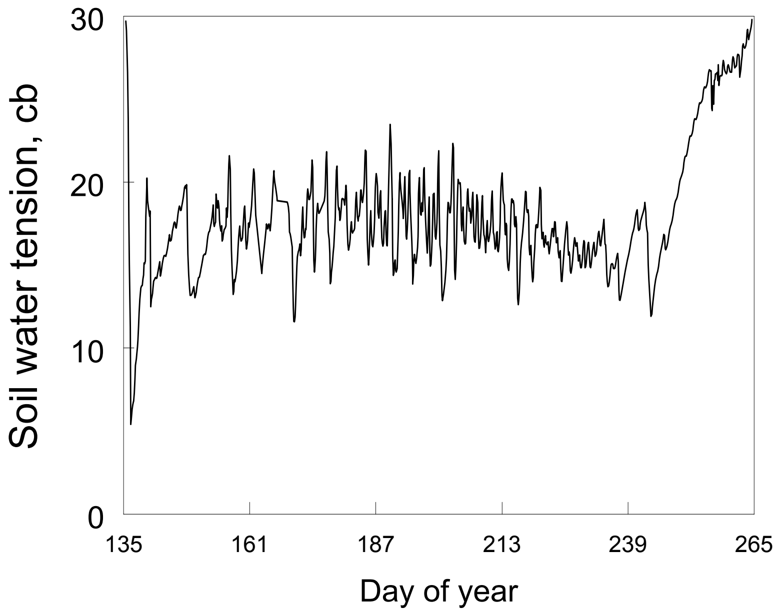


Figure 2. Soil water tension over time for onion drip irrigated automatically at 20 cb.

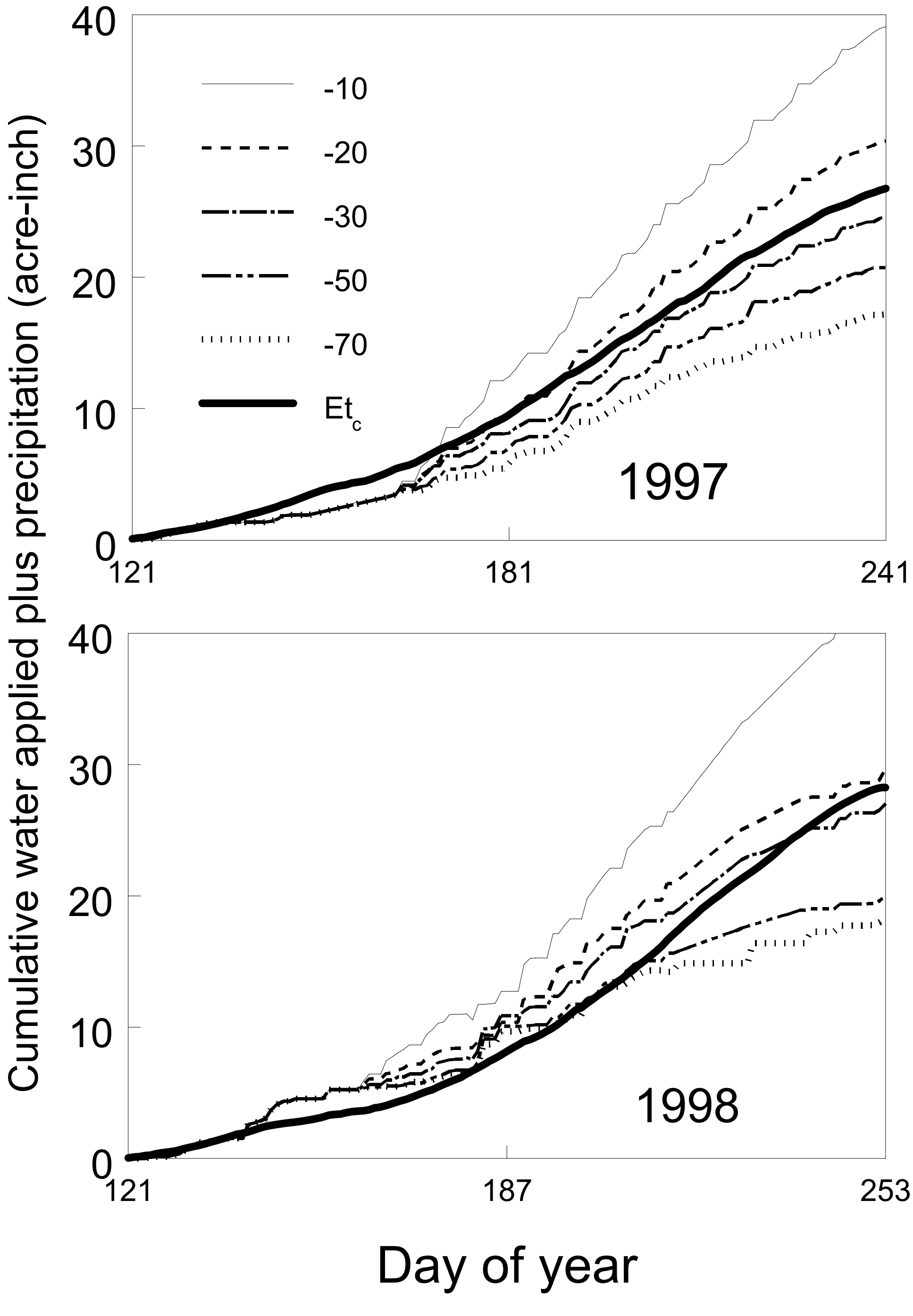


Figure 3. Water applied plus precipitation and ET_c for onion drip irrigated at 5 soil water tensions.

Other research using automated irrigation. The previously described automated drip irrigation system was used to investigate the optimum plant population and N fertilization needs of drip irrigated onion in 1999, 2000, and 2001 (Shock et al., 2004). Each N rate plot had plant populations as subplots. All plots were irrigated automatically, as previously described, at a soil water tension treshold of 20 cb. This research showed that with a carefully managed automated drip irrigation system, onion N fertilizer requirements were very low. With drip irrigation, leaching tension was low and the crop could utilize the substantial amounts of N derived from N mineralization. Onion bulb size distribution was sensitively affected by plant population.

The low intensity, high frequency drip irrigation as used in our earlier drip-irrigated onion research. If applied on a farm scale, low intensity, high frequency drip irrigation might result in large water application disuniformity and inefficiencies, because of water losses from the frequent charging and drainage of the drip irrigation system. In addition, growers might not be able to allocate water nearly continuously to each field, which low intensity irrigation requires. In 2002 and 2003, the same automated drip irrigation system used in 1997 and 1998 was used to determine the influence of irrigation intensities higher than 0.06 inch per irrigation on onion yield and grade (Shock et al., 2005). Onions were submitted to 8 treatments as a combination of 4 irrigation intensities (0.06, 0.12, 0.24, and 0.48 inch per irrigation) and two emitter flow rates. The datalogger was programmed to irrigate each plot automatically and separately according to the 4 irrigation intensities. Irrigation intensities of 0.5 inch per irrigation slighthly increased onion yield and grade above the irrigation intensity of 0.06 inch per irrigation. An irrigation intensity of 0.5 inch did not result in an increase in water applied (Figure 4) nor in any significant difference in average soil water tension (Figure 5). Lowering the emitter flow rate from the currently used of 0.132 gal/hour to 0.066 gal/h resulted in slightly lower onion yield and grade.

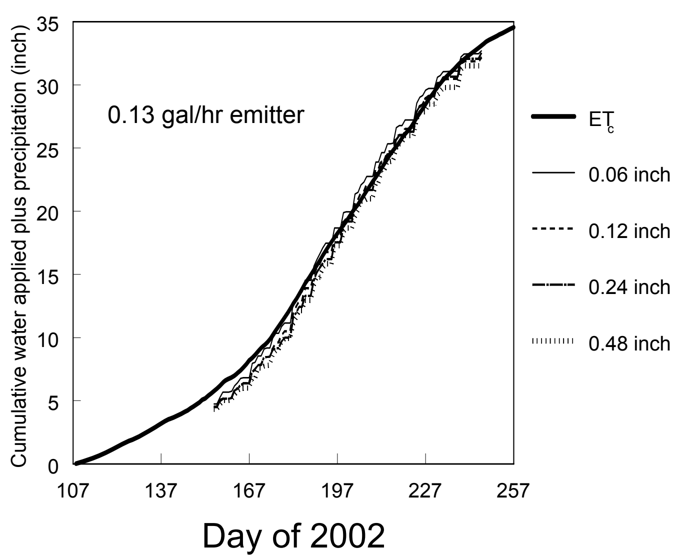


Figure 4. Onion evapotranspiration and total water applied plus precipitation over time for two drip emitter flow rates and four drip irrigation intensities in 2002.

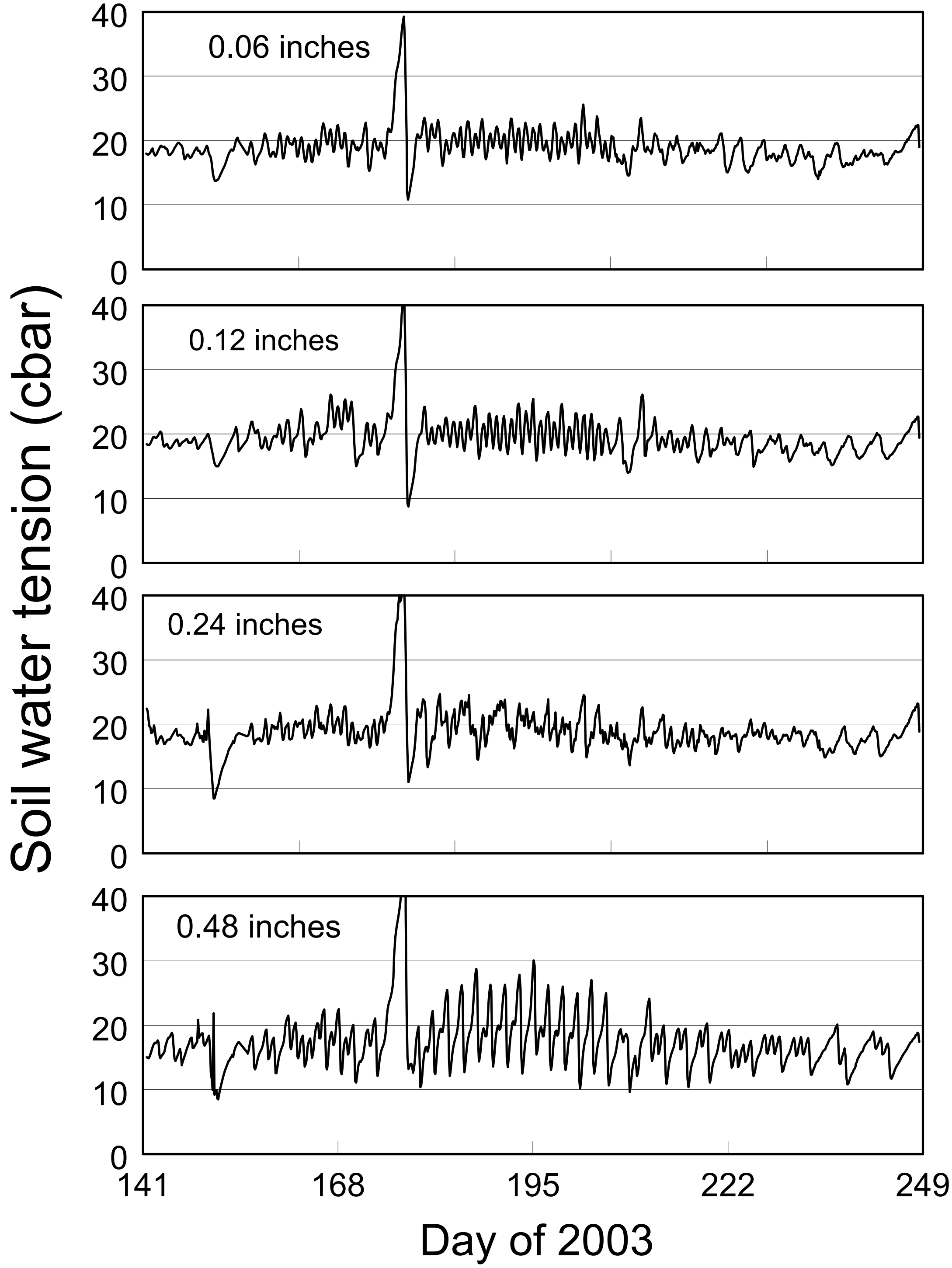


Figure 5. Soil water tension at 8-inch depth over time in 2003 for onions drip irrigated at four intensities with an emitter flow rate of 0.13 gal/h.

In 2000 and 2001, research with potato was conducted to determine the optimum soil water tension and drip tape placement for drip-irrigated potato (Shock et al., 2002). The previously described automated drip irrigation system (Shock et al., 2000) was used to submit potato to 4 soil water tension thresholds for initiating drip irrigations (15, 30, 45, and 60 cb) and two drip tape placements (one tape per row or one tape per two rows). The plots were irrigated automatically up to 4 times per day applying 0.1 inch of water per irrigation whenever the soil water tension reached the treatment level. The results showed that drip irrigated potato on silt loam should be irrigated at a soil water tension of 30 cb using one tape per row.

Test of commercial automatic irrigation systems. In 2004 and 2005, 3 commercial automatic irrigation systems were compared to the currently used Campbell Scientific system for onion. Each system was replicated three times. The datalogger for each system was programmed to make irrigation decisions every 12 hours: zones were irrigated for eight hours (0.5 inch of water) if the soil water tension exceeded 20 cb.

Campbell Scientific. This system was similar to that used above (Shock et al., 2000) using a soil water tension irrigation criterion of 20 cb.

Automata. Each one of the three zones had four GMS connected to a datalogger (Mini Field Station, Automata, Inc., Nevada City, CA). The dataloggers at each zone were connected to a controller (Mini-P Field Station, Automata) at the field edge by an internal radio. The controllers (Mini-P Field Station, Automata) at the field edge were connected to a base station (Mini-P Base Station, Automata) in the office by radio. The base station was connected to a desktop computer. Each zone was irrigated individually using a solenoid valve. The solenoid valves were connected to and controlled by the controller. The desktop computer ran the software that monitored the soil moisture in each zone and made the irrigation decisions. The Mini Field stations were powered by solar panels and the Mini-P Field station was powered by 120 V AC.

Watermark Monitor. Irrometer manufactures the Watermark Monitor datalogger which can record data from seven GMS and one temperature probe. The soil temperature is used to adjust the soil water tension calibrations. Each of the three Watermark Monitor zones had seven GMS connected to a Watermark Monitor. Data was downloaded from the Watermark Monitor with a laptop computer. The Watermark Monitors were powered by solar panels. Irrigation decisions were made daily by reading the GMS at each Watermark Monitor. When the soil water tension reached 20 cb the zone was irrigated manually for eight hours. This system only had an automatic recording system.

Acclima. Acclima (Meridian, ID) manufactures a Digital TDT™ that measures volumetric soil moisture content. Each zone had one TDT sensor and four GMS. The GMS were only used for comparison and were not used in irrigation automation. The TDT sensors were connected to a model CS3500 controller (Acclima) at the field edge. The controller monitored the soil water content and used the soil water content data to control the irrigations for each zone separately using solenoid valves. The controller was powered by 120 V AC. To monitor what the controller was doing, data was downloaded from the controller using a laptop computer. For comparison and calibration, the GMS were connected to the Campbell Scientific datalogger which monitored the soil water tension as described above. The CS3500 controller was programmed to irrigate the zone when the volumetric soil water content was equal to or lower than 27%. The soil water tension data was compared to the volumetric soil water content data to adjust the CS3500 controller to irrigate each zone in a manner equivalent to the irrigation scheduling using the GMS.

All of these systems produced high quality onions at yields considerably above normal commercial expectations.

Expansion of Drip Irrigation

Automated drip irrigation research has facilitated the reliable and reproduceable field results. Irrigation criteria, how to reduce N applications, ideal plant populations, and irrigation rates and frequencies have been carefully determined. These findings have encouraged the adoption of drip irrigation systems and helped growers understand how to manage their systems.

Conclusion

Automated irrigation of water sensitive crops such as potato and onion controlled by data loggers holds the promise of determining irrigation criteria that optimize yield or quality under the constraint of conserving water and minimizing off site contamination through irrigation runoff or nutrient leaching. Automated drip irrigation research has facilitated the development of efficient management guidelines that have aided the expansion of drip irrigation managemnet. Computer programs written for data loggers can be effective research tools in establishing and maintaining small differences in irrigation treatments and closely matching crop water needs to water applied.

References

Shock, C.C., J. Barnum, and M. Seddigh. 1998a. Calibration of Watermark soil moisture sensors for irrigation management. *In* Proceedings of the International Irrigation Show. Irrigation Association. pp. 139-146. San Diego, CA.

Shock, C.C., E.B.G. Feibert, and L.D. Saunders. 1998b. Onion yield and quality affected by soil water potential as irrigation threshold. HortSci. 33:1188-1191.

Shock, C.C., E.B.G. Feibert, and L.D. Saunders. 2000. Irrigation criteria for drip-irrigated onions. HortScience. 35:63-66.

Shock, C.C., E.P. Eldredge, and L.D. Saunders. 2002. Drip irrigation management factors for 'Umatilla Russet' potato production. Oregon State University Agricultural Experiment Station Special Report 1038: 157-169.

Shock, C.C., E.B.G Feibert, and L.D. Saunders. 2004. Plant population and nitrogen fertilization for subsurface drip-irrigated onion. HortScience 39: 1722-1727.

Shock, C.C., E.B.G. Feibert, and L.D. Saunders. 2005. Onion response to drip irrigation intensity and emitter flow rate. HortTechnology 15: 652-659.

EFFECT OF IRRIGATION FREQUENCY FOR LIMITED SUBSURFACE DRIP IRRIGATION OF CORN

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ABSTRACT

A three-year field study (2002-2004) was conducted to examine the effect of irrigation frequency on limited subsurface drip-irrigated field corn on the deep silt loam soils of western Kansas. Results indicate that SDI frequency on this soil type is not a major issue in corn production. Grain yield was only affected in 2002, an extreme drought year, with less frequent, larger irrigation events being advantageous. The grain filling stage was also unaffected by irrigation frequency as was seasonal water use and water use efficiency. Higher plant population (34000 plants/acre) was advantageous in the good production year, 2004, and had no negative effect in the extreme drought years 2002 and 2003.

INTRODUCTION

Subsurface drip irrigation (SDI) is a relatively new technology in the U. S. central Great Plains but producers are beginning to adopt and adapt the technology to their farms. Many of the SDI systems are manually operated and SDI event duration is often 12 to 24 hours to match available labor schedules. This will result in approximate irrigation frequencies of two to six days for irrigated corn depending on SDI system capacity. There are a few fully automated SDI systems which can shift irrigation between the various zones on a more frequent basis. Although it is often assumed that high irrigation frequency is a "given" with microirrigation systems, a literature review of SDI (Camp, 1998) indicates that SDI frequency is often only critical for shallow rooted crops on shallow or sandy soils. At least two studies conducted in the U. S. Great Plains indicate that irrigation frequencies from 1 to 7 days had no effect on corn yields provided soil water was managed within acceptable stress ranges (Caldwell et al., 1994; Howell et al., 1997). However, the question arises about what effect irrigation frequency may have when SDI is limited by institutional or hydrologic constraints on pumping.

Limited or deficit irrigation of corn is difficult to implement successfully without reducing grain yields (Lamm et al., 1993; Eck, 1986; Musick and Dusek, 1980; Stewart et al., 1975). However, some strategies are more successful than others at maintaining corn yields under limited irrigation. Conceptually, one limited irrigation method that might work successfully (both economically and water efficient) is to provide small frequent supplemental, but deficit, amounts of irrigation using subsurface drip irrigation (SDI). These frequent "doses" might attenuate crop water stress allowing crop processes to continue and also allowing the crop to "scavenge" the soil profile for its remaining daily crop water needs. In 2002, Kansas State University initiated a field study to evaluate the effect of frequency for limited SDI for field corn production.

PROCEDURES

This experiment was conducted at the Kansas State University Northwest Research-Extension Center at Colby, Kansas, USA during the period 2002-2004. The deep silt loam soil can supply about 17.5 inches of available soil water for an 8-foot soil profile. The climate can be described as semi-arid with a summer precipitation pattern with an annual rainfall of approximately 19 inches. Average precipitation is approximately 12 inches during the 120-day corn growing season.

The treatments were four irrigation frequencies at a limited irrigation capacity plus the addition of a fully irrigated and non-irrigated treatment each with three plant populations. The four irrigation frequencies were 0.15 inches/day, 0.45 inches/3 days, 0.75 inches/5 days and 1.05 inches/7days which are equivalent but limited capacities. As a point of reference a 0.25 inch/day irrigation capacity will match full irrigation needs for corn for center pivot sprinkler irrigation in most years. The fully irrigated treatment was limited to 0.30 inches/day. The non-irrigated treatment only received 0.10 inches in a single irrigation to facilitate nitrogen fertigation for those plots. However, the non-irrigated treatment was irrigated each year in the dormant season to replenish the soil water in the profile. Irrigation was scheduled using a climatic water budget, but was limited to the specific irrigation frequency treatment. Irrigations were scheduled when the calculated soil water depletion exceeded 1 inch for a given treatment.

The driplines with a 12-inch emitter spacing were spaced 60 inches apart with an installation depth of 17 inches. Each dripline was centered between two corn rows spaced 30 inches apart on the 60 inch crop bed. The nominal flow rate was 0.25 gal/min for each 100 ft of dripline. There were four driplines in each plot and each whole plot was 330 ft long. Each plot was instrumented with a municipal-type flowmeter to record total accumulated flow. Mainline pressure entering the driplines was first standardized to 20 psi with a pressure regulator and then further reduced with a throttling valve to the nominal flowrate of 3.3 gpm/plot that resulted in an operating pressure of approximately 10 psi.

The three target plant populations were approximately 34000, 30000, and 26500 plants/acre. The experiment was conducted in a randomized complete block, split-plot design with four replications. Plant population was the split plot variable and irrigation level was the whole plot variable. Pioneer[1] hybrid 32R42 was used in 2002 and its corn borer resistant related hybrid 32R43 was used in 2003 and 2004. This hybrid is a full season hybrid for the region with an approximately 118 day comparative relative maturity requirement. The corn was planted on May 1, 2002, April 30, 2003 and May 3, 2004. Pest (weeds and insects) control was accomplished with standard practices for the region. A starter fertilizer application was banded at planting at the rate of 30 lbs N/acre and 45 lbs $P_2 0_5$/acre. Nitrogen fertilizer was applied to the study area through the SDI system in multiple events during mid to late June each year for an additional total amount of 200 lbs N/acre. These fertilizer rates can be described as non-limiting for high corn yields. The corn rows were planted parallel with the dripline with each corn row approximately 15 inches from the nearest dripline. A raised bed was used in corn production. This allows for centering the corn rows on the dripline and limits wheel traffic to the furrow (Figure 1). This controlled traffic can allow for some shallow cultivation procedures.

Soil water content was measured on a periodic basis (weekly or biweekly) with a neutron attenuation moisture meter in 1-ft increments to a depth of 8 ft at the corn row (approximately 15 inches horizontally from the dripline. Corn production data collected during the growing season included irrigation and precipitation amounts, weather data, and yield components (yield, harvest plant population, ears/plant, kernels/ear, mass/100 kernels). Yield samples (20 row ft from the center of the plot) from selected treatments were hand harvested on an approximately biweekly schedule during the month preceding corn physiological maturity to ascertain the effect of frequency on grain filling. Weather data were collected with an automated weather station approximately 0.35 mile from the research site to schedule irrigation. Factors calculated after the season included seasonal water use and water use efficiency.

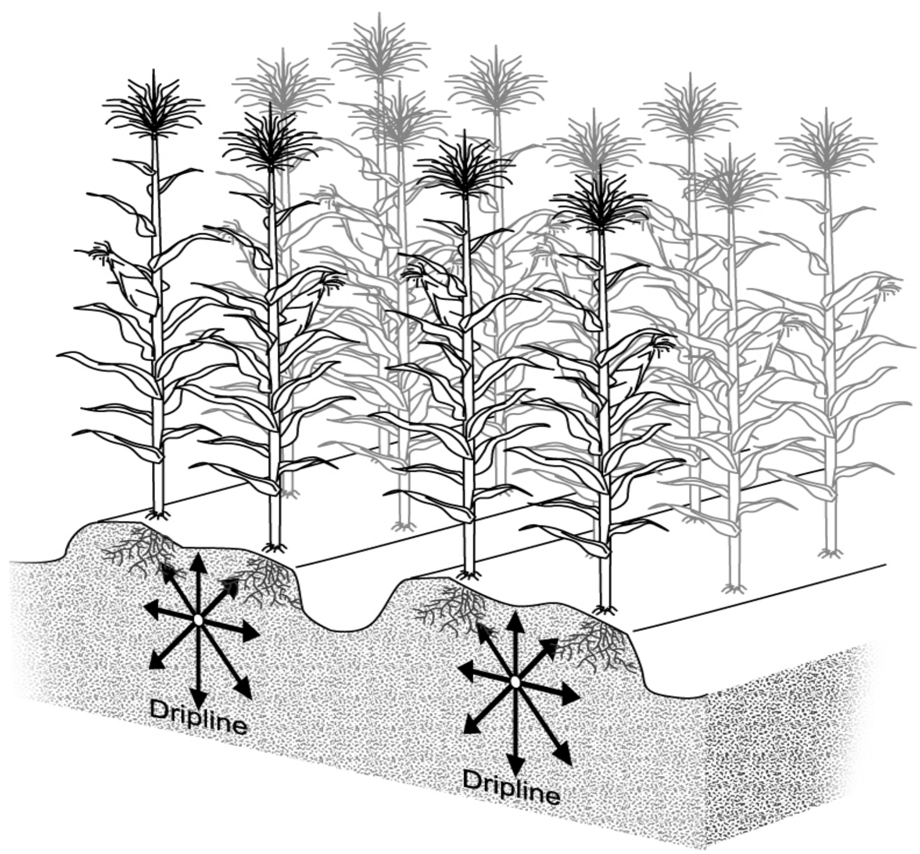

Figure 1.   Physical arrangement of the subsurface dripline in relation to the corn rows.

RESULTS AND DISCUSSION

Weather Conditions

Briefly, the weather conditions can be specified as a severe drought (both hot and dry) during 2002 and 2003 and near normal conditions in 2004. Precipitation during the cropping season was 10.58, 9.12, and 12.24 inches for the respective years, 2002 to 2004 as compared to a normal amount of approximately 12 inches. Calculated evapotranspiration for the 120-day period May 15 through September 11 was much above normal in 2002 and 2003 (27.68 and 25.96 inches, respectively) and near long-term normal (23 inches) at 22.56 inches in 2004. Hot and dry conditions during 2003 led to an increased problem with spider mites which could not be controlled with two insecticide applications.

Corn Yield and Yield Components

Corn yields were high in all three years for all irrigated treatments ranging from 192 to 282 bushels/acre (Table 1, 2, and 3 and Figure 2.) Only in 2002 did irrigation frequency significantly affect yields and the effect was the opposite of the hypothesis. In the extreme drought year of 2002, the less frequent irrigation events with their larger irrigation amounts (0.75 inches/5 days and 1.05 inches/7 days) resulted in yields approximately 10 to 20 bushels/acre higher. The yield component most greatly affected in 2002 was the kernels/ear and was 30-40 kernels/ear higher for the less frequent events. It is suspected that the larger irrigation amounts for these less frequent events sent an early-season signal to the corn plant to set more potential kernels. Much of the potential kernel set occurs before the ninth leaf stage (corn approximately 24-36 inches high), but there can be some kernel abortion as late as two weeks after pollination. It is believed that for this study, the early period (ninth leaf stage) is when the effect occurred. Kernels/ear was numerically higher for the fully irrigated treatment in both 2002 and 2003 which may be further indication of the severity of early season drought conditions in those years. There was no consistent effect of irrigation frequency on corn yields in 2003 and 2004. It is thought the grain filling was truncated in 2003 due to heavy spider mite pressure and this is also the implication of the lower 100 kernel weight that was obtained in 2003. The crop year 2004 was excellent during the grain filling period with very mild conditions. However, even in 2004 there was no consistent effect of irrigation frequency on any of the yield components. The results suggest that irrigation frequencies from daily to weekly should not have much effect on corn yields in most years.

The average daily yield gain for the periods August 30 to October 8, 2002 (39 days), August 25 to September 19, 2003 (25 days) and September 7 to October 5, 2004 (28 days) were calculated for the various treatments. There was no consistent advantage for any of the frequency treatments over another and they often had daily yield gains similar to the fully irrigated treatment (Figure 3).

Averaged over the three years of the study, the deficit irrigated frequency treatments produced 97% of the fully-irrigated treatment yield on 70% of the full irrigation amount. The deficit irrigated treatments required approximately 12.4 inches of irrigation, but outyielded the non-irrigated treatment by 126 bu/acre.

Table 1. Summary of corn yield and water use data from 2002 SDI frequency study, Colby Kansas.

Irrigation Treatment	Plant Pop. Trt.	Yield bu/a	Plants/ acre	Ears/ Plant	Kernels/ Ear	100 Kernel Weight, g	Irrigation inches	Water use inches	WUE lb/a-inch
0.15 in/d	34.0 K	222.2	31145	0.99	523	35.49	13.05	25.46	489
	30.0 K	212.7	28096	0.98	550	35.83		26.58	448
	26.5 K	195.0	25047	0.97	572	35.02		25.19	435
0.45 in/3 d	34.0 K	199.2	32234	0.96	477	34.28	13.50	26.32	424
	30.0 K	223.7	29185	0.98	553	36.01		25.89	485
	26.5 K	199.7	25264	0.91	611	36.04		25.57	438
0.75 in/5 d	34.0 K	213.2	32016	0.97	507	34.43	13.50	26.56	449
	30.0 K	232.0	28750	0.96	588	36.56		26.58	490
	26.5 K	218.0	26790	0.87	642	37.50		26.46	462
1.05 in/7 d	34.0 K	240.6	32452	0.94	543	36.94	13.65	26.42	510
	30.0 K	225.4	28967	0.94	559	37.70		26.60	474
	26.5 K	231.1	26571	0.90	664	36.92		26.85	484
0.30 in/d (Full)	34.0 K	264.1	32017	0.97	612	35.61	20.40	29.32	505
	30.0 K	236.0	28750	0.99	595	35.68		29.41	450
	26.5 K	231.3	26354	1.00	597	36.92		29.00	447
No irrigation	34.0 K	67.9	31363	0.78	218	32.34	0.10	15.47	243
	30.0 K	85.6	28314	0.82	290	32.25		15.92	302
	26.5 K	64.2	24394	0.85	240	32.97		16.28	220
Mean of Irrigation Trt									
0.15 in/d		210.0	28096	0.98	548	35.75	-	25.74	457
0.45 in/3 d		207.5	28895	0.95	547	35.44	-	25.93	449
0.75 in/5 d		221.0	29185	0.93	579	36.16	-	26.53	467
1.05 in/7 d		232.4	29330	0.93	588	37.19	-	26.62	489
0.30 in/d (Full)		243.8	29040	0.98	601	36.22	-	29.24	467
No irrigation		72.6	28024	0.81	249	32.52	-	15.89	255
LSD (p<0.05)									
Any 2 irrigation means within same P Pop		6.3	NS	0.03	19	0.50	-	0.33	15
Mean of P Pop Trt									
34.0 K		201.2	31871	0.93	480	34.85	-	24.92	436
30.0 K		202.6	28677	0.94	522	35.67	-	25.16	441
26.5 K		189.9	25737	0.92	554	36.12	-	24.89	414
LSD (p<0.05)									
Any 2 P Pop means within same Irr Trt Pop		19.2	592	NS	67	1.80	-	NS	50

Table 2. Summary of corn yield and water use data from 2003 SDI frequency study, Colby Kansas.

Irrigation Treatment	Plant Pop. Trt.	Yield bu/a	Plants/ Acre	Ears/ Plant	Kernels/ Ear	100 Kernel Weight, g	Irrigation inches	Water use inches	WUE lb/a-inch
0.15 in/d	34.0 K	209.8	34413	0.98	491	32.39	12.60	26.20	449
	30.0 K	206.4	30057	1.03	507	33.51		26.74	433
	26.5 K	204.1	27225	1.03	532	34.71		26.10	439
0.45 in/3 d	34.0 K	211.7	33759	0.98	496	32.86	12.60	25.94	457
	30.0 K	192.2	30274	0.96	510	33.04		25.85	417
	26.5 K	210.1	27007	1.05	535	35.25		25.88	456
0.75 in/5 d	34.0 K	220.4	33977	0.99	494	33.88	12.75	26.97	458
	30.0 K	228.8	31581	1.02	535	33.78		27.09	473
	26.5 K	193.8	27443	1.00	521	34.47		26.76	406
1.05 in/7 d	34.0 K	203.1	35284	0.95	476	32.76	12.60	26.79	425
	30.0 K	206.9	31799	0.99	492	34.16		26.62	436
	26.5 K	200.0	26354	1.08	532	33.82		26.37	425
0.30 in/d (Full)	34.0 K	235.8	31799	1.01	562	33.20	18.30	28.54	463
	30.0 K	217.5	29839	1.02	522	34.77		28.58	427
	26.5 K	217.4	27225	0.97	557	37.42		28.58	426
No irrigation	34.0 K	33.1	32670	0.40	238	28.46	0.10	15.95	115
	30.0 K	44.7	30928	0.54	229	29.48		16.17	155
	26.5 K	58.5	27007	0.69	265	30.79		15.96	206
Mean of Irrigation Trt									
0.15 in/d		206.7	30565	1.01	510	33.54	-	26.35	440
0.45 in/3 d		204.6	30347	1.00	514	33.72	-	25.89	443
0.75 in/5 d		214.3	31000	1.00	517	34.04	-	26.94	446
1.05 in/7 d		203.3	31145	1.00	500	33.58	-	26.59	428
0.30 in/d (Full)		223.6	29620	1.00	547	35.13	-	28.56	439
No irrigation		45.5	30202	0.54	244	29.58	-	16.02	158
LSD ($p<0.05$) Any 2 irrigation means within same P Pop		5.8	NS	0.03	15	0.70	-	0.31	15
Mean of P Pop Trt									
34.0 K		185.6	33650	0.88	460	32.26	-	25.06	394
30.0 K		182.7	30746	0.93	466	33.12	-	25.17	390
26.5 K		180.7	27044	0.97	490	34.41	-	24.94	393
LSD ($p<0.05$) Any 2 P Pop means within same Irr Trt Pop		NS	539	0.10	52	2.47	-	NS	NS

Table 3. Summary of corn yield and water use data from 2004 SDI frequency study, Colby Kansas.

Irrigation Treatment	Plant Pop. Trt.	Yield bu/a	Plants/ Acre	Ears/ Plant	Kernels/ Ear	100 Kernel Weight, g	Irrigation inches	Water use inches	WUE lb/a-inch
0.15 in/d	34.0 K	282.0	35284	0.98	519	40.17	10.65	25.45	621
	30.0 K	268.1	30928	0.96	536	42.63		25.32	594
	26.5 K	251.2	27878	0.98	531	44.20		25.24	559
0.45 in/3 d	34.0 K	267.1	34195	0.94	526	40.13	10.80	25.14	595
	30.0 K	268.1	31363	0.94	544	42.60		25.75	583
	26.5 K	243.5	27661	0.96	541	43.43		24.98	546
0.75 in/5 d	34.0 K	270.3	33106	0.97	529	40.57	11.25	25.54	594
	30.0 K	264.8	31146	0.98	525	42.01		25.31	586
	26.5 K	253.0	28314	0.97	538	43.61		25.12	564
1.05 in/7 d	34.0 K	274.2	35066	0.97	509	40.19	11.55	26.33	584
	30.0 K	266.8	31146	0.97	532	42.16		26.02	574
	26.5 K	243.0	23789	0.96	562	43.23		25.77	528
0.30 in/d (Full)	34.0 K	273.5	33324	0.95	541	40.81	14.70	26.21	585
	30.0 K	256.4	30710	0.94	534	42.29		26.49	542
	26.5 K	240.7	26572	0.95	553	44.14		26.20	514
No irrigation	34.0 K	180.9	34195	0.97	480	28.94	0.10	17.99	563
	30.0 K	180.2	29839	0.94	546	30.15		18.24	553
	26.5 K	170.1	26354	0.98	507	33.27		18.04	529
Mean of Irrigation Trt									
0.15 in/d		267.1	31363	0.97	528	42.33	-	25.33	591
0.45 in/3 d		259.5	31073	0.94	537	42.05	-	25.29	575
0.75 in/5 d		262.7	30855	0.97	531	42.06	-	25.32	581
1.05 in/7 d		261.3	31000	0.97	534	41.86	-	26.04	562
0.30 in/d (Full)		256.9	30202	0.95	542	42.41	-	26.30	547
No irrigation		177.0	30129	0.96	511	30.79	-	18.09	548
LSD ($p<0.05$) Any 2 irrigation means within same P Pop		5.2	NS	NS	NS	0.57	-	0.28	12
Mean of P Pop Trt									
34.0 K		258.0	34195	0.96	517	38.47	-	24.44	590
30.0 K		250.7	30855	0.96	536	40.31	-	24.52	572
26.5 K		233.6	27261	0.96	538	41.98	-	24.22	540
LSD ($p<0.05$) Any 2 P Pop means within same Irr Trt Pop		19.0	1928	NS	46	2.00	-	NS	43

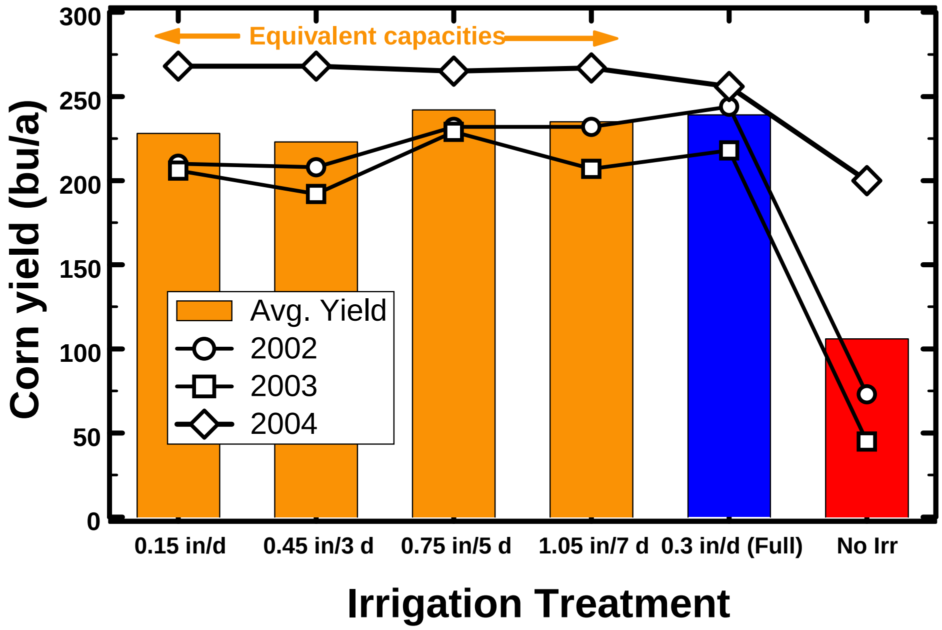

Figure 2. Corn grain yields as affected by irrigation treatment, Colby, Kansas, 2002 to 2004.

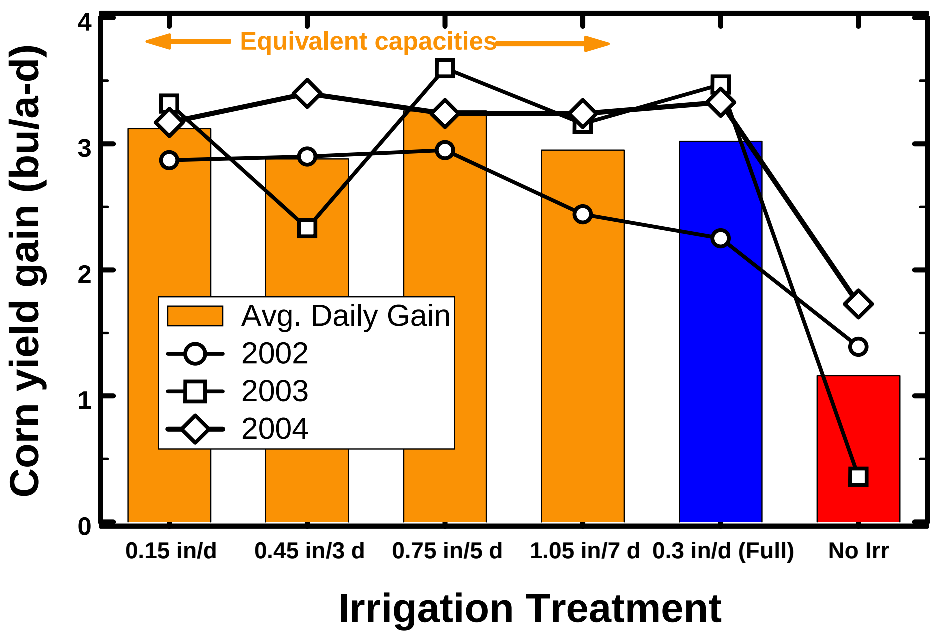

Figure3. Average daily yield gain for corn as affected by irrigation treatment, Colby, Kansas, 2002 to 2004.

Plant population had little effect on corn yields in 2002 and 2003 (Tables 1 and 2) but higher plant population had a large effect in 2004 (Table 3) increasing yields by approximately 15-20 bu/acre. This is consistent with an earlier study (Lamm and Trooien 2001) that indicated that higher plant population was seldom a drag on yield but allowed for higher yields in good years.

Water use and Water Use Efficiency

Water use for the 8-ft soil profile tended to be slightly higher for the less frequent irrigation treatments (0.75 inches/5 days and 1.05 inches/7 days) and was significantly higher in 2002 which may explain the higher yields for those treatments in that year (Tables 1, 2 and 3). Water use for the deficit irrigated frequency treatments averaged only 7% less than the fully irrigated treatment although irrigation was 30% less. This indicates the deficit irrigated treatments were effective at "mining" soil water and also perhaps had less deep percolation losses. Water use efficiency (yield divided by total water use) was significantly higher for the less frequent treatments in 2002, but tended higher for the more frequent treatments in 2003 and 2004.

Plant population did not affect total water use in any year. This would be anticipated since there is little difference in water use after sufficient leaf area index is obtained. These populations were sufficiently high to obtain good ground cover early in the season. Water use efficiency was higher for the higher plant population in 2004, reflecting the increased yield with plant population.

SUMMARY AND CONCLUSIONS

Corn production was not strongly affected by SDI frequency in two of three years and less frequent larger irrigation events were beneficial in the extreme drought year of 2002. Further research is being conducted to determine why early season corn kernel set can be affected in extreme drought years. Average daily yield gain during the grain filling stage was not affected by SDI frequency. Water use and water use efficiency for the 8-ft soil profile also were not strongly affected.

Combining these results with earlier studies from the U.S. Great Plains and elsewhere (Camp, 1998; Howell et al., 1997; Caldwell et al., 1994) continues to suggest that SDI frequency is not a significant issue for corn production on these deeper silt loam soils. Irrigators may want to continue to use less expensive manually operated systems unless they are engaged in automated nutrient management programs.

Higher plant population is generally beneficial in corn production with SDI systems even under deficit irrigation.

REFERENCES

Caldwell, D. S., W. E. Spurgeon, and H. L. Manges. 1994. Frequency of irrigation for subsurface drip-irrigated corn. Trans. ASAE 37(4):1099-1103.

Camp, C. R. 1998. Subsurface drip irrigation: A review. Trans. ASAE 41(5):1353-1367.

Howell, T. A., A. D. Schneider, and S. R. Evett. 1997. Subsurface and surface microirrigation of corn—Southern High Plains. Trans. ASAE 40(3):635-641.

Eck, H. V. 1986. Effects of water deficits on yields, yield components, and water use efficiency of irrigated corn. Agron. J. 78:1035-1040.

Lamm, F. R. and T. P. Trooien. 2001. Irrigation capacity and plant population effects on corn production using SDI. In Proc. Irrigation Assn. Int'l. Irrigation Technical Conf. And Exposition, Nov. 4-6, 2001, San Antonio, TX. Pages 73-80. Available from Irrigation Assn., Falls Church VA. Also available at http://www.oznet.ksu.edu/sdi/ under K-State Reports in 2001.

Lamm, F. R., M. E. Nelson, and D. H. Rogers. 1993. Resource allocation in corn production with water resource constraints. Appl. Engr. in Agric. 9(4):379-385.

Musick, J. T. and D. A. Dusek. 1980. Irrigated corn yield response to water. Trans. of the ASAE 23(1):92-98, 103.

Stewart, J. I., R. D. Misra, W. O. Pruitt and R. M. Hagan. 1975. Irrigating corn and grain sorghum with a deficient water supply. Trans. ASAE 8(2):270-280.

[1] *Mention of tradenames is for informational purposes and does not constitute endorsement of the product by the authors or Kansas State University.*

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Ultra-slow Release of Trifluralin from Polymers

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Abstract

Slow release of trifluralin to inhibit root intrusion into drip irrigation emitters is a well-known technology. Ultra-slow release to double the expected life of such products, has recently been developed.

The concept is based on the recognition that nanometer sized inert inorganic particles, such as nanometer sized clay particles, can be incorporated into a polymeric host carrier, in order to control the diffusion rate of a dispersed slow-release material. The active slow-release material may comprise a bioactive chemical such as a fungicide, bactericide, insecticide or herbicide. The presence of the nano-clay particles reduces the porosity of the polymer, or otherwise obstructs the diffusion of the active material being released, thereby increasing the length of the path of the diffusion through the host polymer. This further slows the rate of release of the slow-release material. The method of blending the materials proves to be critical.

Introduction

There are products in the marketplace that depend upon slow-release technology. One product slowly releases a herbicide from a polymer into soil in order to inhibit root intrusion into that area (Burton et. al. 1992). Flea repellent dog collars are another example where an insecticide is slowly released from the polymer in the collar. In many cases more of the active material is released than is necessary to efficiently meet the product requirements. In other words, a lower rate of diffusion through the polymer would result in a longer effective product life.

The application discussed in this paper is a drip irrigation device that inhibits root intrusion by incorporating trifluralin (an herbicide) into the drip emitter. This technology has been successful in protecting buried drip irrigation devices from root penetration for periods of more than fifteen years. The herbicide is incorporated into a polymer matrix, which protects the trifluralin from chemical or biological degradation. This simultaneously provides a controlled, sustained release of the herbicide to the soil adjacent the device. The blending of a nano-clay into the polymer can extend the expected life of the herbicide by as much as 90%.

Materials and Methods

An intercalation material comprised of an inert fine particulate inorganic material with a layered structure (a nano-clay) is incorporated into a mixture of the slow-release bioactive material and the host polymer. The slow-release material is accommodated within spaces between the layers of the intercalation material to slow the diffusion rate of the slow-release material through the host polymer, as compared to the diffusion rate of the same slow-release material through the same host polymer not containing the dispersed intercalation material. The intercalation material is surface-treated to expand the spaces between the platelets that form the dispersed material. The active material is released at a controlled reduced rate, but at a level sufficient to maintain its effectiveness, while the resinous carrier maintains its structural properties.

The nano-clay is a montmorillonite, an alumino-silicate. The particles are in layered form, i.e., formed as platelets. These particles measure on the order of one micron (0.00004 inches) in diameter and a thickness of about 0.001 micron (or one nanometer), giving them an aspect ratio of about 1,000:1. Relatively small amounts of nanometer-sized clay particles, approximately 2% to approximately 10% by weight, are dispersed in the resinous matrix formed by the host polymer and the dispersed active material. The use of nano-clay materials to reinforce the mechanical properties of plastic materials such as nylons and polyolefins is described in by Sherman (Sherman, 1999).

Three masterbatches were prepared.

“Mix” refers to a simple mechanical mixing without the application of heat or shear. “Compound” refers to mixing under heat and shear, followed by pelletizing, in order to produce nearly homogeneous granules.

“MBN” is the nano-clay masterbatch. Nano-clay is compounded in a polyethylene resin in the ratio of 40:60. Intercalation techniques similar to those described in the Qian (Qian et. al., 2001) were used for surface treating the nano-clay particles with a surface modifier to expand the spacing between platelets. Polyethylene resin was mixed with the clay particles to form a co-intercalate material

MBT is the trifluralin masterbatch. The trifluralin-containing material was made of 50% polyethylene resin, 25% trifluralin, and 25% carbon black. These components were blended and then compounded in a twin screw compounding extruder into a masterbatch according to techniques disclosed in Burton (Burton, et. al. 1992).

MBTN is the combined masterbatch. The component materials for MBT were mixed together, but not compounded. MBN was added. The ratio of materials was: polyethylene 30%, trifluralin 15%, carbon black 15% and MBN 40%. The resulting mix was compounded in a twin screw compounding extruder.

For the first experiment, two mixes were prepared. MBT was mixed with linear-low density polyethylene (LLDPE) in the ratio of 75:25. And, MBTN was mixed with LLDPE in the ratio of 58.33:41.67. Both mixes contained 6.25% of trifluralin.

For the second experiment, the MBN and MBT masterbatches were mixed to produce the following three mixes:

TABLE 1

	1	2	3
MBN	0.00	12.49	24.98
LLDPE	75.02	62.53	50.04
MBT	24.98	24.98	24.98
Total	100.00	100.00	100.00
(MBN/MBT)%	0%	50%	100%

In both experiments, the mixes were injection molded to form drippers. Four drippers in each set were placed in an aluminum foil dish and weighed. Initial weight of the drippers was 16 gm. They were then placed in an oven, using a slow extraction fan to remove the trifluralin as it left the drippers. The first experiment was conducted at 56.67º C (134º F.); and the second experiment at 88.90º C. (192º F.) In order to observe the extraction rate, the samples were weighed periodically over until the rate of extraction leveled off and the majority of the trifluralin contained in the parts had been lost.

Results and Discussion

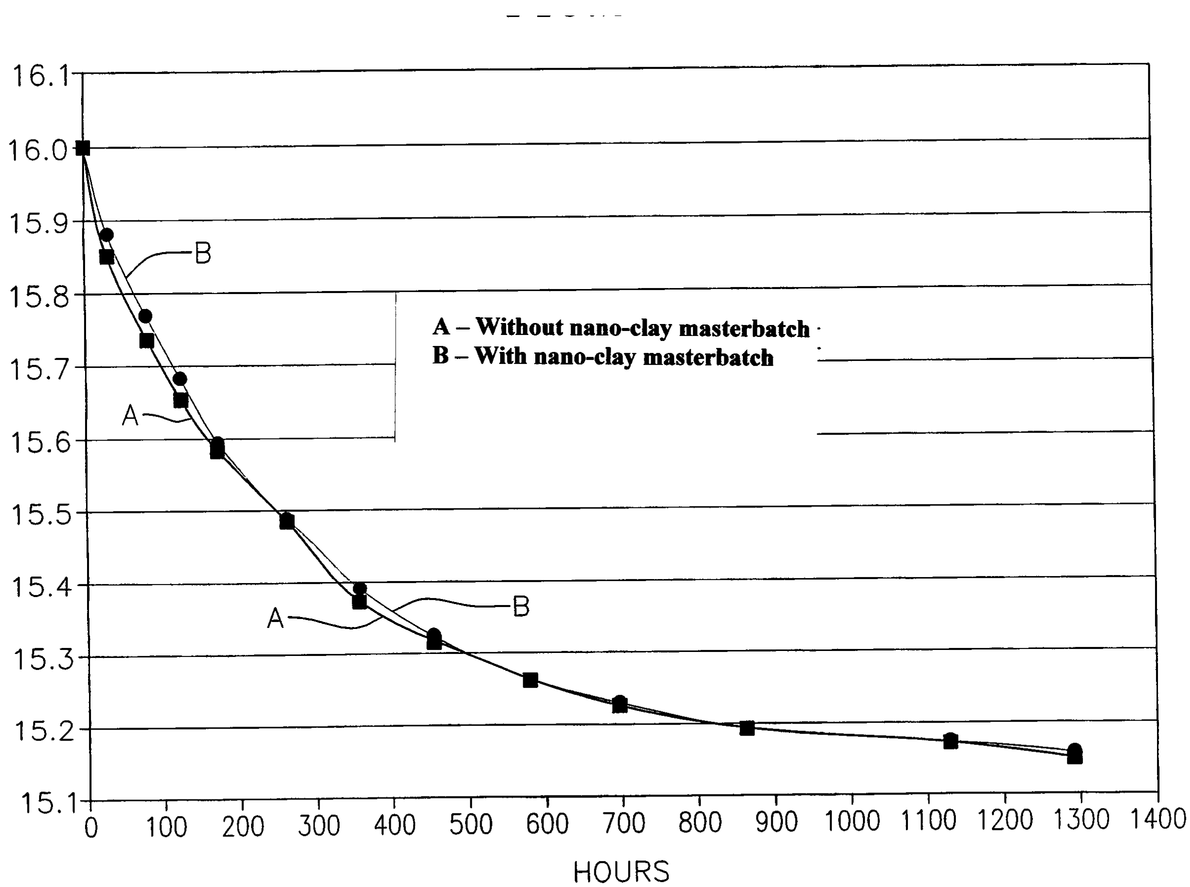

Figure 1: MBT and MBTN. Loss of weight in gms. against time in hours.

The first experiment: The graph shown in FIG. 1 illustrates the extraction rate of trifluralin from the drippers. The data shows that extraction rate (or release rate) of trifluralin from the drippers is not effected by the presence of the nano-clay. This result was most disappointing. The project was dropped for six months.

The second experiment: The graph shown in FIG. 2 illustrates the extraction rate of trifluralin from the drippers molded from the mixes shown in Table 1. The data shows that extraction rate (or release rate) of trifluralin from the drippers progressively decreases with a proportionate increase in the level of nano-clay contained in the dripper body.

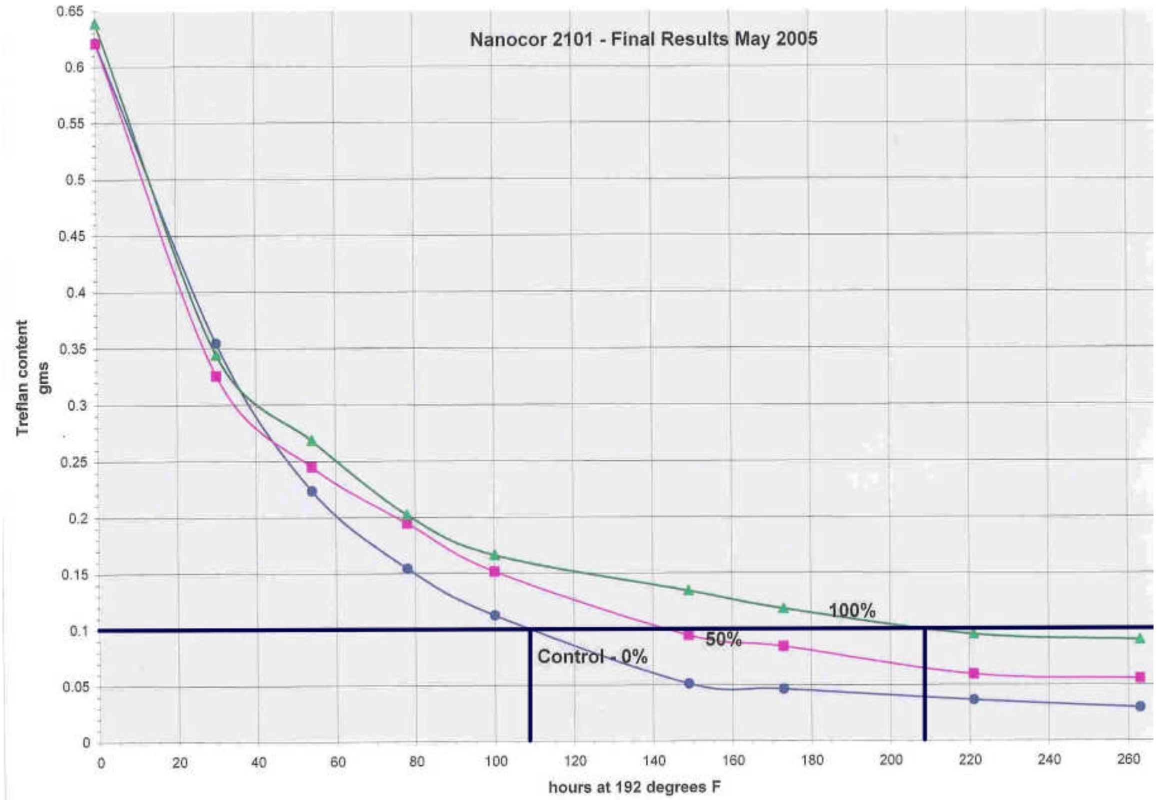

Figure 2: Reduced rate of loss of weight with increase concentration of nano-clay – MBN

More specifically, from Fig. 2, the time for the remaining concentration of trifluralin to drop to 0.1 gms is:

Control	109 hours
50%	145 hours - 41% increase
100%	209 hours - 92% increase

Apparently, the bond of the trifluralin with the carbon black is so strong that in the first experiment, adding the nano-clay did not decrease the rate of release; however, by adding the two masterbatches separately, the rate of diffusion from the carbon black was reduced by the barrier of the nano-clay in the LLDPE carrier.

It is believed that the process of utilizing dispersed nano-clays for slowing the diffusion rate of the active material from the polymeric carrier is caused by the phenomenon known as "intercalation." Intercalation compounds are formed when the "guest" molecule, in this case trifluralin, can be accommodated in the spaces between adjacent layers of the "host" molecule, in this case, the montmorillonite. Over time, trifluralin will diffuse out of the clay particles and the polymer at a rate that is slower than the release rate from a similar structure not containing the nano-clay particles. Such layered, inert, inorganic, fine particulate materials which are effective in controlling slow-release active materials, such as bioactive chemicals or herbicides, to slow their release rates are referred to as "intercalation materials." The phenomenon known as "intercalation" is described in "Preparation of inorganic - organic nanocomposites by intercalation and its application to materials," published by *Applied Chemistry*.

Conclusions

The data above shows that the addition of a nano-clay, in the manner described, is effective because the addition of 10% of a nano-clay resulted in a 92% increase in the time to loose approximately 83% of the trifluralin incorporated into the molded dripper. This, of course, means that there will be an equivalent increase in the effective life.

This paper claims that the manufacture of two separate masterbatches is essential, and that combining the manufacture of the masterbatches into one single masterbatch does not result in any slow-down of the release process.

This process can be applied to many slow release applications, such as termite barriers, fertilizers, anti-graffiti paint etc. (Ruskin 2004).

Further Research

Following the argument above, it is possible that by first compounding the MBN with all the LLDPE to get the desired concentration, and then adding the MBT, an even slower release rate could be produced.

Literature Cited

Burton, F.G., Cataldo, D.A., Cline, J.F., and Skiens, W.F. 1992. U.S. Patent No. 5,116,414

Sherman, L.M. 1999. "Nanocomposites, a Little Goes a Long Way," *Plastics Technology*, June 1999, Pages 52 to 54,

Qian, G, Cho, J.W., and Lan, T. 2001. Preparation and Properties of Polyolefin Nanocomposites. Polyolefins 2001, Houston, TX, Feb 25-28, 2001.

Ruskin, R. 2004. U.S. Patent No. 6,821,928 B2

Forage Subsurface Drip Irrigation using Treated Swine Effluent

K. C. Stone, P. G. Hunt, J. A. Millen, and M. H. Johnson

Abstract

An experimental subsurface drip irrigation (SDI) system was initiated to evaluate the use of treated swine effluent on a bermuda grass forage crop. The SDI system was installed in Duplin County, North Carolina at the location of an innovative swine wastewater treatment system. The effluent from the treatment facility was applied to Bermuda grass forage crop at agronomic nutrient rates. Treated wastewater application below the soil surface reduces nutrient loss potential through volatilization and places nutrients in the rooting zone. Results from the forage SDI system indicated that treatments receiving treated waste as their nutrient source had higher biomass yields.

Introduction

In the eastern US during the early 1990's, animal production has expanded rapidly. In North Carolina, the number of swine has increased from approximately 2.8 million in 1990 to more than 9 million by 1996 (USDA-NASS, 2004). This rapid expansion of animal production has resulted in greater amounts of concentrated animal waste to be utilized or disposed of in an efficient and environmentally friendly manner. It has exceeded the pace at which new innovative treatment systems have been developed, and it has resulted in the animal production industry aggressively investigating and adapting new alternative wastewater treatment technologies. Additionally, the expansion of animal production has led to fewer, more concentrated operations that are challenged to treat, utilize, and/or dispose of the waste in an environmentally friendly manner. Additional challenges and concerns from these operations are odors, ammonia emissions, and pathogens. Many new and innovative systems still rely on the final land application of treated wastewater which typically uses high volume sprinkler irrigation systems.

Subsurface drip irrigation (SDI) systems can help address some concerns about land application of treated animal effluent. The SDI systems apply effluent below the soil surface and can eliminate spray and drift from land application thereby reducing odors and ammonia volatilization. The SDI systems may also be used during periods of high wind or low temperatures when sprinkler application would not be acceptable.

Subsurface drip irrigation systems have been used in Kansas to apply beef lagoon effluent with successful results (Lamm et al., 2002). In the southeastern Coastal Plains, little research has been conducted using SDI systems for application of wastewater. The objective of this work is to determine the feasibility of and management guidelines for SDI systems applying treated wastewater in the eastern Coastal Plains.

Methods

Site Description

The study was conducted on a 4-ha site of Autryville loamy sand (Loamy, siliceous, subactive, thermic Arenic Paleudults) in Duplin County, North Carolina. A subsurface drip irrigation (SDI) system was installed in the summer 2003.

The forage SDI system was approximately 0.53 ha. The system consisted of 36 total plots (9.6 x 9.6 m) with 9 treatments. The treatments were irrigation application amount (75 or 100% of ET), nutrient source (commercial or treated effluent), SDI lateral spacing (0.6 and 1.2 m), and a non-irrigated control.

The SDI laterals were installed 0.3 m below the soil surface using two poly-hose injection shanks mounted on a tool bar. The irrigation system for each plot consisted of individual PVC pipe manifolds for both the supply and discharge. Discharge manifolds were flushed back to the adjacent lagoon. Irrigation laterals had in-line, pressure compensating labyrinth emitters spaced 0.6 m apart with each delivering 1.9 L/h.

Control System: The SDI irrigation system was controlled by a 200 GHz Pentium PC running a custom Visual Basic (VB) program. The VB program operated a digital output PCI board, an A/D input board, and a counter/timer board. The digital output board operated supply pumps and solenoid valves. The A/D input board read supply line pressures. The counter/timer board recorded flows. Float switches controlled tank levels.

Each water source had a dedicated pump and supply tank. Selected treatments could receive treated effluent and all treatments could receive well water. Screen filters were used for both well water and wastewater . A media filter with sand and gravel was used to filter the treated effluent before it reached the screen filter.

Flow meters were used on each water source as well as each treatment. Supply pressures were monitored using pressure transducers which were placed before and after the screen filter for each water source.

Weather Station: A tripod mounted weather station was installed at the irrigation site. The station used a CSI data logger to measure relative humidity, air temperature, solar radiation, wind speed, wind direction and rainfall. The data logger tabulated data at 5 minute intervals. The data was downloaded daily to the irrigation control PC via broad spectrum radio modems.

Irrigation Scheduling: Once the weather data was received from the data logger, potential ET was calculated using a SAS program. Potential ET was then multiplied by a crop coefficient to obtain daily ET value for the crop. The ET and daily rainfall were accumulated for the previous seven days. When the cumulative ET for the previous days exceeded the accumulated rainfall by greater than 6 mm, an irrigation event was initiated.

Wastewater Treatment System: An innovative swine wastewater treatment system was designed and tested at full-scale on a 4,400-head finishing farm as part of the agreement between the Attorney General of North Carolina and Smithfield Foods/Premium Standard Farms to replace current anaerobic lagoons with environmentally superior technology (Vanotti, 2004). The treatment system was developed with the objectives 1) to eliminate animal-waste discharge to surface and ground waters, 2) to eliminate contamination of soil and groundwater by nutrients and heavy metals, and 3) to eliminate or greatly reduce the release of ammonia, odor, and pathogens.

The effluent treatment system consisted of three modules. The first module separated solids and liquids. The second module removed nitrogen using a combination of nitrification and denitrification. The third module removed phosphorous in the Phosphorus Separation Module, developed by USDA-ARS (Vanotti et al., 2001), and it recovered the phosphorus as calcium phosphate. This process required only small additions of liquid lime. The alkaline pH with this process reduced ammonia volatilization losses and killed pathogens. Treated wastewater was recycled to clean swine houses and for the SDI systems. The system removed 97.6% of the suspended solids, 99.7% of BOD, 98.5% of TKN, 98.7% of ammonia, and 95% of total P. Average inflow concentrations and system outflow nutrient concentrations are shown in table 1. Effluent grab samples were taken before each wastewater irrigation. These wastewater samples were analyzed to determine nutrients applied and to adjust subsequent wastewater applications.

Table 1. Typical Treated Effluent Characteristics.

Water Quality Parameter	Raw Flushed Manure (mg/L)	Treated Effluent (mg/L)
pH	7.6	10.5
TSS	11,051	264
BOD_5	3,132	10
COD	16,138	445
Soluble P	135	8
TP	576	29
TKN	1,584	23
NH_4-N	872	11
NO_3-N+NO_2-N	1	224

Crop Management

Bermuda Grass Forage: Bermuda grass was over sown with SS FFR535 wheat variety using the no-till grain drill on December 2, 2003. The winter cover crop was mowed after heading and bailed on May 27, 2004. Bermuda grass hay was then harvested on July 1, August 10, and September 21, 2004. In 2004, the Bermuda grass was over sown with wheat in December and harvested in June 2005. Bermudagrass hay was harvested on July 12, and August 15, 2005.

Results and Discussion

There were three Bermuda grass hay cuttings in 2004 and two cuttings in 2005 (Table 2). For this experiment, there were two water application rates, 100% and 75% calculated ET. The first cutting in 2004 produced yields that appeared to be counter intuitive. The treatments using commercial fertilizer had much lower yields than the treatments with treated wastewater for both lateral spacing and for both application rates. This was partially explained by residual nutrients in the plots that were irrigated with treated wastewater during the winter wheat season.

Table 2. Bermudagrass hay yields for 2004 and 2005

			Harvest										Mean	
			1		2		3		4		5			
			Yield (kg/ha)		Yield (kg/ha)		Yield (kg/ha)		Yield (kg/ha)		Yield (kg/ha)		Yield (kg/ha)	
			Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Spacing (m)	**Nutrient Source**	**% ET**												
0	**C**	**0**	2640	583	2713	289	2786	506	6113	2071	3655	630	3582	1636
0.6	**C**	**75**	1903	460	3227	266	2372	216	5759	861	4221	195	3496	1476
		100	1738	379	2885	305	2084	484	5432	655	3809	424	3189	1425
	W	**75**	2825	441	2793	182	2364	416	6162	790	3872	386	3603	1472
		100	2806	1174	3081	541	2106	562	4957	1259	3910	1064	3372	1325
1.2	**C**	**75**	1907	527	3080	696	2218	771	4910	1847	3804	1326	3184	1510
		100	1878	594	2187	673	1586	527	5044	1426	3206	962	2780	1517
	W	**75**	3761	239	3149	650	3410	615	5354	521	4230	467	3981	920
		100	3124	695	2952	638	2515	588	5607	1708	3816	1215	3603	1460
$LSD_{0.05}$			897		740		783		1953		1211		892	

For the second and subsequent cutting, results for both the commercial and treated waste water treatments were similar. For this cutting, there was little difference between lateral spacing, fertilizer source, and irrigation applications. Generally, irrigated treatment yields were higher than the non-irrigated treatment. The irrigation treatments with wastewater typically had higher yields than those with irrigated conventional fertilizer. This may be attributed to additional small nutrient applications with the wastewater, whereas the conventional fertilizer was applied immediately after harvest. Leaching of nutrients out of the root zone for the conventional fertilizer plots may have also occurred. The lack of differences between the yields for the different lateral spacing could assist future designs and lower the initial cost of SDI systems by using wider lateral spacings with little yield differences.

In addition to the yield results, the total water quantities and total nutrients applied to each treatment will be tabulated. The nutrient concentrations in the soil profile and in the pore water from suction lysimeters are being analyzed to determine the overall water and nutrient budgets for the crop.

References

Lamm, F. R., T. P. Trooien, G. A. Clark, L. R. Stone, M. Alam, D. H. Rogers, and A. J . Schlegel. 2002. Using beef lagoon wastewater with SDI. In Proc. Irrigation Assn. Int'l. Irrigation Technical Conf., Oct. 24-26, 2002, New Orleans, LA. Available from Irrigation Assn., Falls Church, VA.

USDA-NASS. 2004. Agricultural statistics database (http://www.nass.usda.gov:81/ipedb/). U.S. Department of Agriculture, National Agricultural Statistics Service, Washington, DC.

Vanotti, M.B., A.A. Szogi, P.G. Hunt. 2001. Wastewater treatment system. Patent Application Serial 09/903,620, allowed Apr. 21, 2004. US Patent & Trademark Office, Washington, DC.

Vanotti, M.B. 2004. Evaluation of Environmentally Superior Technology. Final Report for Technology Determination per Agreements Between the Attorney General of North Carolina and Smithfield Foods, Premium Standard Farms and Frontline Farmers. http://www.cals.ncsu.edu:8050/waste_mgt/smithfield_projects/phase1report04/A.9Super%20Soil%20final.pdf

ENERGY USE FOR MICRO-IRRIGATION

Tom Trout and Jim Gartung[1]

ABSTRACT

Micro-irrigation systems can operate with low pressure. Micro-irrigation emitters require only 7 - 20 psi. Cleaning and delivering the water to the emitters on flat fields typically requires an additional 15 psi. A survey of 312 California micro-irrigation systems showed that 60% of the systems exceed these pressures, and 25% exceed by over 10psi. Pressure could be reduced by an average of 15 psi in 60% of the systems. Pressure was lost at the filter station, in the distribution system, at pressure regulators, in the lateral inlets, and at the emitters. Higher pressure is required to irrigate undulating land. Reducing system pressure by 15 psi in a system could save about $25 per acre per year in electricity costs, and reducing pressure by 15 psi for 60% of the 1.7 million acres of micro-irrigation in California would save 220 Gigawatt-hrs/yr of energy and 90 Megawatts of peak load. It will often be economical to invest more in the system to save pressure and energy costs, but energy-saving changes may decrease system flexibility and simplicity or increase risk of system failures.

INTRODUCTION

Electric energy rates increased by about 30% in California in 2001. Cost for pumping irrigation water now exceeds 12 cents per kw-hr in most cases. Electricity shortages and the high cost of marginal supplies on the spot market induced California to offer irrigators financial incentives to reduce peak electricity demand.

Energy is used to lift water from groundwater wells to the fields and to pressurize the irrigation system. Gravity irrigation methods generally do not require pressurization and are often the lowest energy option. However, gravity systems may be less water use efficient than pressurized systems, resulting in higher well pumping costs. Most sprinkler systems require 50 - 80 psi to operate efficiently. The development of low pressure sprinklers and sprayers, largely in response to energy cost increases in the 1970s, reduced pressure requirements of moving lateral (center pivot, lateral move) sprinkler systems to 30 - 50 psi.

Micro-irrigation is a low pressure alternative to sprinkler systems that can efficiently and uniformly apply irrigation water. Micro-irrigation is used on 1.7 million acres in California and 3 million acres in the U.S. (Irrigation Journal 2001). Drip emitters require 7 - 15 psi, and most micro-sprayers operate well at 15 - 25 psi. However, unlike sprinkler systems which are usually designed for minimal pressure losses between the pump and sprinkler, most micro-irrigation systems use 10 to 30 psi to clean, regulate, and deliver water to the emitters. Thus, pressure requirements are sometimes no lower than with low-pressure sprinkler systems.

Table 1 shows pressure requirements and pressure losses for two types of micro-irrigation

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systems, hose drip systems and micro-spray (jet) systems, based on equipment specifications, design standards, and interviews with micro-irrigation system designers. About 15 psi is needed to clean, control, and deliver water to the emitters for fields on level ground. An additional 7 – 25 psi is required for good emitter operation, depending on the type of emitter. Most filters have minimum pressure requirements for backflushing varying from 20 to 45 psi.

There may be potential to reduce pressure, and thus energy, requirements of micro-irrigation systems through alternative design, equipment selection, or management. A 10 psi pressure reduction would reduce power requirements by about 36 kw-hr/ac.ft. of water pumped or about 220 million kw-hr/yr for California's 1.7 million acres of micro-irrigation.

Energy use in irrigation can be reduced by reducing the amount of water pumped (increased efficiency or deficit irrigation), by increasing the efficiency of the pumping plant, or by reducing the system pressure. For example, for a 100 ac. California orchard that requires 3 ft. of water annually with a well pump with a 100 ft. lift, energy costs can be reduced by about $1800 per year either by increasing the irrigation efficiency from 75% to 85% (ie: reducing the water pumped from 4 to 3.5 ac-ft/ac), by increasing the pumping plant efficiency from 60% to 68%, or by reducing system pressure requirement from 40 to 30 psi. If the water supply is surface water, the irrigation efficiency would need to be increased to 100% or the efficiency of the booster pump to 80% to gain the same savings as reducing system pressure by 10 psi.

The objective of this study is to determine the pressures used with micro-irrigation systems, the sources of pressure loss, and ways to reduce pressure requirements.

Table 1. Pressure losses for micro-irrigation systems.

		Well-designed System*	
System Component	**Range** ***(psi)***	**Microspray** ***(psi)***	**Drip** ***(psi)***
Emitter (microspray, dripper)	7-25	20	15
Lateral hose	1-5	2	2
Manifold	1-5	1	1
Main and Sub-main pipelines	2-10	5	5
Filter (allowable loss)	3-10	5	5
Other losses: (Press. Regulators, Chem. injectors, Control Valves, Flow Meters; Fittings)	1-20	2	2
Total Cumulative	15-75	35	30

* 40 ac. orchard or vineyard on level land with a sand media and screen filter.

METHODS

Several hundred California irrigation systems have been evaluated by mobile irrigation labs using procedures developed by the Irrigation Training and Research Center (Burt et al. 2000). As part of these evaluations, system pressures are measured at several points in the irrigation system. We summarized pressure data from evaluations of 312 micro-irrigation systems in California's San Joaquin Valley and central coast carried out by the Irrigation Training and Research Center[2] (Cal Poly, San Luis Obispo), Kings River Conservation District (Fresno), and USDA-ARS-WMR over the last 5 years. We included only systems that irrigated more than 10 ac. These systems were predominately hose drip systems in vineyards, microspray systems in orchards, and drip tape systems in strawberries. Table 2 shows the breakdown of systems by crop group and system type.

Table 2. Evaluated Irrigation Systems included in Database by Crop Type and Micro-irrigation method.

Crop	Drip Hose	Microspray Jets	Microspray Spinners	Drip Tape	Total
Orchards (fruit and nut)	61	111	22		194
Vineyards	50				50
Strawberry				38	38
Other Annual				3	3
Unknown	27				27
Total	138	111	22	41	312

In these evaluations, pressures were recorded downstream from the pump and at several locations in the irrigation laterals (at the emitters). Measurements were often also taken at the filter downstream of the filter station (inlet of the distribution system). In addition, all evaluations recorded the type of emitters and most recorded the type of filters and the presence and location of regulating values. Evaluators recorded if the fields were "undulating", however, we found that information inadequate, so we located as many of the fields as possible (258) on topographic maps and determined the general slope in the area, and when, possible (240 fields), estimated the elevation of the water supply and high and low elevations for the field. Based on field slope and elevation difference information, fields were categorized into 4 topographic categories: Flat (less than 4.5 ft (equivalent to 2 psi) elevation difference, low slope (less than 11.5 ft (5 psi) elevation difference), moderate slope (< 35 ft (15 psi) elevation difference), and high slope (>35 ft elevation difference). Table 3 shows the number of fields by slope category and irrigation method.

Table 3. Evaluated Irrigation Systems included in Database by Elevation Category and Irrigation Method (values in ( ) are the portion of the systems with pressure compensating emitters).

Irrigation Method	Flat	Low Slope	Moderate Slope	High Slope
Drip Hose (PC)	36 (9)	23 (5)	36 (19)	17 (5)
Micro-Jets	42	30	11	3
Micro-Spinners (PC)	8 (4)	7 (5)	4 (2)	0 (0)
Drip Tape	6	19	6	10
Total	92	79	57	30

[2] Funding provided by U.S. Bureau of Reclamation and CA Dept of Water Resources

RESULTS

Figure 1 shows the range and distribution of pump pressures (downstream of the pump and, in most cases, upstream of the filter and any valves) in the 312 micro-irrigation systems. The figure shows a cumulative distribution curve, or the percentage of the total systems with pressures smaller than the x-axis value. For example, in Fig. 1, 60% of the systems had pump pressures less than 40 psi and 40% had pressures greater than 40 psi. The range of pump pressures is wide – from about 10 to 100 psi. About 30% of the systems operated with less than 30 psi pressure, and 20% had over 50 psi pump pressure.

Also shown on Figure 1 is a cumulative distribution curve of pressure available to filter, regulate and convey the water to the emitters. This *available pressure* was calculated as:

Pump Pressure – (highest field elevation – well elevation) – pressure required by emitter.

As the figure shows, although 60% the systems use more than 15 psi (Table 1) to clean, regulate, and distribute the water, 25% of the systems use over 30 psi and 10% use over 40 psi for these purposes. These data indicate potential opportunities to reduce system pressures.

These *available pressure* data are likely biased (underestimates) because systems often were not pumping to the highest field elevation when the pump discharge pressures were measured. When pressure required to distribute and elevate the water to the emitters is reduced, the pump discharge pressure will decrease and flow rates increase unless the pump discharge is throttled with control valves or pressure regulators. This will result in a bias towards underestimation of available pressure. Consequently, many of the very low available pressures may be underestimates.

High system pressures should result in improved irrigation water distribution uniformity (DU) both by reducing the relative pressure differences due to elevation or friction loss, and by enabling use of in-field pressure regulation. Figure 2 shows the relationship between low quarter DU as calculated in the irrigation evaluation (Burt et al. 2000) and available pressure for the systems that operated on flat or low-slope fields. The figure shows no relationship between available pressure and DU, even for systems with very low pressure. This indicates there is no water distribution or water saving benefits to high system pressures.

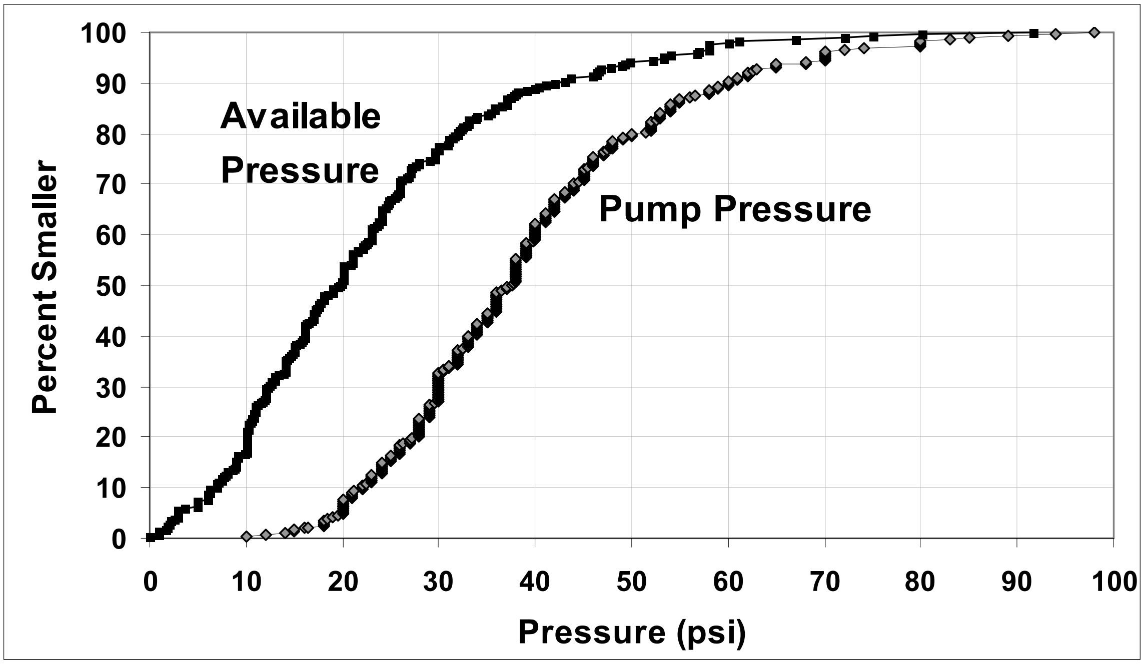

Figure 1. Cumulative distribution of pump pressures and pressure available to clean, regulate and distribute water in 312 California micro-irrigation systems.

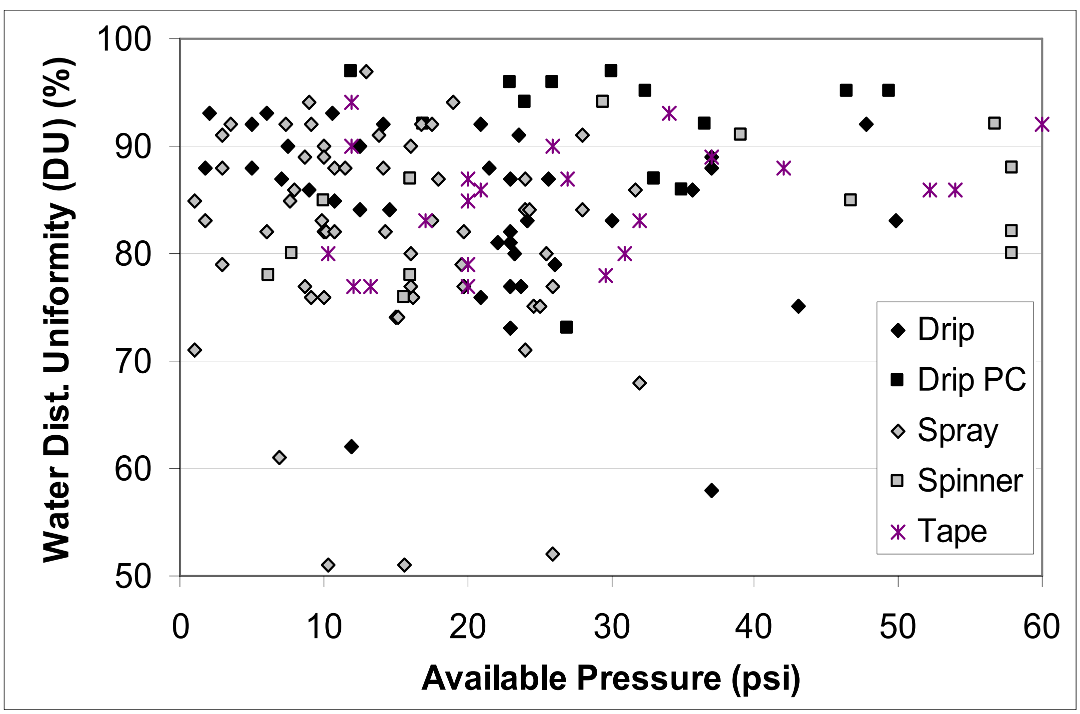

Figure 2. Measured water distribution uniformity as a function of available pressure for 150 California micro-irrigation systems on flat or low-slope fields.

Sources of Pressure Losses

Filter Station. The majority of the evaluated systems had sand media filters and/or tubular screen filters. Table 4 shows the types of filters and water source for the evaluated systems. Also listed are pressure loss expected when the filter is clean and the operating pressure required to backflush (clean) the filter, based on typical manufacturer recommendations. System designers often design for about 5 psi pressure loss for the filter, to allow for pressure loss when the filter has accumulated particulates and is ready for cleaning.

Overflow screens, commonly used with surface or low pressure water supplies, discharge water at atmospheric pressure and require a downstream booster pump for system pressure. Consequently, there is no pressure loss data for these screens.

Table 4. Numbers of different types of filters used in the evaluated micro-irrigation systems, by water source, and typical manufacturer's specified head loss when clean, and pressure required to backflush the filters

Filter Type	Water Source				Operating Pressure	
	Well	Surface	Both	Total	When Clean	Backflush
Sand Media (+ screen)	79 (6)	73 (5)	49(3)	201 (14)	1 – 3	20 – 45
Tubular Screen (vacuum)	34 (7)	14	4	52 (7)	1 – 5	0 - 25
Disk	11	7	1	19	1 – 5	35 – 45
Sand Separator	6	0	1	7	4 – 11	4 – 11
Overflow	1	8	19	28		(35)
None				2	0	0

Figure 3 shows the distribution of filter and filter station losses. Filter loss is often measured by differential pressure gauge connected to the inlet and outlet of the filters. Filter station loss is the difference between the pressure downstream of the pump and somewhere near the outlet from the filter station and inlet to the distribution system. About 1/3 of the systems indicated no measurable pressure loss across the filter. Very small loss is possible, but this likely often indicates a faulty gauge. Filter losses over 2 – 3 psi indicate the filters were not clean at the time of measurement (evaluators do not backflush filters), or that the filters are undersized or require substantial pressure loss to operate (sand separators and other centrifugal filters). Pressure loss above 7 psi indicates either a plugged filter in need of cleaning or repair, or a drastically undersized filter. There were no obvious differences in measured pressure losses for the various types of filters.

The scattered data points on Figure 3 are the filter station loss for the filter on the cumulative distribution curve (ie: same ordinate (y) value). Data points to the right of the curve indicates filter station losses in addition to those through the filter, due to fitting losses, control valves, chemigation injectors, etc. Thirty-one of the 280 systems had at least 5 psi pressure loss in addition to filter loss (or at least 8 psi loss if filter loss was listed as 0), and 15 of the systems had at least 10 psi loss in addition to the filter loss. For 7 of those systems, most of the loss was attributed to partially-closed manual or automatic pressure control valves, with valves dissipating over 15 psi for 5 of the systems. This is most likely due to a pumping plant over-designed for the conditions at the time of the measurement – for example for use of sprinklers, capacity needs for frost control, or pressure requirements to deliver water to higher fields. The right cumulative distribution curve in Figure 3 represents the filter station (including filter) loss. Twenty percent of the systems had filter station losses exceeding 8 psi.

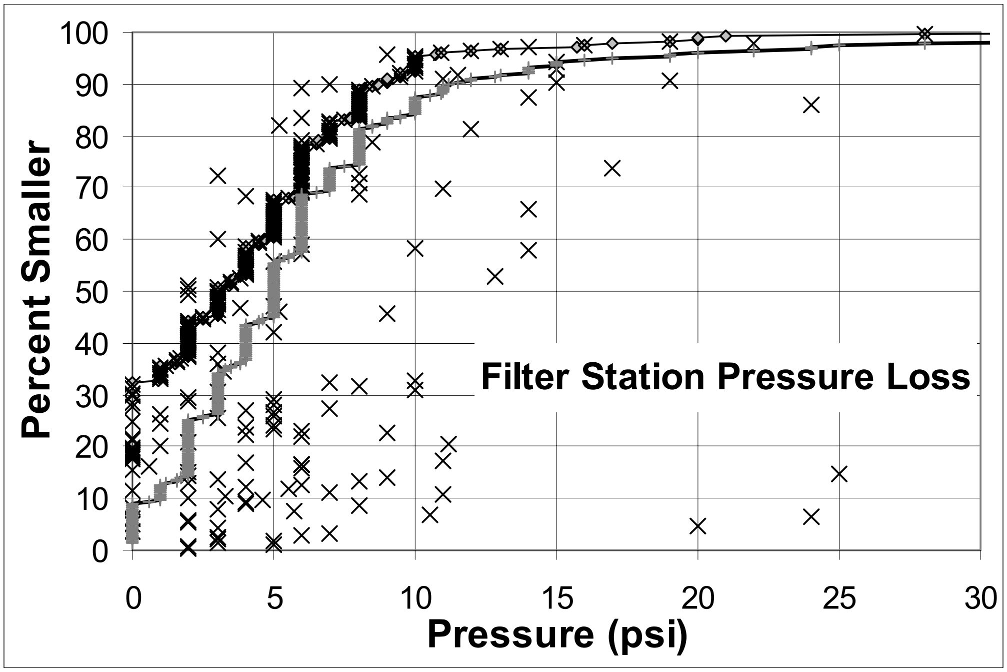

Figure 3. Cumulative distribution of pressure loss across the filters (left curve) and at the filter station (right curve). Scattered data are the filter station losses distributed horizontally from the associated filter loss.

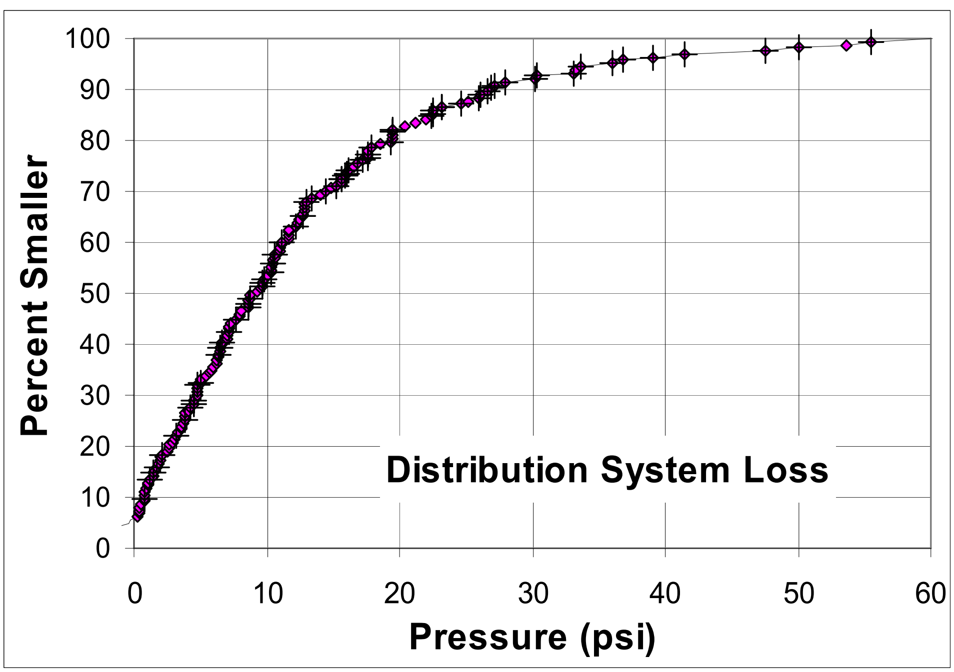

Figure 4. Cumulative Distribution of Pressure Losses in the Distribution System between the filter station and the manifolds for 163 flat and low slope systems. Cross (+) data points represent systems with pressure control valves.

Distribution System. Figure 4 shows the cumulative distribution of pressure losses in the distribution systems between the filter station and the manifold. The data represents the pressure difference between downstream of the filter station and average pressure at the inlet to the first lateral on each of three measured blocks. Thus, this represents distribution losses not to the furthest point but to an average of a near, far, and intermediate block, and does not include losses in the manifold. Elevation changes from the well to the highest field have been subtracted from the losses so that they represent only friction losses, and only flat or low slope fields have been included.

Nearly 50% of the systems exceed 10 psi pressure loss in the distribution system (main and sub-main pipeline and control valves), and nearly 20% exceed 20 psi loss. These high losses are surprising considering surveyed designers estimate typical main and submain losses at 3 – 6 psi. Many designers use two criteria for pipeline design – flow velocities less than 5 ft/sec between the filter station and block valves, and total distribution loss (including laterals) less than 3 psi downstream of the block valve. Limiting flow velocities to 5 ft/sec will result in flow velocity varying between 3.5 and 5 ft/sec (depending on flow rate and available pipe sizes) and pressure losses that average about 5 psi per 1320 ft (1/4 mi - the length of a square 40 ac field) of pipeline. Distributing water from one corner of a 40 ac field to the farthest block at the opposite corner would result in about 10 psi loss with the 5 ft/sec criteria. These data seem to indicate that either some systems use undersized pipelines, or there are significant losses in addition to pipeline friction losses. The most likely source are losses in control valves and block valve and fittings.

Ninety-five of the 312 systems had pressure control valves at the block (set) control points, 31 systems used pressure regulation at the inlet to the laterals, and 6 systems used both block and lateral pressure control valves. Seventy-six of 171 systems (45%) on flat or low slope fields used pressure control valves in the distribution system (cross data in Fig. 4). Over 75% of the systems on flat or low slope fields with distribution system loss over 15 psi had pressure control valves. Thus, a significant portion of the high distribution system losses shown in Fig 4 likely occur at pressure control valves.

Manifolds and Laterals. Figure 5 shows the average measured pressure loss in the manifolds of the 154 systems that operated on flat or low-slope fields without hose pressure control. These data were calculated as the difference between the inlet pressure in the lateral nearest the manifold inlet and the last lateral on the manifold, and represent the average of three measured manifolds on each field. Ten percent of the systems had slightly higher pressure at the tail end of the manifold than at the head end, and an additional 15% had no average pressure loss in the laterals, indicating the manifolds sloped downhill and elevation gain equaled or exceeded friction loss. However, 20% of the systems exceeded 2 psi pressure loss in the laterals and 10% exceeded 3 psi loss, which is excessive both for good distribution uniformity and pressure loss.

Another source of pressure loss in the manifold is the lateral inlet assembly. Hose screens are often used at the inlet to drip and microspray hose laterals. The evaluators checked these screens for plugging, and rechecked lateral pressures after cleaning. Before and after pressure measurements indicate the pressure loss due to hose screen plugging. On 18% of the drip hose and microspray systems, these screens generated over 1 psi of pressure loss, and on 10% of the systems, the loss was greater than 2 psi. For drip tape systems, small diameter polyethylene "spaghetti" tubing is usually used to connect the drip tape to the manifold. These connectors are often undersized in strawberry drip systems and generate substantial pressure loss. These losses were measured or calculated in the 38 strawberry drip systems, and over 50% caused more than

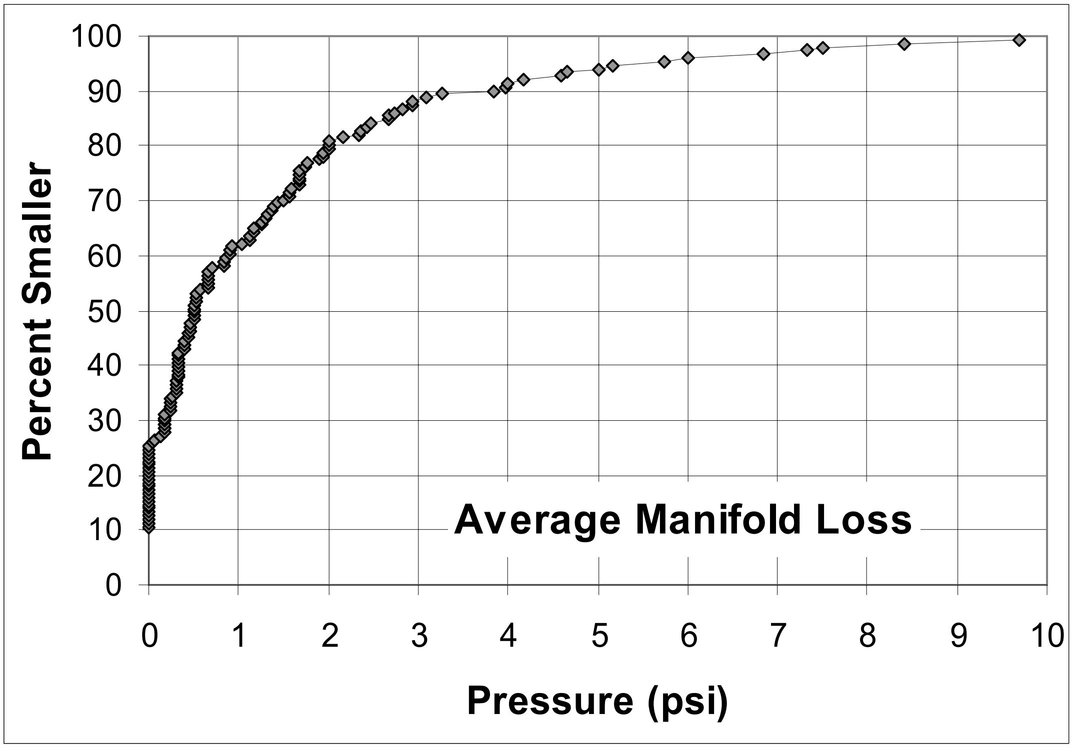

Figure 5. Cumulative Distribution of average measured pressure loss in the manifold for flat and low slope fields without hose pressure control.

2 psi of pressure loss. In 30% of the systems, these connectors caused over 4 psi of pressure loss.

Figure 6 shows the average pressure loss in the lateral hoses and tapes for 5 types of micro-irrigation systems. As expected, drip tapes, which have the lowest operating pressure, have the lowest losses, and micro-spray spinners which operate at relatively high pressures, and drip hose with pressure compensating (PC) emitters, have the highest loss. High distribution uniformity requires less than 10 or 15% pressure variation within laterals for non-PC emitters, with would be about 1 psi loss in tape, 2 psi loss in hose drip, and 3 psi in microsprays. About 50% of the systems exceed these limits. All but one of the spinners with pressure loss over 3 psi had pressure compensation. Where PC emitters are used to compensate for undulating terrain, they solve an important problem. Where they are used to allow use of long laterals or small hose size, they reduce initial costs at the expense of higher energy costs. About one-third of the PC drip systems were used on flat or low-slope fields, but over 80% of the PC spinners were used on flat or low-slope fields.

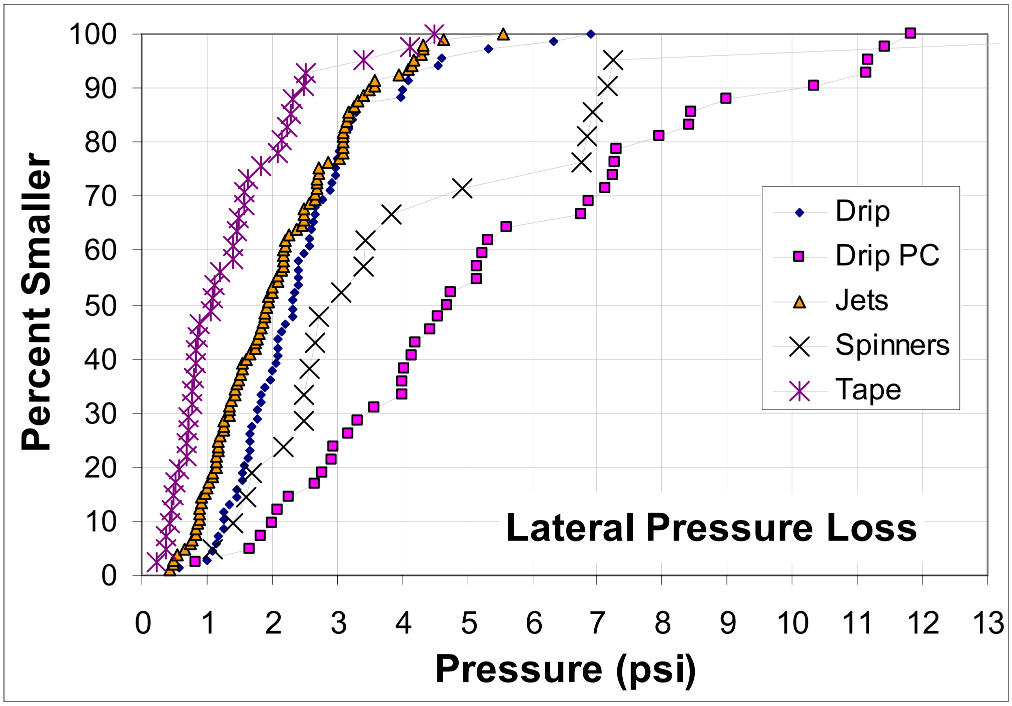

Figure 6. Cumulative distribution of average pressure loss in the laterals for 5 types of micro-irrigation systems.

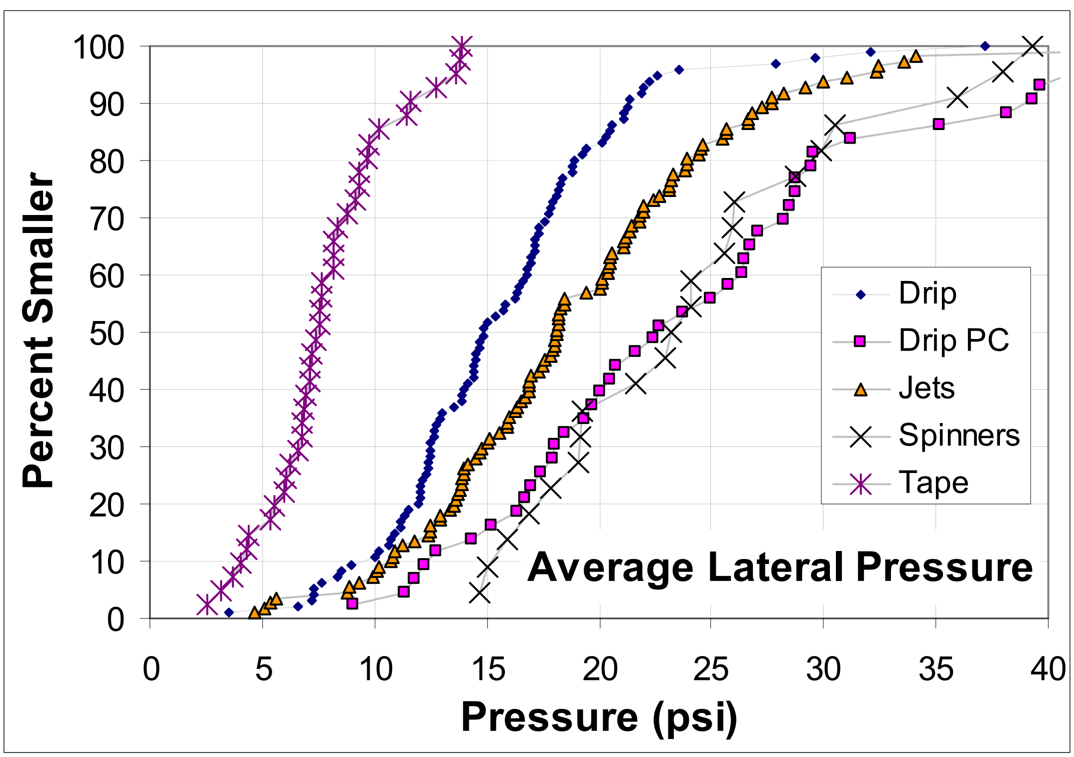

Figure 7. Cumulative distribution of average measured lateral pressure for 5 types of micro-irrigation systems.

The average pressure in the laterals is shown in Figure 7 for the 5 types of emitters. Non-PC drip emitters and jets have no minimum or maximum pressure allowance other than the pressure capacity of the hose or tape. Micro-irrigation designers consistently specify 8 – 10 psi for thin-walled drip tape, based on tape burst pressure; 12 – 15 psi for thick walled tape and hose, based on maintaining adequate velocities in the tortuous flow path to flush sediments; 20 psi in jets to create adequate wetting diameters; and 25 psi in spinners to assure rotation. These values are near the median measured for the various systems. Although tape systems are constrained by burst pressures, about 20% of the remaining systems exceeded these target values by 5 psi. In undulating terrain, high lateral pressure is required to maintain minimum pressures. Otherwise, this extra pressure increases energy used without substantial improvement in water distribution uniformity. Over 50% of the drip (non-PC) and jet systems with high lateral pressures were on flat or low-slope fields.

POTENTIAL FOR REDUCING SYSTEM PRESSURES

The evaluation data indicate that, although a portion of the systems operate at low to moderate pressure, there is potential to reduce pressure in many systems. Table 1 suggests that 15 psi should be adequate to clean and deliver water to the emitters for most systems (not including lift to high fields). Micro-irrigation designers in the San Joaquin valley estimated the pressure required to clean and deliver water to emitters between 11 and 25 psi for flat fields. Figure 1 shows that about 60 percent of the measured systems exceed this value, and 30% of the systems exceed by over 10 psi. Even if we allow for an additional 5 psi for pressure regulation on the one-third of the fields with undulating terrain, there is potential to reduce system pressures by and average of 15 psi in those 60% of the systems with excess pressure. Much of the potential savings are on the 20% of the fields with the highest available pressures, where the average potential savings is 29 psi.

Table 5 shows the annual energy cost savings (@ $0.12 per kw-hr) for a range of system pressure reductions for varying field sizes (3.64 kw-hr is required to pressurize 1 ac-ft of water to 1 psi @65% pumping plant efficiency). A 15 psi pressure reduction for an 80 ac. orchard or vineyard micro-irrigation system (with appropriate pumping plant modifications) would save $2000 per year in energy costs.

Table 5. Potential annual energy cost savings from system pressure reduction.

Area	Irrigation Amount	System Pressure Reduction (psi)					
		2	5	10	15	20	30
acre	ft/ac						
1	3	$2.62	$7	$13	$20	$26	$39
1	4	$3.49	$9	$17	$26	$35	$52
40	3	$105	$262	$524	$786	$1,048	$1,572
40	4	$140	$349	$699	$1,048	$1,397	$2,096
80	3	$210	$524	$1,048	$1,572	$2,096	$3,144
80	4	$279	$699	$1,397	$2,096	$2,795	$4,192
160	3	$419	$1,048	$2,096	$3,144	$4,192	$6,288
160	4	$559	$1,397	$2,795	$4,192	$5,590	$8,385

Assumptions: 65% pumping plant efficiency; $0.12/kw-hr electricity cost.

If these data are representative and pressures could be reduced by 15 psi on 60% of the 1.7 million acres with micro-irrigation in CA, this would save 220 gigawatt-hr/yr of power and about

90 megawatts of peak demand. The potential for reducing energy use is substantial.

The data consistently show that for most sources of pressure loss, the range of losses is large – about a quarter of the systems have very low loss and about 20% have high loss. Figure 2 shows that irrigation uniformity is not low in low-pressure systems. This shows that low pressure systems can work in many situations, and most of the potential for reducing energy loss is concentrated in a small portion of the systems. It is more difficult from the irrigation evaluation data to determine the reasons for the high losses, since the data was not collected for the purpose of assessing energy efficiency.

Much of the potential for pressure loss reduction is in the distribution system. Even though designers state that they design for only 3 – 6 psi losses in the distribution system, nearly 50% of the systems on flat and low-slope fields had more than 10 psi loss between the filter station and manifolds, and 20% of the systems had more than 20 psi loss. These losses include friction loss in pipelines, fittings, and valves; and pressure drop at regulators. Most designers use a limiting pipeline design criteria of 5 ft/sec velocity, which will usually result in friction loss in the range of 0.2 – 0.5 psi/100 ft and over 7 psi loss to the most distant manifold in typical systems. Designers generally do not calculate fitting losses, but allow for fitting loss as part of a "safety factor".

The economics of initial cost vs. energy cost for distribution system pipe sizes and layout is not difficult to calculate. For example, increasing pipe size by one size (ie: from 6" to 8") will increase material costs for the pipe by about 40% and reduce pressure loss by 60 to 80%. If a designer uses 5 ft/sec flow velocity as the size criteria for a 1320 ft. 6" mainline, increasing the pipe to 8" will save about 2.5 psi, with an annual energy savings of about $175 (for 160 ac-ft pumped, 65% pumping plant efficiency, and $0.12/kw-h electricity cost) and an increased initial cost of about $900. Whether the larger pipe is economic for the farmer depends on his availability and cost of capital and the inflation in energy cost. Full assessment would also require evaluating the impact of the larger pipe on more uniform pressure and water distribution. Greater than 10 psi pressure loss in the distribution system will result in substantially reduced DU unless pressure regulation is used.

Forty percent of the systems on relatively flat fields used block or lateral hose pressure regulators. Designers typically allow 5 psi for operation of pressure regulators, and many of the high distribution loss systems on flat and low-slope fields had regulators. Pressure regulation on flat fields is not necessary, but is a means of simplifying system design and operation, reducing the cost of distribution system pipelines, and reducing risk from operational errors. Regulation allows the operator to vary set sizes and use pumps that produce excess pressure for the micro-irrigation system. Although regulators are necessary to make micro-irrigation practical on undulating fields, they are overused on flat fields where good hydraulic design can replace the need for regulation. However, the added energy cost of less than $9 per acre per year (4 ac-ft of water @ 5 psi) for a fruit or vegetable crop, may be a good investment if it improves system flexibility and water distribution uniformity, and reduces risk of system (and crop) damage from over-pressured laterals or fittings.

Pressure loss is substantial in some systems at the lateral inlet. High losses were measured or estimated in undersized spaghetti tubing for drip tape systems in strawberries, and plugged hose screens. Undersized shutoff ball valves at lateral risers can also cause substantial pressure loss. These pressure losses can result in poor water distribution uniformity, because they often aren't uniform. However, they will not likely result in reduced energy use because theses losses are not normally calculated by designers and thus are not added into pump pressure requirements.

In low pressure systems, pressure required to backflush the filter may establish the low limit on system pressure. Backflush pressure requirement varies with the type of screen and manufacturer (Table 4). Manufacturers may over-specify backflush requirements to allow for excessive pressure loss in the backflush discharge piping and for infrequent backflushing. The majority of the evaluated systems used sand media filters. With proper piping and operation, sand media filters can adequately backflush at less than 20 psi. Self-cleaning screen and disk filters require 10 to 20 psi more pressure than media filters for effective backflushing, but generate less backflush water. Designers should help micro-irrigation system purchasers evaluate the real cost of a filter system that increases system pressure requirements. For example, a filter system that increases system pressure requirements by 5 psi on a 160 ac. orchard will increase annual energy cost by about $1400.

Designers allow for a safety factor when designing micro-irrigation systems of from 2 to 5 psi. The reasons are to cover uncalculated fitting losses, higher than anticipated filter losses, pumps that do not operate as specified, and well drawdown. Although it is easy to reduce pressures in an over-pressurized system (ie: partially close a valve), it is difficult to increase pressures in an under-pressurized system, and farmers will likely fault the designer if a system has inadequate pressure or capacity at the field. As with the 5 psi filter backflush example above, this contingency can be expensive in terms of energy costs for large systems. In some cases, this extra pressure helps provide filter backflush pressure.

A common constraint to energy efficient design for micro-irrigation systems is the desire to use a pre-existing pump or to use a pump that is also used for high pressure sprinkler systems. System designers often point out the farmer criteria to match a system to an existing well pump. Some of the very low pressure systems in the dataset were likely designed to match the discharge characteristics of existing wells used for flood irrigation. Many of the high pressure systems utilize pumps that also pressure sprinklers during crop establishment, frost control, and/or to irrigate rotation vegetable crops. Although excess pump capacity can sometimes be used to increase flow rates without increasing system pressure, high pump efficiency cannot be maintained at two operating points. I suspect that a substantial portion of the high pressure systems are the result of a pre-existing or specified high pressure pumping plant. Before using an existing over-capacity pump, the designer should evaluate the energy benefits of modifying the pump or installing a new pump designed for the system. For systems that occasionally require additional pressure or capacity, such as to sprinkle newly-planted or frost-endangered crops, use of a booster pump should be evaluated. A 20 HP booster pump that is used 10% of the time to boost 700 gpm from 30 to 60 psi will save 35,000 kw-hr ($4000) per year.

Systems that irrigate undulating ground require a pumping plant to irrigate the area at the highest elevation, and thus, the pump is over-designed for the rest of the area. Like the example above, booster pumps that are used to produce the occasional high pressure needs will save significant energy and should be evaluated.

Variable frequency drives (VFD) can be very efficient in systems that operate over a range of pressure or flow rate requirements. On systems with varying flow rate requirements, VFDs can maintain a constant pressure. In systems on undulating ground that irrigate equal-sized (and flow rate) sets at varying elevations, they can maintain a constant flow rate and vary speed to automatically maintain the pressure required at the manifold. In both cases, not only does the VFD reduce energy when full capacity is not required, but it also can avoid the use of pressure regulation and the pressure loss required by regulators. A VFD can also efficiently provide the higher flow or pressure required when the filter backflushes. Variable frequency pumping plants must be well designed to insure that the pump operates most of the time in its high efficiency range. Variable frequency drives also have energy losses (3 - 5%) that must be considered when evaluating their benefits. Costs of VFDs have decreased as technology improves and demand expands. A 50 HP VFD controller can currently be installed for about $10,000 (compared to $3000 for a standard pump panel. In an 80 ac. system in which pressure requirements vary by 30 psi, this cost could be repaid in 4 years.

There are many choices made during system design that impact pressure requirements. Most choices that reduce energy use increase initial system cost. Designers should evaluation the economic tradeoffs and discuss them with the grower. Unfortunately, designers, who commonly work for equipment dealers, may propose low cost systems without revealing the high energy costs in order to win a contract bid. Growers, even when given the economic information, sometimes choose to save initial costs in spite of higher deferred energy costs.

Conclusions

There is potential to reduce energy use in California micro-irrigation systems. Most of the potential savings is in the 20% of the systems that operate at highest pressures. Distribution system pipelines and pressure regulation are the largest sources of pressure loss. Some high pressure systems use a single pumping plant to operate both micro-irrigation and sprinkler irrigation. Booster pumps or variable frequency drives could potentially save significant energy costs for these dual systems or systems that irrigate undulating land.

Recommendations

- Economically evaluate the best pipe sizes for distribution systems.
- Use pressure regulators or PC emitters only where the benefits in initial costs, water distribution uniformity and system operation is greater than the energy costs.
- Design filter backflush systems that do not limit system pressures.
- Use lateral inlet fittings (ball valves, hose screens, spaghetti tubing) that cause little (<0.5 psi) pressure loss.
- Use booster pumps or variable frequency drives when a pumping plant must operate over a range of pressures or flow rates.

REFERENCES

Irrigation Journal. 2001. 2000 Annual Irrigation Survey Continues Steady Growth. Irrigation Journal, Jan/Feb 2001 pp 12-30, 40,41.

Burt, Charles, R. Walker, S. Styles, and J. Parrish. 2000. Irrigation Evaluation. Irrigation Training and Research Center (ITRC), Cal Poly, San Luis Obispo. 200pp.

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Trade names mentioned are for the benefit of the reader and do not imply endorsement or preferential treatment by USDA.

Computational Fluid Dynamics Analysis and Verification of Hydraulic Performance in Drip Irrigation Emitters

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Abstract:

The Computational Fluid Dynamics (CFD) method was applied to investigate the hydraulic performance of labyrinth type emitter. The characteristic of the emitter (COE), the relationship between the flow rate of the emitter and the pipe pressure, was numerically calculated using CFD model, and the standard k–ε turbulence model was introduced in the calculation. The modeling results were compared with the laboratory test results. The CFD modeling results show a good correlation with measured results. The pressure and velocity distributions in the flow path of the labyrinth emitter were numerically simulated by the CFD method, and were compared to the pressure distribution obtained from a prototype of the emitter manufactured with the dimensional ratio of 10:1. Both modeling and the measured results indicated that the pressure was reduced linearly with the length of the emitter flow path. The CFD method was found to be an effective method to investigate the hydrodynamic performance of drip emitters.

Introduction:

The emitter is an important component in a drip irrigation system. As water flows into the emitter from the lateral pipe, the turbulent flow path of the emitter dissipates energy and thereby reduces pressure. Ordinarily, the emitter flowrate increases with the static pressure in a lateral pipe in an exponential relation (Karmelli, 1977). The relationship between the emitter flowrate and the static pressure of the pipe, which is called characteristic of emitters (COE), is very important to a drip irrigation system. This relationship is used in designing the desired emitter flow path. Computational Fluid Dynamics (CFD) numerical technique was applied to investigate the flow, heat and mass transfer for many years. CFD technique has many advantages compared with other numerical calculation methods. The simulation can maintain a stable boundary condition while CFD modeling can be easily simulated with the change of the structure specification (Lee and Short, 2000). The numerical calculation results can help researcher analyze the hydraulic performance of the emitters and modify the geometries of the flow path, thus reducing time and cost for producing new emitter designs (P. Salvador et al, 2004).

The objective of this study was to apply the Computational Fluid Dynamics (CFD) numerical method to investigate the hydraulic performance of drip irrigation emitters, and to simulate the

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distributions of pressure and velocity in the flow path of the labyrinth emitter. The CFD modeling results are validated by measuring results in the laboratory.

Materials and Methods

Labyrinth Emitters

An emitter with standard labyrinth flow path was selected for this study. There are many zigzag teeth on both sides of the emitter (Figure 1), and the space among the teeth forms the flow path of the emitter. The length of flow path for the emitter was 19.8 mm, the depth of the flow path was 0.7 mm, and the distance between the teeth was 1.5 mm.

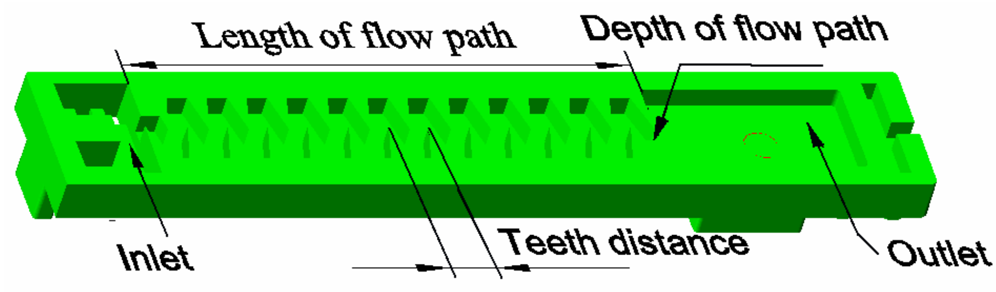


Figure 1 Structure of the labyrinth emitters

CFD Numerical Modeling

The CFD method divides the calculation domain into finite control volumes, and numerically solves the Reynolds–averaged form of the Navier–Stokes equations (Fluent, 1998) within the volumes. The Reynolds–averaged form considers the instantaneous flow parameters as the sum of a mean and a fluctuating component of turbulence (Hinze, 1975; Bennet and Myers, 1995). Since the high–frequency and small–scale fluctuations of turbulent flow could not be directly quantified; turbulence numerical modeling relates some or all of the turbulent velocity fluctuations to the mean flow quantities and their gradients.

1. The water flow inside the emitter was assumed to be an incompressible steady flow. The governing equation included the following continuity equation and Navier-stokes equation (Anderson, 1995):
2. Continuity equation: $$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0$$
3. Navier-Stokes equation：$$\frac{\partial(\rho u)}{\partial t}+\nabla\cdot(\rho u U)=-\frac{\partial p}{\partial x}+\mu\nabla^2 u+\rho f_x$$ $$\frac{\partial(\rho v)}{\partial t}+\nabla\cdot(\rho v U)=-\frac{\partial p}{\partial y}+\mu\nabla^2 v+\rho f_y$$ $$\frac{\partial(\rho w)}{\partial t}+\nabla\cdot(\rho w U)=-\frac{\partial p}{\partial z}+\mu\nabla^2 w+\rho f_z$$
4. Where U is the flow velocity：$U=u\vec{i}+v\vec{j}+w\vec{k}$（$\mathrm{ms^{-1}}$），$u$，$v$，$w$ are the components of the velocity vector in x，y，z axis; ρ (kg m^{-3}) and μ (Pa s) are the density and dynamic viscosity coefficient of the fluid. The pressure of the fluid is p (Pa); f_x f_y f_z are

the components of the body force.

5. There are two flow patterns in the flow path, laminar flow and turbulence flow, which can be discriminated by Reynolds Number of the flow. But the flow path in emitters is so complicated that the signs of turbulence flow appear with low Reynolds Number. In this study, the standard k– ε turbulence model was selected to describe the flow in emitters because its results were very close to the practical flows (Launder and Spalding, 1974). In the k– ε model, the turbulent kinetic energy (k) and the dissipation rate of (ε) can be expressed as the following equations:

$$k = \frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$$

$$\varepsilon = \mathbf{v}\overline{(\frac{\partial u_i'}{\partial x_k})(\frac{\partial u_i'}{\partial x_k})}$$

Where u'、v'、w'（ms^{-1}）are the fluctuating components of the velocity, ν (m^2 s^{-1}) is the kinematics viscosity coefficient of the fluid. In the standard k– ε turbulence model, the transport equations of the turbulent kinetic energy (k) and the dissipation rate of (ε) are:

Where μ_T is turbulent eddy viscosity, G_k represents the generation of turbulence kinetic energy

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k U) = \frac{\partial}{\partial x_i}[(\mu + \frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_i})] + G_k + G_b - \rho\varepsilon - Y_M$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon U) = \frac{\partial}{\partial x_i}[(\mu + \frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_i})] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

caused by the mean velocity gradients, G_b is the generation of turbulence kinetic energy caused by buoyancy, Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, and $C_{1\varepsilon}$、$C_{2\varepsilon}$、$C_{3\varepsilon}$、σ_k、σ_ε are the turbulent Prandtl numbers for k and ε respectively.

6. The grid generation is very important in CFD numerical calculation. The hexahedron cells with 0.1 mm were applied to generate the grid, and the cell number in the domain of the flow path of the emitter was about 10^5 (figure 2).

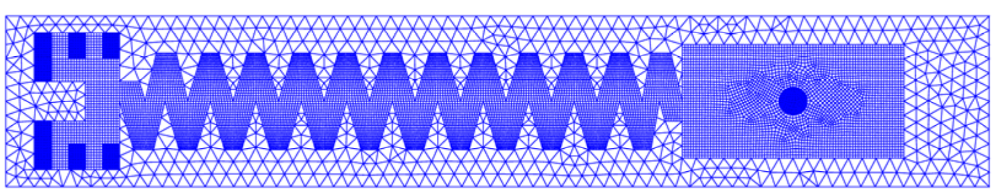


Figure 2. Grid generation of the labyrinth emitter

After completing the grid generation, a grid file was created and fed as input into FLUENT. The boundary conditions were set in FLUENT according to the practical flow situation. The inlet of the emitter was set as a pressure-inlet boundary condition, and was directed into with 3m, 5m, 8m, 10m, 12m, 15m, 18m, and 20m water heads respectively. The outlet of the emitter was set as a pressure-outlet boundary condition; the local atmospheric pressure was included in the calculation as the operational condition.

The local Reynolds number in the boundary layer region near the walls was so small that viscous effects were predominant over turbulent effects. Two methods were used to account for this effect and for the large gradients of variables near the wall; one method applied the wall function to solve the flow near the wall, another method improved the turbulence model to solve the problem. The wall function method, with low calculation load and high accuracy, was applied extensively in the practical engineering calculations. In this study, the standard wall function was applied in the region near the wall, and the roughness of the wall inside the emitter was set as 0.01 mm, which is the ordinary technology level of plastic molding.

Measurement Procedure

The measurements were conducted in the laboratory of irrigation and drainage in China Agricultural University. The measurements included two parts: the COE measuring and the measuring of pressure inside an amplifying model.

The emitters are always integrated into the lateral pipeline after molded from plastic. The topside of the emitter clings to the inner wall of the pipe; the wall of the pipe near the emitter outlet is punctured through when integrating. Then the water can flow into the inlet of the emitter, flow around every tooth, and discharge from the outlet pore. The drip pipe with twenty-five emitters was installed in an experimental facility (figure 3). The measuring cups were used to collect the water discharged from the emitters in a given duration to calculate the flowrate of the emitters. Before the measuring, the air in the pipe was exhausted firstly, opened the valve little by little. When the pipe pressure remained in a steady condition, the static pressure from the manometer was recorded, as well as the duration and the amount of every emitter. The flow rate of the emitter at any given pressure was calculated from the average of the twenty-five emitters. Finally the COE curve can be made by regression analysis on the data.

It was very difficult to measure the pressure inside the flow path of the prototype emitters directly because of their tiny size. So an amplifying model of the emitter was manufactured with the dimension ratio 10:1 to verify the CFD modeling results of pressure distribution along the flow path (Wang, 2004). The amplifying model was made by steel and based on the similarity theory. Five pores with pressure tubes connected to manometers were made on the top wall of the amplifying emitter along the flow path. The pressures inside the flow path can be measured by the manometers.

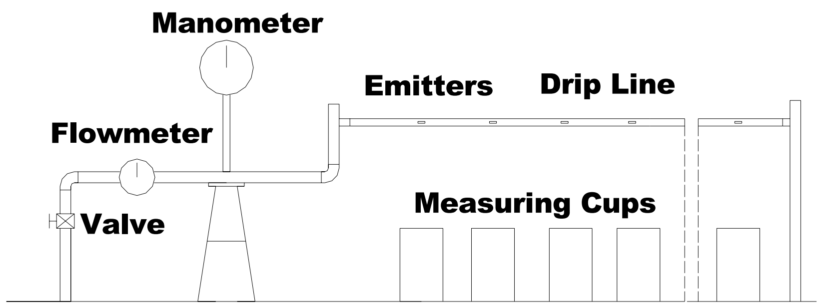
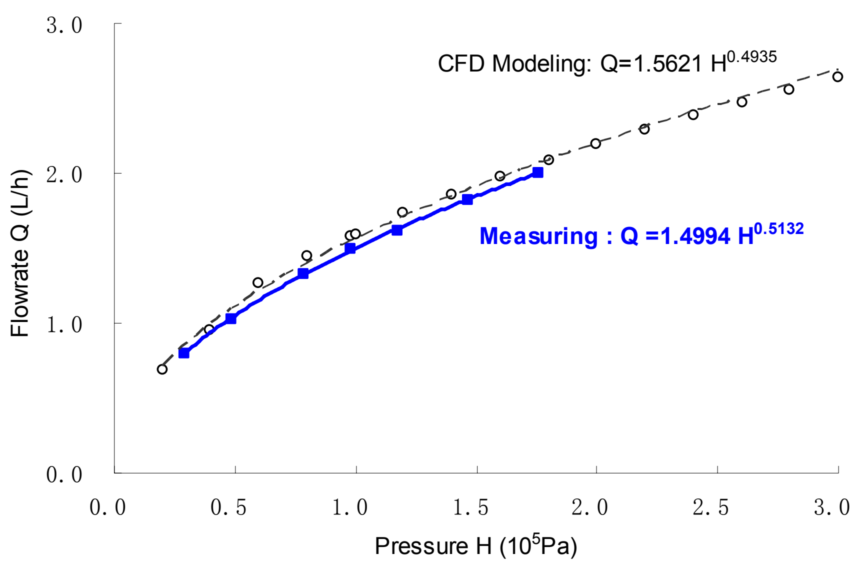


Figure 3. Schematic diagram of the experimental facility

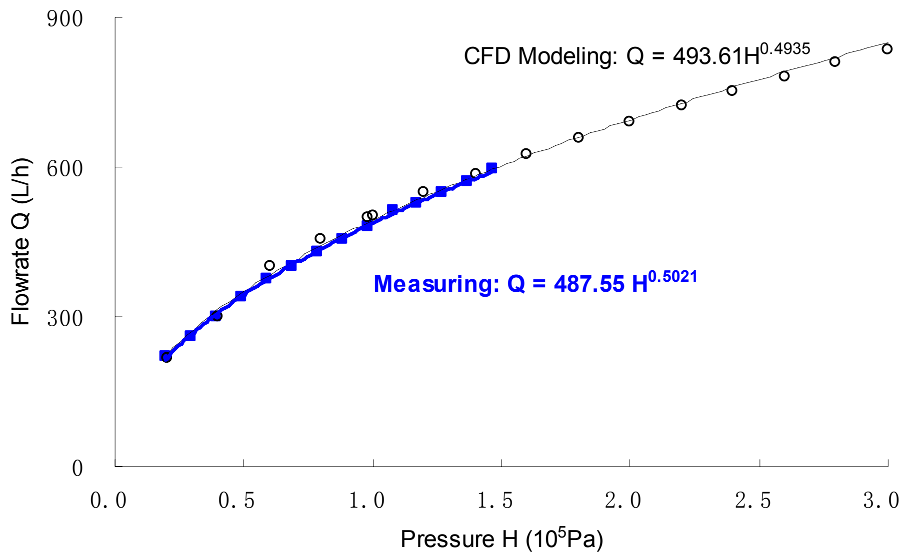
Results and Discussions

COE comparison between CFD modeling and the measuring

Figure 4 shows the COE curves of prototype emitter and amplifying model made by regression analysis from the CFD modeling data and the measuring data. The broken curves are the CFD modeling results, and the continuous lines are the measuring results. It is showed that COE curves made by CFD modeling data are very close to that by measuring data, the CFD modeling results correlate well with the measuring results. The mean differences between the modeling results and the measuring results do not exceed 5 %. It is indicated that the COE can be numerically calculated by CFD method with high accuracy.



(a) Prototype emitters



(b) Amplifying model

Figure 4. COE comparisons between the CFD modeling data and the measuring data
(Broken line: CFD modeling; Continuous line: measuring)

Pressure distribution inside the flow path

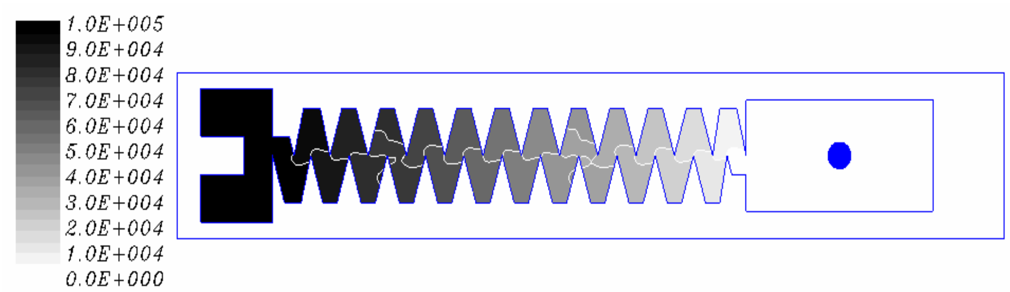
The pressure distribution inside the flow path influences the hydraulic performance of the emitter greatly. Figure 5 a gives the pressure distribution inside the flow path of the emitter from the inlet to the outlet simulated by CFD method. The static pressure of the pipe was 10 m water head, the pressure unit in the legend was Pascal, and the grey level represents the pressure magnitude. The pressure in the left inlet area was higher than it was in the right outlet area, and reduced gradually from the inlet to the outlet. The detail pressure distribution between two teeth is given on figure 5 b. The direction of the arrow is the direction of the flow velocity of the position, and the white lines are the contour line of the pressure. The contour lines near the peak of the teeth were intensive, and the pressure gradient is very great there. When the water flows around the peak of the teeth, the flow direction is changed, and the flow pattern becomes unstable. So the structure and dimension of the peak of the teeth are very important to the hydraulic performance of the emitters; more attentions need to be paid to this aspect when designing a new emitter.

In order to further investigate the pressure distribution inside the flow path of the emitter, the pressures in sixteen positions along the flow path were numerically calculated by CFD method and were analyzed by standardized method. The pressure in every position was replaced by non-dimensional standardized pressure p_s, which was obtained by dividing the modeling pressure p_i in the position by the static pipe pressure p_P when modeling.

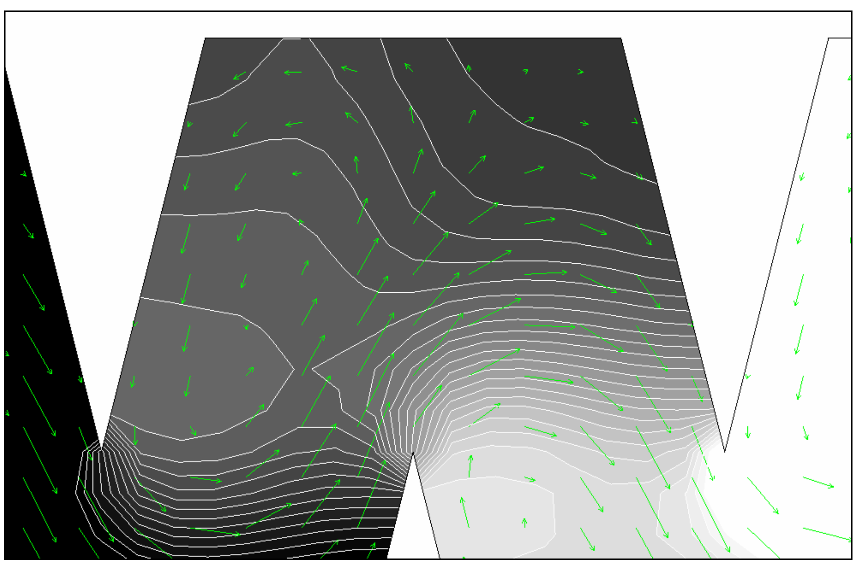
The standardized pressures p_s were only determined by the positions, so we can compare the

$$p_s = \frac{p_i}{p_P}$$

pressures with varying static pressure of the pipe. The standardized pressures by CFD modeling are shown with broken line on figure 6. The pressure decreases linearly with the length of the flow path. The pressures measured in the amplifying model at five positions are also shown with continuous line on figure 6. The pressures were also standardized by static pipe pressure when measuring. There is a linear regression relationship between the pressure and the length of the flow path with high coefficients of determination. The two regression curves by CFD modeling and by measuring are very close, and the average difference between the modeling pressure and the measuring pressure is no more than 3%. The pressure distribution modeling results agreed well with the pressure measuring results in amplifying model of the emitter.



(a) Pressure distribution from the inlet to the outlet of the emitter



（b）Pressure distribution between the teeth

Figure 5. Pressure distribution inside the flow path of the emitter

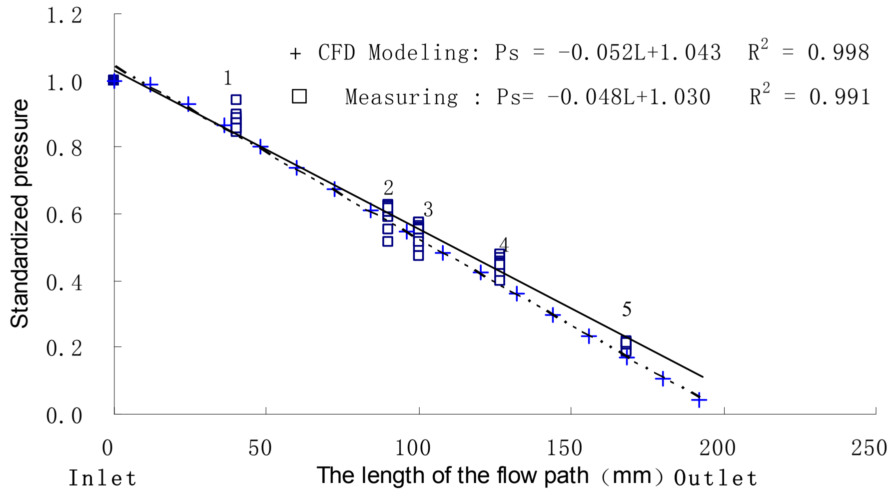
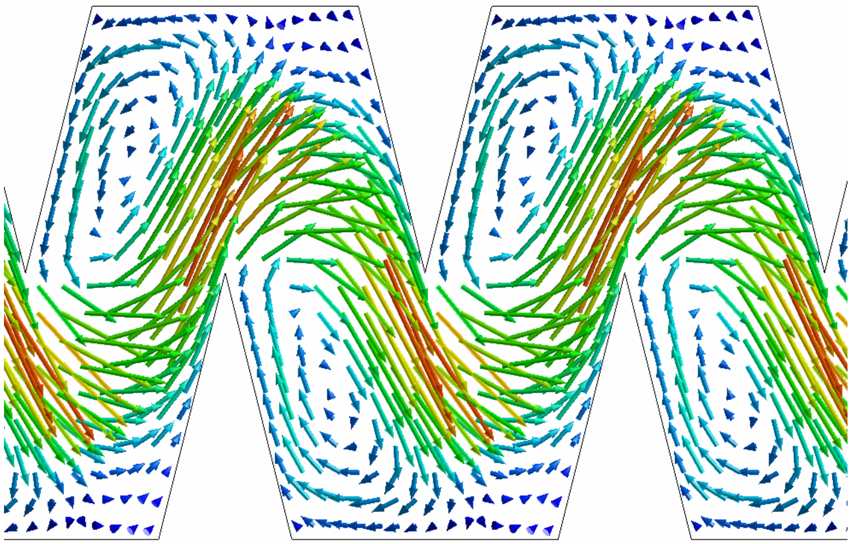


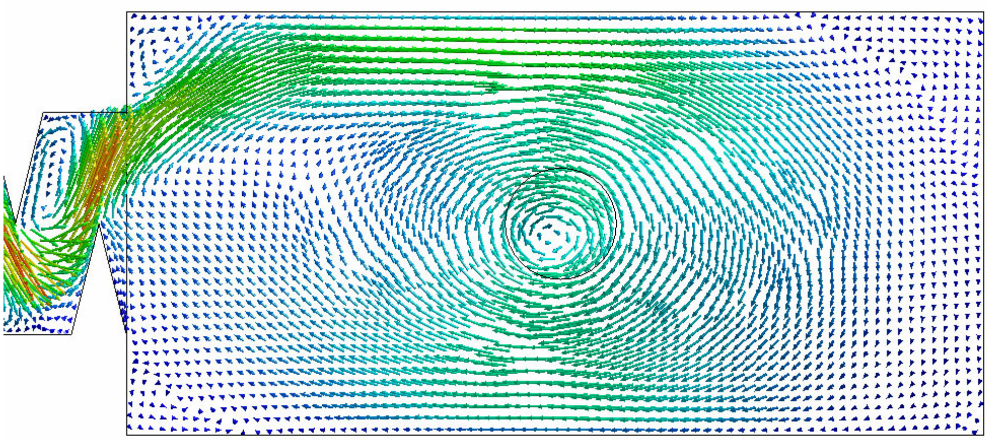
Figure 6. Standardized pressure curves comparison between CFD modeling and measuring

Flow velocity field inside the flow path

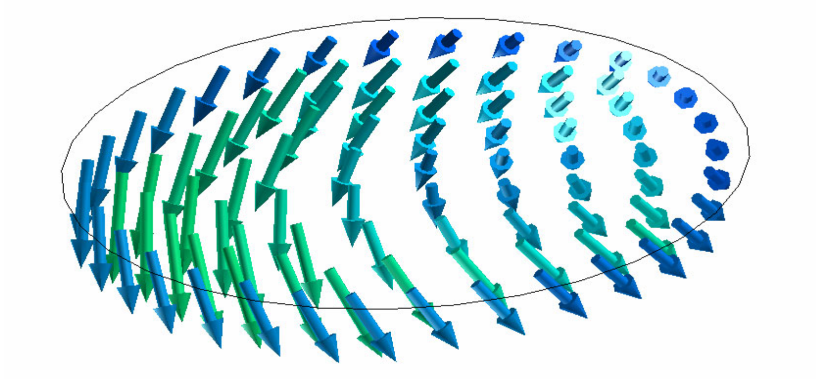
The flow field in the flow path of the emitters is very difficult to investigate by traditional methods. The flow velocity among the teeth by CFD modeling is shown on figure 7 a; the arrows are the velocity vectors in the flow field. It was found that the flow velocity near the peak of the teeth is much more than those at other places, a vortex is formed at the downstream side of the teeth, and the flow velocity in the area of the vortex is low. The vortex inside the flow path can improve the anti-clogging performance of the emitters because the vortex has a rinsing effect inside the flow path. A vortex is also formed in the outlet area of the emitter while the water discharge out the outlet pores (figure 7 b, c). The outlet area of the emitters in this study has a quadrilateral shape, and the water is stagnant in the four corners. The corner areas are easy to clog up if the irrigation water is not clean. The cylindrical outlet area would ameliorate the anti-clogging performance of the emitters; but it will require verification by experiments in future.



（a）Flow velocity vectors inside the flow path



（b）Velocity distribution in the outlet area of the emitters



（c）Velocity vectors at the outlet pore of the emitters

Figure 7. Flow velocity field inside the flow path of the emitters by CFD modeling

Conclusions

1. The characteristics of the emitters (COE) were investigated by Computational Fluid Dynamics (CFD) method, and the modeling results were validated by measuring results in the laboratory. The CFD modeling results showed a good correlation with the measuring results; the average difference was no more than 5%. The CFD method was proved an effective method for the numerical calculation of COE with a high degree of accuracy.
2. The distributions of pressure and velocity in the flow path of the labyrinth emitter were numerically simulated by CFD method. An amplifying model of the labyrinth emitter was manufactured with dimension ratio 10:1 to verify the pressure distribution along the flow path. Both the modeling results and the measuring results indicated that the pressure was reduced linearly with the length of the flow path. The pressure distribution modeling results agreed well with the pressure measuring results in the amplifying model of the emitter. The average difference between the modeling results and the measuring results was no more than 3%.
3. The flow velocity near the peak of the teeth is much more than those at other place. A vortex is formed at the downstream side of the teeth, and the flow velocity in the area of the vortex was low. The vortex inside the flow path can improve the anti-clogging performance of the emitters because of rinsing effect.

Reference

1. Bennet, C. O., and J. E. Myers. 1995. *Momentum, Heat, and Mass Transfer.* New York, N.Y.: McGraw–Hill.
2. Fluent. 1998. *The user's Manual of Fluent*, version 6.1. Lebanon, N.H.: Fluent Inc.
3. Hinze, J. O. 1975. *Turbulence*, 2nd Ed. New York, N.Y.: McGraw–Hill.
4. I B, Short. T H. 2000. Two-dimensional numerical simulation of natural ventilation in a multi-span greenhouse. Transaction of ASAE*,* 43(3): 745 –753
5. John D., Anderson. *Computational Fluid Dynamics: The basics with application* [M].McGraw-Hill Inc, New York, 1995.
6. Karmeli D.1977. Classification and flow regime analysis of drippers. Journal of Agricultural Engineering Research 22:165-173.
7. Launder, B. E., and D. B. Spalding. 1974. The numerical computation of turbulent flows. Computer Methods in Applied Mechanics and Engineering 3: 269–289.
8. Palau Salvador, G. Arviza Valverde, J. Bralts, V. F. Hydraulic Flow Behavior through an In-line Emitter Labyrinth using CFD Techniques. 2004. ASAE/CSAE Annual International Meeting. Paper Number: 042252 Ottawa, Ontario, Canada, August 2004.
9. Wang, Jiandong. 2004. Study on the Hydraulic and Anti-clogging Performance of Emitters. Dissertation Paper. China Agricultural University. Beijing China.

2005 IA Technical Presentation

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Aqua Engineering, Inc.

Kent Lusk
Producer

Title: Case Study: Subsurface Drip Irrigation in Southeastern Colorado

Four years of drought and more restrictive ground water pumping regulations from the State Engineer forced Kent Lusk of Rocky Ford, Colorado to evaluate his current farming operation. The extended drought in the Arkansas River Valley resulted in little or no surface irrigation water. During this same time, the State of Colorado increased the restrictions on the pumping of well water by more closely regulating ground water augmentation plans. Lusk was faced with leaving previously irrigated land fallow, converting irrigated land to dryland, or improving the efficiency and effectiveness of his irrigation practices. As a matter of survival, Kent chose the latter.

Lusk installed his first 66 acres of SDI in 2003. With the help of the Natural Resources Conservation Service (NRCS) Environmental Quality Incentives Program (EQIP) cost share program Lusk has installed an additional 29 acres in 2004, and 33 acres in 2005 with plans to install another 43 acres in the next year or two.

The NRCS EQIP was authorized in the Farm Security and Rural Investment Act of 2002 (Farm Bill) to provide a voluntary conservation program for farmers and ranchers that promotes agricultural production and environmental quality as compatible national goals. EQIP offers financial and technical help to assist eligible participants install or implement structural and management practices on eligible agricultural land. EQIP may cost share up to 75 percent of the cost of certain conservation practices. All conservation practices must be planned and implemented per NRCS standards. The local conservation district is responsible for approving the plan.

As Lusk reviewed irrigation options to replace his current flood irrigation system and practices for improved irrigation efficiency, he quickly narrowed in on Subsurface Drip Irrigation (SDI). Since his farm was leveled to accommodate furrow irrigation, and all of the fields were rectangular in shape, SDI fit the best. Overhead irrigation, either through a solid set or center pivot/lateral move system, was ruled out due to the potential mold and fungus problems with melon crops. In addition, the layout of his farm did not work well with the constraints of a center pivot or lateral move system. His farm would have required at least three center pivot/lateral move systems to irrigate most of the 171 acres he is currently irrigating, or planning to irrigate, with SDI. Also, given the variety of crops grown by Lusk, including melons, onions, peppers, tomatoes, corn, alfalfa, beans, and small grains, the SDI system allows for more control of water, and nutrient application, as well as other farming operations.

As Lusk stated “Installing SDI is like buying the farm all over again. It is expensive. The NRCS EQIP program has really helped financially”. The NRCS EQIP cost share helped Lusk to install more of his farm acreage under SDI in a shorter time frame than he could have on his own. His total acreage under SDI will be 171, with 105 acres installed with the help of the EQIP program. Lusk applied for EQIP in 2002 and was approved for a 50% cost share per the program that was in place at the time. As part of the Colorado NRCS requirements system design drawings must be developed by a registered Professional Engineer or NRCS Technical Service Provider (TSP) and approved prior to installation.

In addition to water savings, Lusk hoped to realize improved crop yields and quality, reduced fertilizer application, and a reduction in disease and pest problems. He couldn’t be more pleased with the results. Water savings has been impressive. For example, 3 to 4 acre-ft of water was required for each acre of melons using flood irrigation. Currently, Lusk is using about 1 acre-ft per acre with the SDI system. Fertilizer applications have been reduced by 30 %. Crop yields have improved by at least 40% across the board. The quality of the produce has also improved, especially the melon crops. Lusk credits the use of SDI, along with plastic mulch, as the reason the number of melons with ground spots or worms has decreased dramatically, while the percentage of No. 1 melons has increased.

Although the results have been outstanding, some concerns were, and still are, in the back of Lusk’s mind regarding SDI. His concerns include salt build up in the soil profile and seed germination. To keep the potential salt build up in the soil due to the high TDS water in check, Kent is having soil and water chemisty analysis completed each year to help him develop a management plan. He is also injecting sulfuric acid into the water to lower the pH. Reducing the water pH has also lowered the soil pH which has improved the soil structure.

Lusk has also kept his old gated pipe around, and has installed risers on the SDI system mainline so he can flood irrigate if needed to leach salts beyond the root zone of the crops. So far, neither the salinity or germination has been a problem, but he is keeping a close eye on both. For the most part, germination has not been a problem either. To ensure complete germination for onions, which are very costly to plant, Lusk has flood irrigated after planting to help the onion seeds in the outer edge of the planting beds germinate.

Lusk also indicated that there is a definite “learning curve” with SDI. Due to the small emitter outlets, keeping a handle on filtration and water chemistry is vital to the long term success of the system. Lusk flushes each SDI zone every two to three weeks. Flushing helps him track changes in the appearance of the water being flushed through the system. He also checks the filter and monitors pH daily. This year for example, he began noticing a black precipitate in the flush water. Upon closer inspection, some of the tubing was beginning to plug. He is working with a drip product supplier to change his chemical injection program to solve the plugging problem. Lusk has leaned that water chemistry can change from year to year and you have to continuously monitor the operation of the system to keep small problems from becoming huge. You can't start the system in the spring and walk away, you have to continuously monitor and maintain the system to keep the system working.

Survival forced Kent Lusk to review his farming operation. Although he set out to save water, in the end he found saving water can result in many other benefits including increased yields, higher quality crops, lower fertilizer input, and a better overall environment. In short, his family farming operation is healthier and better poised to compete down the road due to the implementation of SDI technology and the help of the NRCS EQIP program.

SYSTEM DESIGN, SPECIFICATION, AND INSTALLATION

A 105 acre SDI was designed under the NRCS EQIP program. The 105 acres to be installed under the NRCS cost share program was designed to properly work with the existing 66 acres installed by Lusk prior to the NRCS involvement.

The 105 acres of crop land to be irrigated is broken into 9 different fields. All of the fields are currently flood irrigated with gated pipe or siphon tubes. The system will be designed with the following mix of crops, 50% vegetables, 20% alfalfa, and the remaining 30% in either dry beans, wheat, soybeans, or a combination of the three.

Water Requirements

The irrigation water requirements for these systems has been estimated using the procedures outlined in Chapter 2, Part 623 of the National Engineering Handbook. More specifically, the SCS Technical Release No. 21 was utilized to estimate the irrigation water requirements.

Assuming the crop mix as noted above, 20% of the land will be planted to alfalfa, 50% to vegetables, and 30% in dry beans, wheat, soybeans, or a combination of the three. The water requirements for dry beans were used in the calculations. The peak season water requirements for dry beans is higher than that calculated for soybeans or wheat so the water requirements for dry beans were used in the table.

Table 1 presents the peak system requirements assuming a normal, or average, rainfall. Average rainfall is assumed to have a probability of occurring 5 out of 10 years. Table 2 presents the irrigation water requirements for a dry year. A dry year is assumed to be the level of rainfall that can be expected 8 out of 10 years. The SCS Technical Release 21 was followed to estimate the dry year rainfall.

TABLE 1
Lusk Farm
Estimated Monthy Water Use
Normal Year (50% Chance)

Crop Mixture	Alfalfa			Vegetables			Dry Beans			Totals
	Acres----->		21	Acres----->		52.5	Acres----->		31.5	105.00 Acres
	Net Irrig/Re In/day	GPM/ Acre	Crop Flow GPM	Net Irrig in/day	GPM/ Acre	Crop Flow GPM	Net Irrig in/day	GPM/ Acre	Crop Flow GPM	System Flow GPM
Month										
March	0.04	0.83	17							17
April	0.08	1.83	38							38
May	0.14	3.26	69	0.02	0.55	29	0.05	1.11	35	132
June	0.25	5.67	119	0.13	2.97	156	0.19	4.37	138	413
July	0.26	5.93	125	0.18	4.07	214	0.26	6.07	191	529 **Peak Flow**
August	0.22	5.10	107	0.16	3.58	188	0.15	3.40	107	402
September	0.15	3.50	73							73
October	0.07	1.64	34							34

TABLE 2
Lusk Farm
Estimated Monthy Water Use
Dry year (80% Chance)

Crop Mixture	Alfalfa			Vegetables			Dry Beans			Totals
	Acres----->		21	Acres----->		52.5	Acres----->		31.5	105.00 Acres
	Net Irrig/Re In/day	GPM/ Acre	Crop Flow GPM	Net Irrig in/day	GPM/ Acre	Crop Flow GPM	Net Irrig in/day	GPM/ Acre	Crop Flow GPM	System Flow GPM
Month										
March	0.04	0.97	20							20
April	0.09	2.02	42							42
May	0.16	3.57	75	0.04	0.82	43	0.06	1.38	43	162
June	0.26	5.95	125	0.14	3.21	168	0.20	4.61	145	439
July	0.28	6.36	134	0.19	4.46	234	0.28	6.46	203	571 **Peak Flow**
August	0.24	5.41	114	0.17	3.88	203	0.16	3.70	117	434
September	0.16	3.66	77							77
October	0.08	1.74	37							37

A flow of 529 gpm will be required to met peak ET demands for the 105 acres of crops assuming normal rain fall and a flow of 571 gpm is required assuming a dry year. These calculations assume that all of the water lost to ET is replaced by the irrigation system each month, and that the soil moisture level is not depleted month to month.

Assuming the existing 66 acres of SDI will have a similar crop mixture, the flow required to irrigated the entire 171 acres of SDI will be 529 gpm + 529 gpm x 66/105 = 861 gpm assuming normal precipitation and 571 + 571 x 66/105 = 929 gpm assuming a dry year. Again, these calculations assume that all of the water lost to ET is replaced by the irrigation system each month, and that the soil moisture level is not depleted month to month.

Using water stored in the crop root zone is a valid management tool to reduce the peak season irrigation requirement for many crops. The use of a Management Allowed Deficit

(MAD) of 50% is typical and will be used to calculate a reduced system flow requirement.

The MAD is based upon the crop rooting depth, and the water holding capacity of the soil. Per the Otero County Soil survey the three main soils at the Lusk farm are:

Kornman & Neesopah (KnA) loam, with a water holding capacity of 1.32 to 2.40 inches per foot of soil.

Olney (OnA) Sandy Clay Loam, with a water holding capacity of 1.32 to 2.16 inches per foot of soil.

Numa (Nma) clay-loam, with a water holding capacity of 1.68 to 2.52 inches per foot of soil.

A conservative water holding capacity of 1.32 inches per foot of soil will be used to calculate peak system flow with a MAD of 50%. Tables 3 and 4 calculate the monthly water requirement and peak system flow assuming a MAD of 50%. Table 3 describes water requirements based upon normal precipitation, and Table 4 assumes a dry year precipitation.

TABLE 3
Lusk Farm
Estimated Monthy Water Use with Management Allowed Deficit Irrigation (MAD)
Normal year (50% Chance)

Crop Mixture	Alfalfa					Vegetables					Dry Beans					Totals
			Acres----->		21			Acres----->		52.5			Acres----->		31.5	105.00 Acres
	Root depth			5 ft		Root depth			3 ft		Root depth			3 ft		
	Water Holding Capacity			1.32 in/ft		Water Holding Capacity			1.32 in/ft		Water Holding Capacity			1.32 in/ft		
	MAD			50 %		MAD			50 %		MAD			50 %		
	Soil Reservoir			3.3 Inches		Soil Reservoir			1.98 Inches		Soil Reservoir			1.98 Inches		
	Maximum Net Irrigation Application, In/day				0.21	Maximum Net Irrigation Application, In/day				0.14	Maximum Net Irrigation Application, In/day				0.2	**System Flow**
	Flow, GPM per Acre				5.15	Flow, GPM per Acre				3.43	Flow, GPM per Acre				4.90	
	Total Crop Flow, GPM				108	Total Crop Flow, GPM				180	Total Crop Flow, GPM				154	443 GPM
	Net Irrig Req'd In/day	Days Irrig Days/mo	Net Irrig Req'd In/Month	Max. Irrig Applied In/Month	Deficiet In/Mo	Net Irrig Req'd In/day	Days Irrig Days/mo	Net Irrig Req'd In/Month	Max. Irrig Applied In/Month	Deficiet In/Mo	Net Irrig Req'd In/day	Days Irrig Days/mo	Net Irrig Req'd In/Month	Max. Irrig Applied In/Month	Deficiet In/Mo	
Month																
March	0.04	20.00	0.72	4.20	0.00											
April	0.08	30.00	2.39	6.30	0.00											
May	0.14	31.00	4.40	6.51	0.00	0.02	15.00	0.36	2.10	0.00	0.05	15.00	0.72	3.00	0.00	
June	0.25	30.00	7.40	6.30	-1.10	0.13	30.00	3.87	4.20	0.00	0.19	30.00	5.70	6.00	0.00	
July	0.26	31.00	8.00	6.51	-1.49	0.18	31.00	5.48	4.34	-1.14	0.26	31.00	8.18	6.20	-1.98	
August	0.22	31.00	6.88	6.51	-0.37	0.16	31.00	4.82	4.34	-0.48	0.15	24.00	3.55	4.80	0.00	
September	0.15	30.00	4.56	6.30	0.00											
October	0.07	13.00	0.93	2.73	0.00											
	Cumulative Deficit Irrigation, Inches--->				-2.95	Cumulative Deficit Irrigation, Inches--->				-1.62	Cumulative Deficit Irrigation, Inches--->				-1.98	

TABLE 4
Lusk Farm
Estimated Monthy Water Use with Management Allowed Deficit Irrigation (MAD)
Dry Year (80% Chance)

Crop Mixture	Alfalfa			Acres----->	21	Vegetables			Acres----->	52.5	Dry Beans			Acres----->	31.5	Totals 105.00 Acres
	Root depth			5 ft		Root depth			3 ft		Root depth			3 ft		
	Water Holding Capacity			1.32 in/ft		Water Holding Capacity			1.32 in/ft		Water Holding Capacity			1.32 in/ft		
	MAD			50 %		MAD			50 %		MAD			50 %		
	Soil Reservoir			3.3 Inches		Soil Reservoir			1.98 Inches		Soil Reservoir			1.98 Inches		
	Maximum Net Irrigation Application, In/day				0.22	Maximum Net Irrigation Application, In/day				0.15	Maximum Net Irrigation Application, In/day				0.22	**System Flow**
	Flow, GPM per Acre				5.39	Flow, GPM per Acre				3.68	Flow, GPM per Acre				5.39	
	Total Crop Flow, GPM				113	Total Crop Flow, GPM				193	Total Crop Flow, GPM				170	476 GPM
	Net Irrig Req'd In/day	Days Irrig Days/mo	Net Irrig Req'd In/Month	Max. Irrig Applied In/Month	Deficiet In/Mo	Net Irrig Req'd In/day	Days Irrig Days/mo	Net Irrig Req'd In/Month	Max. Irrig Applied In/Month	Deficiet In/Mo	Net Irrig Req'd In/day	Days Irrig Days/mo	Net Irrig Req'd In/Month	Max. Irrig Applied In/Month	Deficiet In/Mo	
Month																
March	0.04	20.00	0.84	4.40	0.00											
April	0.09	30.00	2.63	6.60	0.00											
May	0.16	31.00	4.82	6.82	0.00	0.04	15.00	0.54	2.25	0.00	0.06	15.00	0.90	3.30	0.00	
June	0.26	30.00	7.76	6.60	-1.16	0.14	30.00	4.18	4.50	0.00	0.20	30.00	6.01	6.60	0.00	
July	0.28	31.00	8.58	6.82	-1.76	0.19	31.00	6.01	4.65	-1.36	0.28	31.00	8.70	6.82	-1.88	
August	0.24	31.00	7.30	6.82	-0.48	0.17	31.00	5.22	4.65	-0.57	0.16	24.00	3.86	5.28	0.00	
September	0.16	30.00	4.77	6.60	0.00											
October	0.08	13.00	0.99	2.86	0.00											
	Cumulative Deficit Irrigation, Inches--->				-3.40	Cumulative Deficit Irrigation, Inches--->				-1.93	Cumulative Deficit Irrigation, Inches--->				-1.88	

Using a MAD of 50%, the required peak season system flow requirement is 443 gpm assuming normal precipitation, and 476 gpm assuming a dry year.

Assuming the existing 66 acres of SDI will have a similar crop mixture, the flow required to irrigated the entire 171 acres of SDI with a MAD of 50 % will be 443 gpm + 443 gpm x 66/105 = 721 gpm assuming normal precipitation and 476 + 476 x 66/105 = 775 gpm assuming a dry year.

Since adequate water is available, either from well water or a combination of well and canal water, it is recommended that the system be designed to provide a flow capacity of 929 gpm as calculated in Table 2. This assumes a dry year, and no deficit irrigation. This is a conservative system flow and will allow for some cropping pattern changes and calculated above.

A pump test was completed by a State of Colorado certified well tester in January of 2004. The produced a flow of 610 gpm, which is less than required flow to meet peak ET, with using a MAD of 50%. Lusk drilled a new replacement well in 2005. This well provides a flow of approximately 900 gpm, which is adequate as described above.

Water Quality

Water samples were sent to a qualified laboratory to test for all of the parameters required by the Colorado NRCS. The water was tested for Nitrogen as Nitrate, Chloride, Sulfate, Carbonate Calcium, Magnesium, Sodium, Potassium, Boron, Hydrogen Sulfide, Irion, Manganese, TSS, TDS, Total Solids, Hardness, Alkalinity, EC, SAR, pH, and a Total Bacteria plate count. In addition to this, a test was run to check for the presence of Iron Bacteria.

Based upon the results of the labor work, the following was noted about the well water. The salinity hazard for the water is medium, which may affect the growth of moderately sensitive crops. Leaching may be required to reduce the build up of salts in the root zone.

The leaching requirement was calculated using and EC for the irrigation water of 1.6, per the water quality testing analysis, and an EC of the soil of 2.4. The soil EC was estimated to be 1.5 x the irrigation water EC. At this level, a 5 percent leaching requirement is required. Assuming an EC of the soil of 1.8, the leaching requirement will be increased to 15 %. The NRCS CO-ENG-20 work sheet was used to determine the leaching requirement.

Based upon the water requirements for the crops planned, the 15% leaching requirement can be met for all months with the exception of July, during peak ET. From time to time, it may be necessary to flood irrigate the fields to help move the salt accumulations thru the soil profile. In all cases, the existing flood irrigation system can be used for this purpose.

The water pH was 7.38, which is within the acceptable pH range of irrigation water of 6.4 to 7.6 of an acceptable pH range.

Iron bacteria were present in the well test. Although the iron level is low, 0.1ppm, it is high enough to support the growth of iron bacteria in the system. The producer operated the system last year with out any problems from the iron bacteria. If a bacterial slime does develop, continuous chlorination is the recommended approach to the control of any bacteria within the system. An injection pump and tank s is recommended for chlorination of the system at the well. If precipitates become a problem from the injection of chlorine, a media filter may also be required. Chlorine should be injected to provide a continuous dosage of 0.5 – 1.5 ppm.

System Layout

The 105 acres of crop land to be irrigated with SDI is currently flood irrigated. The 105 acres is broken up into nine different fields. The producer has indicated a preference for each field to be broken up into 5 acre zones. Using 5 acres per zone as a guideline, the 9 fields have been further divided up into 20 zones ranging from 3.7 to 5.7 acres each.

The drip tape will be installed in 60-inch rows to accommodate current farming practices. The drip tape selected has a nominal flow of 0.3 gpm per 100' at an operating pressure of 10-14 psi. Both 5/8" diameter and 7/8" diameter drip tape will be required depending on field slope, and row length. The tape operating pressure and diameter is specified to provide the minimum emission uniformity of 85% and a minimum flushing velocity of 1.5 ft. /second as required by current NRCS design standards. Refer to the attached drawing showing the layout and individual zone operating pressure, flow, and estimated flow during flushing.

Each zone has an estimated flow ranging from 104 to 149 gpm. All control valves are manually operated, 3-inch butterfly valves. Each valve is opened to provide the desired discharge pressure. A pressure gauge attached to a shrader valve located at each air relief valve just downstream of each control valve is used to measure operating pressure. The system has been designed to accommodate the future installation of automatic control valves.

The supply manifolds are 4-inch PVC CL160 pipe. In general, two control valves are located side by side in the field, thus reducing potential obstructions. The flush manifolds are 3-inch CL160 PVC pipe, with a flush valve located at each end. Air relief valves will be provided at end of each end of the supply manifold and flush manifold. Drain valves will be provided at the low end of each supply manifold and flush manifold.

The mainline is 80 PSI PVC pipe, and ranges from an 8-inch diameter to a 4-inch size. The mainline was sized to provide maximum flexibility in the management of the system. Installation depth is at a minimum of 30 inches. Gate valves are provided to allow isolation of sections of the system to assist in system winterization and maintenance. Manual drains will be provided at low points in the mainline, and air and vacuum relief valves will be located at all high points, tees, and ends.

Filtration And Pump Station

The existing screen filter has adequate capacity for the system. The 6-inch 200 mesh screen filter with a maximum flow capacity of 900 GPM is in place.

Two booster pumps are in place to provide the pressure required to efficiently operate the system. A 300 gpm, and a 600 gpm pump is in place. If one or two laterals are operated, the 300 gpm pump is used, if two to four laterals are operated the 600 gpm pump is operated, and if 5 or 6 laterals are operated both booster pumps must be operating.

The booster pumps have an electric interlock with the chemical injection pumps so that the chemical injection pumps only operate when the booster pump is operating.

Chemigation

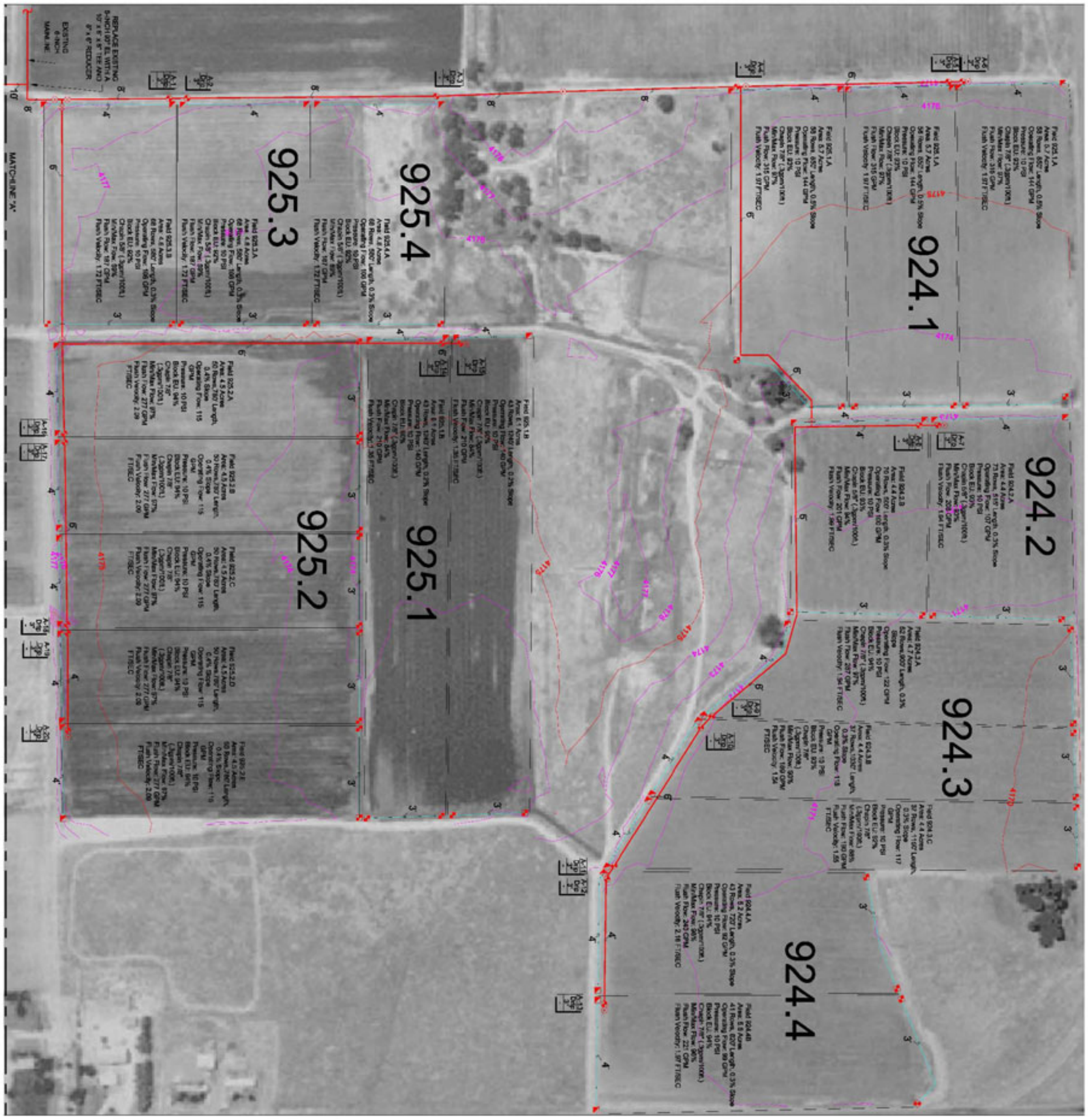
Chemigation is currently in place. The operator must maintain a current chemigation license from the State of Colorado, and the system must conform to all state requirements. A diagram and phone number for more information is attached.

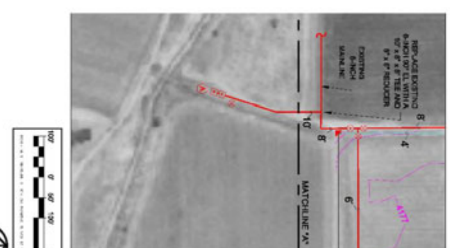
The producer currently injects acid into the system to reduce the pH of the water. He currently uses a pH test kit to adjust the injection rate of the acid to maintain the desired water pH.

The two other chemical injection pumps are for fertilizer. These pumps are adjusted to provide the desired application of fertilizer.

Design Drawings

The following are samples of the drawings developed for the SDI system installed at Lusks farm.

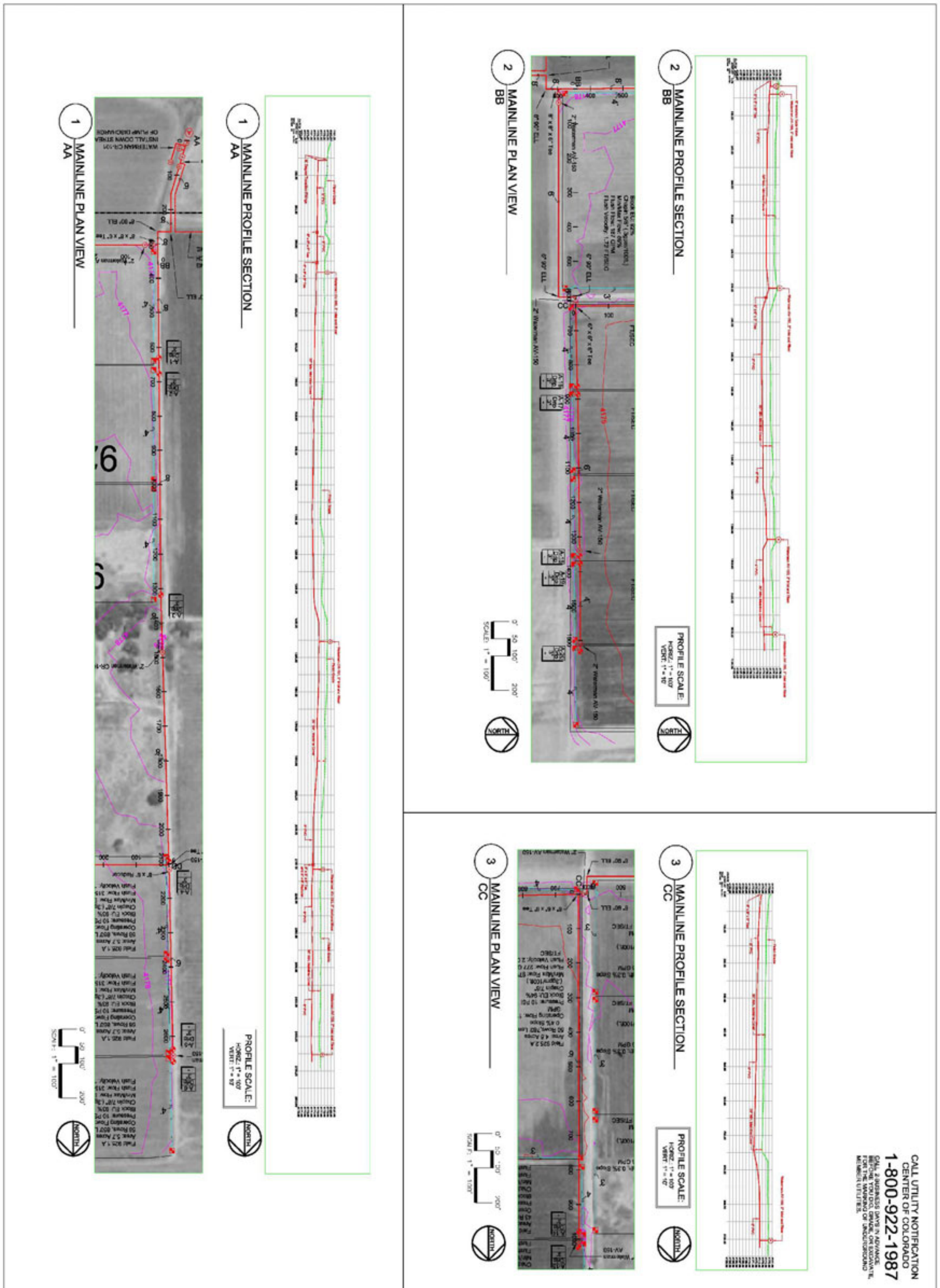




Aqua Engineering, Inc.

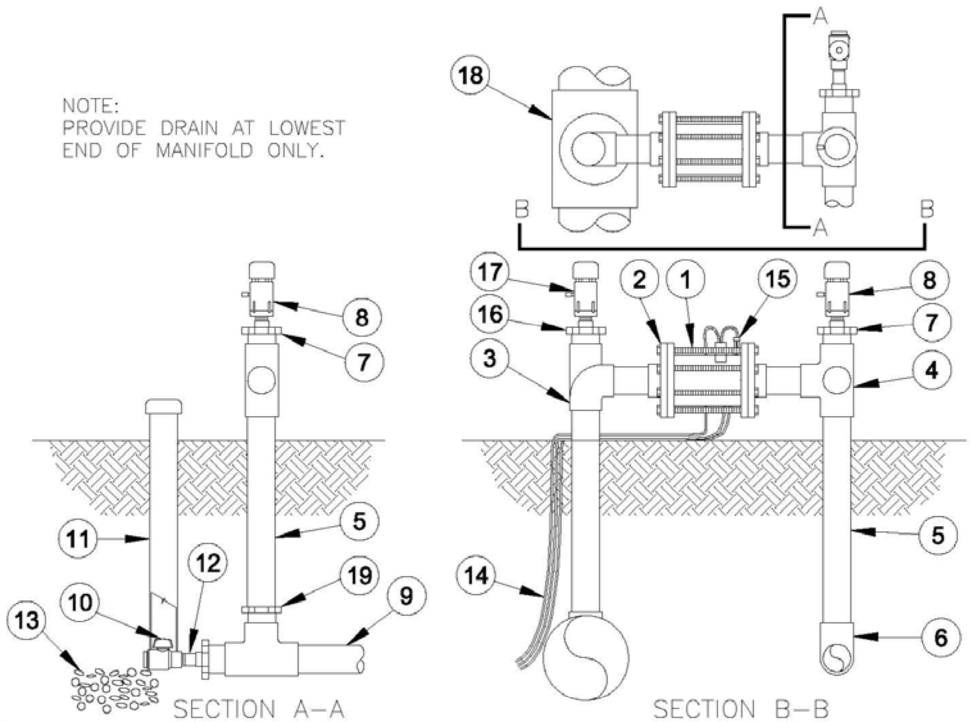
Kent Lusk Farm
Sub Surface Drip Irrigation Layout
Otero, Colorado

SHEET SD1



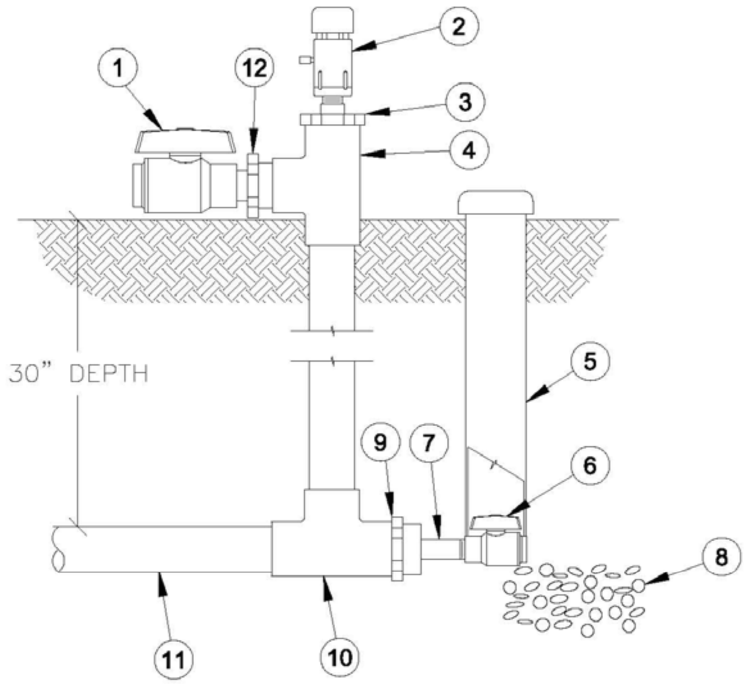
SHEET **SD2**	Aqua Engineering, Inc. Irrigation System Design, Water Management, and Water Feature Engineering	Kent Lusk Farm Mainline Plan and Profile Otero, Colorado	DESIGNED BY: WEE DRAWN BY: WJW CHECKED BY: WEE REVISIONS:

NOTE:
PROVIDE DRAIN AT LOWEST END OF MANIFOLD ONLY.



1. WAFER STYLE CONTROL VALVE: NELSON 800 SERIES
2. PVC SCH 80 FLANGE SOLVENT WELD
3. PVC SCHEDULE 40 90° ELL OR TEE IF AIR VACUUM RELIEF VALVE IS REQUIRED ON MAINLINE
4. PVC SCH 40 TEE
5. PVC CL 160 PIPE, SIZE TO MATCH CONTROL VALVE SIZE
6. PVC SCH 40 TEE OR ELL, SIZE TO MATCH MANIFOLD. PROVIDE REDUCING TEE OR ELL IF NEEDED
7. PVC REDUCING BUSHING WITH 1–INCH FEMALE THREADS
8. AIR VACUUM RELIEF VALVE WITH SCHRADER VALVE: AG PRODUCTS APVV–1
9. SUPPLY MANIFOLD
10. 1–INCH PVC SCH 40 BALL VALVE
11. 3–INCH PVC SLEEVE WITH CAP
12. 1–INCH DIAMETER PVC SCH 80 NIPPLE
13. GRAVEL SUMP
14. CONTROL AND COMMON WIRE
15. WATER PROOF CONNECTOR
16. PVC SCH 40 REDUCER BUSHING WITH 2–INCH OUTLET AND 2–INCH PVC SCH 80 THREADED NIPPLE
17. AIR AND VACUUM RELIEF VALVE. SEE PLANS.
18. PVC 80 PSI TEE OR ELL. OUTLET TO MATCH VALVE SIZE.
19. PVC REDUCER BUSHING, SIZE TO MATCH MANIFOLD AND CONTROL VALVE

DATE: 04–20–04 SHEET: **Lusk-2**	**Aqua Engineering, Inc.** Irrigation System Design, Water Management, and Water Feature Engineering 4803 Innovation Drive Fort Collins, Colorado 80525 Phone (970) 229–9668, FAX (970) 229–3855	**SDI CONTROL VALVE ASSEMBLY**	DESIGNED: WEE DRAWN: CAM CHECKED: WEE REVISION:



(1) FLUSH VALVE: 2-INCH SIZE

(2) AIR VACUUM RELIEF VALVE WITH SCHRADER VALVE: AGRICULTURAL PRODUCTS APVV-1

(3) PVC SCH 40 BUSHING: SIZE TO MATCH PVC SCH 40 TEE WITH 1-INCH FPT FOR AIR VACUUM RELIEF VALVE

(4) PVC SCH 40 TEE: SIZE TO MATCH MANIFOLD PIPE

(5) 3-INCH PVC PIPE WITH CAP

(6) PVC SCH 40 BALL VALVE: SIZE 1-INCH

(7) 1-INCH PVC SCH 80 NIPPLE

(8) SUMP OF 3.0 CUBIC FEET OF 3/4-INCH WASHED GRAVEL

(9) PVC SCH 40 BUSHING: 3-INCH SPIG x 1-INCH FPT

(10) SCH 40 PVC TEE

(11) PVC CL 160 PIPE: SIZE PER PLANS

(12) REDUCER BUSHING, SIZE TO MATCH TEE WITH 2-INCH FPT

NOTE:
INSTALL DRAIN AT LOW END OF MANIFOLD ONLY. DRAIN VALVE IS NOT REQUIRED AT EACH END.

DATE: 04-20-04 SHEET: Lusk-3	**Aqua Engineering, Inc.** Irrigation System Design, Water Management, and Water Feature Engineering 4803 Innovation Drive Fort Collins, Colorado 80525 Phone (970) 229-9668, FAX (970) 226-3855	**MANIFOLD FLUSH VALVE ASSEMBLY (SUPPLY AND FLUSH)**	DESIGNED: WEE DRAWN: CAM CHECKED: WEE REVISION:

Combined LEPA and MESA Irrigation on a Site Specific Linear Move System

Robert G Evans[1] and William M. Iversen[2]

Abstract

An off-the-shelf PLC-based control system has been developed and field tested to enable site-specific irrigation of multiple 50 ft X 80 ft research plots using either mid-elevation spray heads (MESA) and low energy precision application (LEPA) irrigation methods on linear move sprinkler systems. Both methods were installed on one machine to cover the same areas whereas the second system varies application depths. The irrigation method alternates or applied depths can change depending on irrigation treatment for each 50 ft plot width the machines travel down the field. Electric over air-activated control valves are installed on each gooseneck for each system. The PLC controls allow the variable treatments to be used depending on location which is provided by a low cost WAAS enabled GPS system. Pneumatic cylinders lift the LEPA heads above the MESA heads when the MESA is operating over a given plot width and length.

Keywords: precision irrigation, spatial variability, pneumatic controls, sugarbeets, barley, GPS

Introduction

Competition for water with municipalities, industries, recreation, and environmental uses appears to be a globally important issue, with water conservation mandates and related litigation increasing. The implications of these pressures will necessarily result in continued refining of water conservation measures, through improved efficiency in delivery, timing of applications, and, likely, increased use of various deficit irrigation strategies. Maintaining crop production through more efficient use of rain and irrigation is critical to overcoming these problems, which are complicated because their severity varies in both time and space. In order to maintain profitability, irrigators will have to apply water and agrochemicals in an efficient manner to reduce the social as well as the economic costs of diverting or pumping water over relatively long distances. Improved technologies continue to be needed to better manage energy, water and soil resources.

Thus, new and improved strategies and practices are needed to reduce surface and groundwater contamination from agricultural lands, and sustain food production for strategic, economic, and social benefits. Innovative irrigation techniques and management systems will be necessary to increase the cost-effectiveness of crop production, reduce soil erosion, and reduce energy requirements while enhancing and sustaining crop production, the environment and water use efficiency. We believe that precision differential irrigation under self-propelled irrigation systems will be a significant part of the future toolbox for many growers.

Center pivot and linear move irrigation systems are particularly amenable to site-specific approaches because of their current level of automation and large area coverage with a single lateral pipe. Microprocessor controlled center pivot and linear move irrigation systems also

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provide a unique control and sensor platform for economical and effective precision irrigated crop management. These technologies make it potentially possible to vary agrichemical and water applications to meet the specific needs of a crop in each unique zone within a field to optimize crop yield and quality goals while maintaining environmental health (reduced water and agrichemical use) and reduced leaching.

Over the past 50 years, the goal of center pivot and linear move irrigation design engineers has been to have the most uniform water application pattern possible along the entire length of the center pivot or linear move, and they have been relatively successful. Considerable yield variations still exist despite the inherent high frequency and fairly uniform applications of self-propelled center pivot and linear move irrigation systems, which are often attributed to spatial variability in soil water holding capacities and related nutrient availability. Field heterogeneity with respect to soil water holding capacity has been reported in many studies (e.g., Burden and Selim, 1989; Agbu and Olson, 1990, Mallawatantri and Mulla, 1996; Mulla et al. 1996; Evans and Han, 1994). Furthermore, the terrain under center pivot and linear move irrigation systems is often quite variable, causing runoff, channeling, and run-on, which can also profoundly affect crop stand and crop yield.

Terrain variation can also change the system pressure distribution along the lateral pipeline. Intermittent end gun operation can also cause system pressure fluctuations. System pressure changes, in turn, alter the amount of water applied as water pressure varies with applicator orientation and position in the field. While engineering solutions such as flow control nozzles or pressure regulators at each head have somewhat helped this situation, they are still not able to fully compensate for the effects of system pressure changes (Evans et al., 1995; James, 1982; Duke et al., 1997; 1998., 2000). Other factors contributing to non-uniform applications include the types, spacings, and locations of installed nozzles. These factors not only affect the amount of water applied to a given area within the field, but they also compound the problem when applying nutrients across a field. If fertigation is used or if the water supply contains significant nutrients, the nutrient distribution will also not be uniformly distributed across the field (Evans et al., 1995; Duke et al., 2000). As a result of these and other factors, considerable crop yield and leaching variation can occur throughout the field.

In the past, to improve in-season operational efficiencies on a whole-field basis, managers have resorted to practices such as manually changing sprinkler heads to match pre- and post-emergence conditions. Labor costs make this technique unreasonably expensive. For within-field variation in demand during the season, irrigators have had to vary end tower run speeds to adjust water applications. This modifies water applications to more closely meet water requirements of the field for a given angle of rotation. Until computerized center pivot panels became available, the field manager was required to either be at the controller when a speed change was needed or to use a switch at the pivot point and a second percent timer to vary the end tower speed. Now, with the use of a computerized center pivot control panel, the end tower speed can be changed based on a preprogrammed position in the field. This has greatly enhanced the ability of the field manager to apply water to meet spatially variable demand in wedge-shaped segments, but it still assumes an average demand across each wedge-shaped treatment area. Thus, areas of the field continue to be over- or under-irrigated, causing plant stress, reducing yield and quality and increasing potential for leaching water and chemicals.

Precision Irrigation

The term precision irrigation predates site-specific agriculture. Its general meaning in the irrigation industry connotes a precise amount of water applied at the correct time, but uniformly across the field (Evans et al. 2000). In this paper, precision irrigation is further defined to replace the uniformity criteria with the capacity of the irrigation system to have a spatially variable capability. To achieve such capability, an otherwise conventional irrigation machine would potentially need variable-rate sprinklers of some type, position determination (e.g., GPS), modification to the water supply delivery system to handle variable-rate water demands as well as the capability for variable-rate nutrient injection (probably), and variable-rate pesticide application (possibly).

The ability to vary water application along the main lateral of the center pivot based on position in the field allows the field manager to address specific soil and/or slope conditions. By aligning irrigation water application with variable water requirements in the field, total water use may be reduced, decreasing de-percolation and surface run off. Reducing excess water applications will decrease the potential to move nutrients past the plant root zone (King et al., 1995), and the fungal disease pressure should also decrease (Neibling and Gallian, 1997). Precision application technologies can be used to treat small areas of a field with simple on/off sprinkler controls in single span-wide treatment areas or to treat the whole field by controlling all spans. Position in the field can be determined by differential GPS, electronic compasses or electronic resolvers.

The development of control and management technologies that can spatially and temporally direct the amount and frequency of water (and appropriate agrochemical) applications by “precision” self-propelled irrigation systems would be a very powerful tool that would increase productivity and minimize adverse water quality impacts. There is also a need to develop more efficient methods of applying crop amendments (e.g., nutrients, pesticides) that will reduce usage, improve profit margins and reduce environmental impacts.

Variations in precision irrigation using self-propelled center pivot and linear move irrigation machines have been started by researchers in four groups embarked on research to develop site-specific irrigation machines. These were in Ft. Collins, CO (Fraisse et al. 1992; Duke et al. 1992), Aberdeen, ID (McCann and Stark, 1993; King et al. 1995; McCann et al. 1997), Prosser, WA (Evans et al. 1996), and Florence, SC (Camp and Sadler, 1994; Sadler et al., 2002a, 2002b; Camp et al. 2002; Omary et al. 1997). The methods developed in Prosser, WA, were installed on a 3-pivot cluster in a commercial farm in south central Washington state and north central Oregon (Harting 1999; Evans and Harting, 2000).

Early work on low-energy precision application (LEPA) in Lubbock-Halfway, TX, (Lyle and Bordovsky, 1981, 1983) was used to conduct non-spatial irrigation research on cotton (Bordovsky et al. 1992), corn (Lyle and Bordovsky, 1995) and sorghum (Bordovsky and Lyle 1996), and was extended into variable-rate irrigation (Bordovsky and Lascano, 2003).

Controlling Water Depths

Application depths on linear move systems are generally controlled by the speed of the machine. However, this is not sufficient under site-specific conditions where variable amounts are needed along the length of the machine, and varying output from sprinklers depending on location in the field may be a viable option. Nevertheless, adjusting water application depths just based on soil conditions to fine-tune the water management while considering spatial variability of soils and topography can be a significant challenge.

It is possible to control every sprinkler individually, but the cost increases past the point that the system is economically feasible. On the other hand, it would be possible to increase the number of sprinklers per bank, which would decrease cost, but the control system would lose some ability to match pre-selected treatment areas. In addition, individual control of heads may not be feasible since growers can not practically manage areas less than 0.4 to 0.5 ha within a field in other cultural aspects of their operation. Since sprinklers are mounted every 2.5 to 3 m with wetted diameters ranging from 6 to 10 m or more, banks of 3 to 5 heads tends to match these practical operational limits.

Several innovative technologies have been developed to variably apply irrigation water to meet anticipated whole field management needs in precision irrigation, primarily with center pivot and lateral move irrigation systems. Most of these systems use standard, off-the- shelf equipment with much of the research effort directed towards developing the appropriate control systems. Roth and Gardner (1989) used various sized sprinklers along a lateral move to apply different depths of water as the machine moved. McCann et al. (1997) used either two or three boom systems on center pivots which used combinations of two sprinklers sized to deliver or a 0, 1/3 and 2/3 or 0, 2/5 and 3/5 of the maximum application rate to achieve a targeted application depth in an area. Omary et al (1997), Camp et al. (1998) and Sadler et al. (1996) employed a similar approach utilizing combinations of two or three sprinklers applying 0, 1/3 and 2/3 or 0, 1/7, 2/7 and 4/7 (eight steps) of the maximum application depth. King and Kincaid (1996, 2004) developed an approach based on a needle valve concept where the sizes of the nozzle orifices are modified to achieve different discharge rates on a regular irrigation spray head but it required very precise control and high quality water.

It is also possible to apply different depths by pulsing flow and varying cycle times. Other investigators have relied on pulsing individual sprinklers or several sprinkler heads on a manifold to vary the application depths (Fraisse et al., 1992; Evans et al., 1996; Duke et al., 1997,1998). For this project, we have chosen the pulsing approach because of the greater flexibility in application depths, installation simplicity and reduced costs since complicated sprinkler heads or extra sprinklers and multiple valves are not required.

Cycle time is defined as the sum of total on and off times during one pulse cycle for calculation purposes. For example, a total off time of 50 seconds out of every 250 seconds would result in an 80% of maximum application depth (this could be 5 off times of 10 seconds each or whatever other combination is desired depending on the equipment). Evans et al. (1996) used a 250 second cycle time with rotator heads whereas Duke et al. (1998) and Harting (1999) used a 60 second cycle time with spray heads. We are also using a 60 second cycle time in this project, though our software allows us to easily change the cycle time if we need to make changes..

We are utilizing the site-specific implementation of a pulsed system on an artificially imposed spatial variability, such as a field of small research plots in which there are a mix of crops and a prescribed set of water management experiments. Application of these technologies over the top of natural variability is certainly more complicated and more demanding than general site specific field irrigation. Our water management treatments vary either irrigation method or depth water applications as the machine moves through the field. The objective of this paper is to describe the design, installation and testing of a site-specific irrigation system at the USDA-ARS, Northern Plains Agricultural Research Laboratory in Sidney, Montana.

The Sidney Site-Specific Irrigation System

An irrigated sugarbeet-barley crop rotation and tillage research study by irrigation method (LEPA vs MESA) was established near Sidney, MT under an 800 ft linear move irrigation system in 2004. The focus of the project is to assess the environmental impacts of cultural practices and improved management of water, nutrient and chemical applications. This is part of a multi-year team project involving several scientists from ARS and Montana State University. The soils in the field were grid sampled and analyzed for various physical and chemical characteristics prior to the initiation of the project.

The nine acre field is laid out in 14 strips in the direction of travel. Each strip is planted either to sugar beets or malting barley, which alternates from year to year. There are a total of 56 plots with the individual plots being 50 ft wide and 80 ft long including buffers. Each strip is divided into four plots with two plots being irrigated with MESA and two with LEPA that are blocked by replication. Water is applied to meet the calculated ET_a of each crop strip (backed up with soil moisture readings) using data from a nearby weather station. Equivalent depths of water are applied for both irrigation methods. Sugar beets are on 24 inch rows and the malting barley is on 8 inch row spacing.

We are using a Valley[3] (six tower system including the cart) diesel machine with an electrical generator set (480 v, 3 phase) on the cart that provides power for the tower motors, cart motors and the pump. A buried wire alignment system is used with the antennas located in the middle of the machine. The linear move machine uses a screened floating pump intake in a level ditch as its water supply. Nominal operating pressure is about 36 psi. Two double direction boom backs are installed at each of the towers (although not at the cart). Spans are 160 ft in length except for the center span with the guidance system which is a 156 foot span. The machine moves at about 7 ft/min at the100% setting.

A Valley CAMS Pro control panel is used to turn the machine on or off and control machine ground speed. A separate controller, described later, was designed and fabricated to control the precision water applications including irrigation method (and water application depths.)

The Nesson Valley Precision Site-Specific Irrigation System

While not the main topic of this paper, a second PLC control system has also been installed on a 1300 foot (366 m) buried wire-guided Valley linear move irrigation system (160 ft spans except for 156 ft center span and overhangs at both ends). This machine was installed on about 40 acres (16 ha) of the he new North Dakota State University farm in the Nesson Valley area, about 30 km east of Williston, ND near the Missouri River. Water is supplied either from a well or from the

[3] Mention of product names or company names is for informational purposes only and does not imply any endorsement by the USDA, Agricultural Research Service over products not mentioned.

river. The site-specific irrigation control system is similar to the Sidney system except that it is being used to evaluate irrigation frequency effects on sugarbeet-potato-barley rotations using only MESA heads on 60 inch (1.5m) spacing. Water depth is varied by plot during the season to match the respective crop ET as the machines moves down the field.

There are three separate sets of experiments under this machine that all irrigated differentially. The differing irrigation requirements of all of the plots can be met by inputting the required information in the control panel. The irrigation frequency study consists of 72 plots (each 50ft x 80 ft) arranged in a 4 x 18 matrix on a potato, sugarbeet and malting barley rotation. These plots are irrigated on two different frequencies (approximatelyg1 in or 2 inch ET_a replacement). Each of the 18 strips has two of the three crops and each crop is irrigated to match its respective ET_a throughout the season. We also apply nitrogen fertilizer to the beets and potatoes through the system.

To the south of the irrigation frequency study, there are 6 groups of replicated soil quality study plots, which requires half of them to be irrigated and half non-irrigated. To the west of the irrigation frequency set of plots is a barley phosphorus study that extended nearly the length of the linear. All of the plots in each of the three experiments are irrigated with a single pass of the linear move.

Positioning System

At both locations, we are using a WAAS enabled Garmin 17HVS GPS with a DGPS positional accuracy of <3 meters, 95% of the time. It is located at the cart for determining and tracking machine position as it moves across the plots, The GPS readings are used to switch between either the LEPA or MESA treatments (Sidney) or to differentially apply water to the different crops (Nesson) depending on treatments.

Sprinkler arrangement-Sidney

MESA sprinkler heads are spaced every 10 ft with Nelson S3000 spinner (#31 nozzles) with 15 psi regulators. These heads are about 42 inches above the ground on flexible drops with 1 lb weights below each regulator.

The LEPA system uses Senninger Quad-Spray® heads with 10 psi regulators (#10 nozzles) and sliding 2 lb weights above each regulator. The drops are spaced every 48 inches along submanifolds suspended from the truss rods. The bottom Quad-Sprays are about 6 inches above the furrow surface.

Sprinkler arrangement-Nesson

MESA heads are spaced every 5 ft using Senninger LDN (#12 nozzles) with 10 psi regulators. The nozzles are about 42 inches above the ground on flexible drops with 2 lb weights above each regulator.

Lifting Mechanism for the LEPA Heads (Sidney). A system of pneumatically operated cylinders have been designed and tested to lift the LEPA heads above the MESA heads when the MESA treatments are operating. This serves to minimize interference with the MESA spray patterns as well as keep the LEPA heads out of the canopy. When air is applied to solenoid valves (turning them off) on the LEPA manifolds, the cylinders are activated, lifting the LEPA heads.

The 4 foot long pneumatic cylinders have been built out of 2.5 inch aluminum sprinkler tubing. End plates with O-rings were fabricated and installed at each end. The 5 foot plunger rod is 0.5 inch stainless steel and is threaded into a piston machined from acetal. The cylinders are attached to the truss and are hooked to a series of cables and pulleys that lift the LEPA heads. This lifting system was designed in Spring 2005 but was not installed and tested until Fall 2005.

PLC Control System Development

Both the Sidney and Nesson Valley systems utilize the same basic control and valve systems, which are off the shelf components throughout. The PLC controller (Siemens 226 with 3 relay expansion modules) activates electric solenoids (ASCO U8325B1V, 24 volt, 6.9 watt) to control banks of sprinklers or LEPA heads. The ASCO valve, in turn, activates a pneumatic system to close normally-open, ¾-inch plastic globe valves (Bermad, model 205). In the case of the MESA heads, the Bermad valves are located on the gooseneck above each drop to each head in groups of five (at Sidney) or ten (at Nesson). The air-activated Bermad valves are located on three goosenecks that supply water to the submanifolds for the LEPA heads. The ISCO valves were grouped into clusters of six valves and placed on a weather tight plastic enclosure at each tower and the cart. Normally open valves were used on the heads since the failure mode would leave the sprinklers on, however, this also increased the risk with the dual system at Sidney since both the MESA and LEPA heads would be on if the air system failed.

Air was used as the control fluid in both systems since air was much cleaner than the irrigation water from surface supplies, and eliminated foreign material in the water supply from plugging the orifices in the control valves. Another advantage was that air does not freeze and the control system did not need to be flushed or drained for winterization. Any moisture in the air system is eventually vented to the atmosphere through the normal operation. A 1 HP, 3 phase, 480 volt air compressor was located at each cart for easy maintenance with a 3/8 inch line running the length of machine. Air reservoirs were located at each tower to ensure rapid and uniform valve operation.

The wiring cabinets for the PLC and add-ons were custom built (about $6K) using 36 inch steel, water proof enclosures (Figure 1). The software for the PLC and an operator interface panel (UniOp BKDR-16-0045) provides a means to control and monitor the PLC without the need for a laptop computer. The panel's LCD screen displays the status of each bank of sprinklers, the GPS position and associated GPS parameters, the application rate timer settings for each crop and plot area, and if a crop or study area will be irrigated. The interface panel is also used to input timer settings that determine the application rate for each crop or study area, turn off the irrigation for a particular crop or study area, or manually override the GPS unit for demonstration or troubleshooting purposes. The layout of the physical addressing used in the Sidney project is shown in Figure 2.

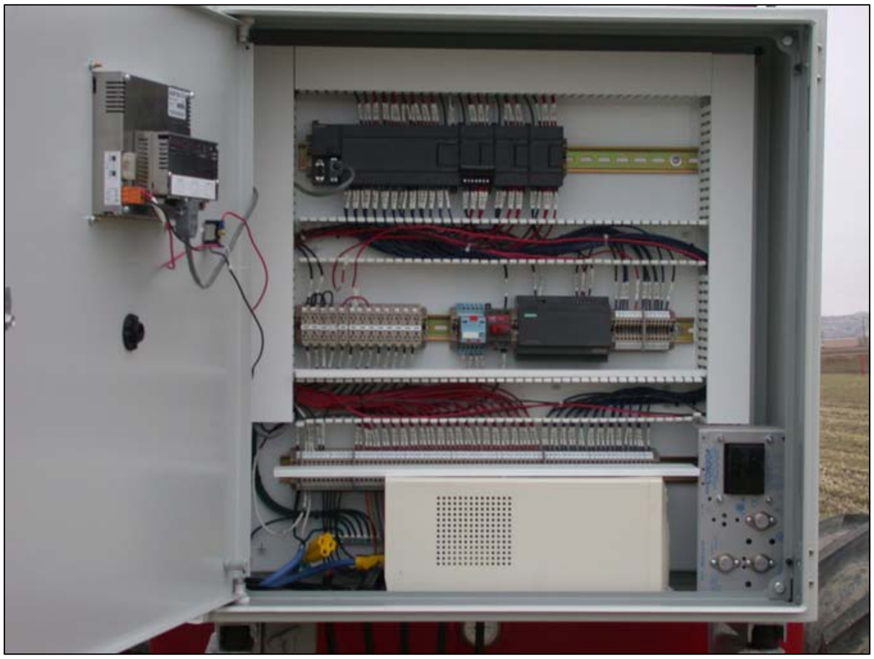

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Figure 1. Photograph of the interior of the wiring cabinet showing the PLC, power supplies, wiring and front interface panel.

Future Directions

One way to achieve the desired level of control would be the use of real-time soil water and micrometeorological sensors distributed across a field for continuously re-calibrating various decision-making model parameters during irrigation events. This type of integrated feedback is necessary because of the tremendous complexities and time constraints involved in solving real-time 3-dimensional modeling of the systems. Simplified assumptions may be used to increase computational speed and the predictive decision support models do not have the opportunity to drift very far from actual conditions since operating parameters are frequently re-initialized and the models rerun from more accurate baselines. Coupling real-time micro-weather stations, plant-based sensors (e.g., fixed canopy level reflectance, infrared temperature or video) and numerous real-time soil water sensors scattered around the field at critical locations with a set of good predictive models into a decision support system also minimizes the need for continuous and expensive agronomic oversight. Assessment of the environmental impacts of best management or “normal” irrigation practices from the integrated set of models in this configuration with real-time feedback will be more realistic and acceptable to both producers and regulators.

We are working on the use of distributed instrumentation (strategically placed, real-time soil water and micro-meteorological sensors distributed or moving across a field to provide continuous feedback) tied to control systems for spatially-varied water applications (using wireless communications technologies). We believe that a synergistic mix of remote sensing and on-the-go within field sensing of soil and plant status can decrease water and energy use through better timing of inputs for water, nutrient and pest management.

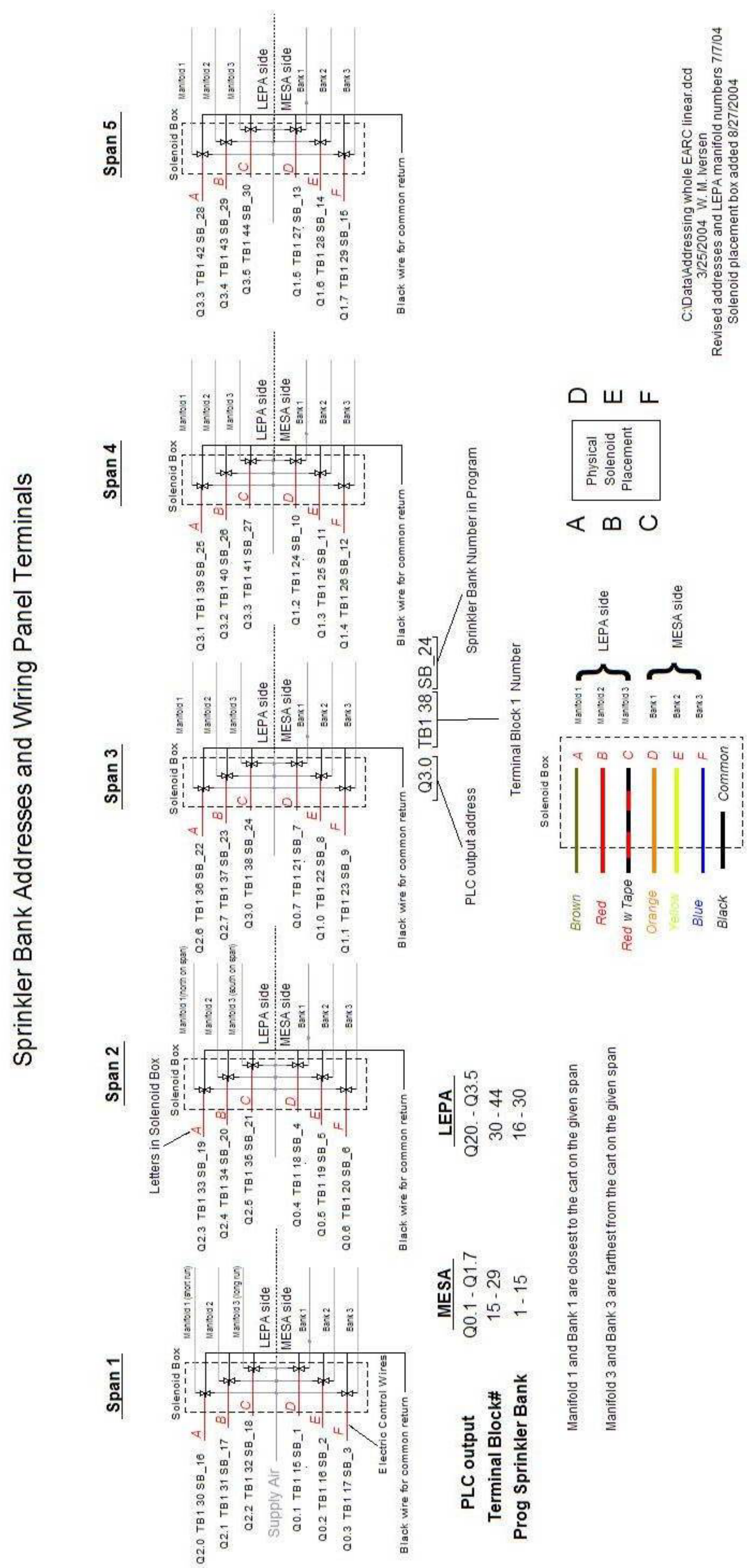

Figure 2. Addressing system used for each span of the Sidney linear move irrigation experiment.

Ultimately, because of the vagaries of "real" field conditions, we will probably need to use strategically placed, real-time soil water and micro-meteorological sensors distributed or moving across a field to provide continuous feedback to re-calibrate and check various model parameters in a decision support framework. There is a real need to improve procedures so that the fewest number of various soil water sensors and sensor systems would be placed for maximum impact to improve water quality.

Conclusions

A precision site-specific irrigation system has been designed, installed and tested on a linear move irrigation system. The PLC-based system has worked for two years (2004-2005). The system successfully switches between MESA and LEPA irrigation methods (Sidney) as it moves down the field. Water application depths can also varied for each crop (Nesson) depending on location as determined by a GPS system at the cart. Position can be determined by low cost GPS systems but it may also be economically feasible to use physical passive radio tag markers in the field to give even greater precision. This equipment greatly increases our research flexibility and allows us to address multiple experiments under the same machine, greatly maximizing results and utility of these expensive machines.

This project shows it is possible to economically install and operate precision site-specific irrigation systems on self-propelled linear move (and center pivot systems.) The knowledge of soil variability within a field is fundamental to the development of site-specific management areas since different soils have different water holding capabilities. The ability to vary water application along the main lateral of the linear move based on position in the field allows the researchers as well as producers to address specific soil, crop and/or special research conditions/treatments. By aligning irrigation water applications with variable water requirements in the field, total water use may be reduced, decreasing deep percolation and surface run off. Reducing excess water applications will decrease the potential to move nutrients past the plant root zone and fungal disease pressure should also decrease. Cropping systems that more efficiently utilize soil water have been shown to reduce costs and energy use as well as reduce water quality concerns.

It should also be mentioned that both the Sidney and Nesson Valley projects are also developing and evaluating minimum tillage practices suitable for self-propelled irrigation systems on these rotations to reduce energy (e.g., tractor fuel) costs and improve soil quality.

References

Agbu, P.A. and K.R. Olson. 1990. Spatial variability of soil properties in selected Illinois mollisols. Soil Sci. 150:777-786.

Bordovsky, J.P. and R.J. Lascano. 2003. Variable rate irrigation using low energy precision application (LEPA). 2003 Electronic Proceedings of the Beltwide Cotton Conferences, Nashville, TN. 8pp.

Bordovsky, J.P. and W.M. Lyle. 1996. LEPA irrigation of grain sorghum with varying water supplies. Transactions of the ASAE 39(6):2033-2038.

Bordovsky, J.P. W.M. Lyle, R.J. Lascano and D.R. Upchurch. 1992. Cotton Irrigation management with LEPA systems. Transactions of ASAE 35(3):879-884.

Burden, D.S. and H.M. Selim. 1989. Correlation of spatially variable soil water retention for a surface soil. Soil Sci. 148(6):436-447.

Camp, C. R., Y.-C. Lu and E. J. Sadler. 2002. Spatial variation in crop response, Part 2: Implications for water and nitrogen management. Irrigation Association Technical Conference, New Orleans, LA. ., 8 p. (CD-ROM)

Camp, C. R. and E. J. Sadler. 1994. Center pivot irrigation system for site-specific water and nutrient management. ASAE Paper # 94-1586. 1994 Winter International Meeting, Atlanta, GA, Dec. 13-16, 9 pgs. ASAE, St. Joseph, MI.

Camp, C. R. and E. J. Sadler. 1997. Capabilities of a center pivot irrigation system for precision management of water and nutrients. In Proceedings of the Irrigation Association Technical Conference. pp. 235-242. The Irrigation Association, Falls Church, VA.

Camp, C. R., E. J. Sadler, D. E. Evans, L. J. Usrey and M. Omary. 1998. Modified center pivot system for precision management of water and nutrients. Applied Engineering in Agriculture 14 (1):23-31.

Duke, H.R., D.F. Heermann and C.W. Fraisse. 1992. Linear move irrigation system for fertilizer management research. In Proceedings of International Exposition and Technical Conference. Fairfax, VA: The Irrigation Association, pp.72-81.

Duke, H.R., G.W. Buchleiter, D.F. Heermann and J.A. Chapman. 1997. Site specific management of water and chemicals using self-propelled sprinkler irrigation systems. In Precision Agriculture 1997. BIOS Scientific Publishers Ltd. pp. 273-280.

Duke, H.R., G.W. Buchleiter, D.F. Heermann and J.A. Chapman, 1998. Site Specific Management of Water and Chemicals Using Self-Propelled Sprinkler Irrigation Systems. Proc. of 1st European Conference on Precision Agriculture. Warwick, England, UK

Duke, H.R., S.C. Best and D.G. Westfall, 2000. Spatial distribution of available nitrogen under center pivot sprinklers. In Proc. of the 4th Natl. Irrigation Symp., ASAE, Phoenix, AZ, pp. 594-599.

Evans, R.G. and S. Han, 1994. Mapping the nitrogen leaching potential under center pivot irrigation. ASAE Paper No. 94-2555. ASAE. St. Joseph, MI. 13 pp.

Evans, R.G., S. Han and M.W. Kroeger.1995. Spatial distribution and uniformity evaluations for chemigation with center pivots. Trans. of the ASAE 38(1):85-92.

Evans, R.G., S. Han, S.M. Schneider and M.W. Kroeger. 1996. Precision center pivot irrigation for efficient use of water and nitrogen. In Proceedings of the 3rd International Conference on

Precision Agriculture, eds. P.C. Robert, R.H. Rust, and W.E. Larson. Madison, WI: ASA-CSSA-SSSA, pp.75-84.

Evans, R.G. and G.B. Harting. 1999. Precision irrigation with center pivot systems on potatoes. In Proceedings of ASCE 1999 International Water Resources Engineering Conference, eds. R. Walton and R.E. Nece, August 8-11. Seattle, WA. Reston, VA: ASCE. CD-ROM, no pagination.

Evans, R. G., G. W. Buchleiter, E. J. Sadler, B. A. King and G. B. Harting. 2000. Controls for precision irrigation with self-propelled systems. In Proc. 4th Decennial National Irrigation Symp., R. G. Evans, B. L. Benham, and T. P. Trooien (eds.), pp. 322-331 ASAE, St. Joseph, MI.

Fraisse, C.W., D.F. Heermann and H.R. Duke. 1992. Modified linear move system for experimental water application. In Advances in Planning, Design, and Management of Irrigation Systems as Related to Sustainable Land Use. Leuven, Belgium, Vol. 1, pp. 367-376.

Han, S., R.G. Evans and S.M. Schneider. 1996. Development of a site specific irrigation scheduling program. ASAE Paper No. 96-2076. ASAE, St Joseph, MI.

Harting, G.B. 1999. As the pivot turns. Resource 6:13-14. St. Joseph, MI: ASAE.

James, L.G. 1982. Modeling the performance of center pivot irrigation systems operating on variable topography. Trans. of the ASAE 25(1):143:149.

King, BA., R.A. Brady, I.R. McCann and J.C. Stark. 1995. Variable rate water application through sprinkler irrigation. In Site-Specific Management for Agriculture Systems, eds. P.C. Robert, R.H. Rust, and W.E. Larson. Madison, WI: ASA-CSSA-SSSA, pp. 485-493.

King, B.A. and D.C. Kincaid, 1996. Variable Flow Sprinkler for Site-Specific Water and Nutrient Management. ASAE Technical Paper No. 96-2074. ASAE. St Joseph, MI..

King, B.A. and D. C. Kincaid, 2004. A variable flow rate sprinkler for site-specific irrigation management. Applied Engineering in Agriculture, American Society of Agricultural and Biological Engineers 20(6): 765-770.

Lyle, W. M. and J. P. Bordovsky. 1981. Low energy precision application (LEPA) irrigation system. Trans. of the ASAE 24(5):1241-1245.

Lyle, W. M. and J. P. Bordovsky. 1983. LEPA irrigation system evaluation. Trans. of the ASAE 26(3):776-781.

Lyle, W.M.,and J.P. Bordovsky. 1995. LEPA corn irrigation with limited water supplies. Transactions of the ASAE 38(2):455-462.

McCann, I.R., B.A. King and J.C. Stark, 1997. Variable rate water and chemical application for continuous-move sprinkler irrigation systems. Applied Engineering in Agriculture. 13(5):609-615.

McCann, I.R. and J.C. Stark. 1993. Method and apparatus for variable application of irrigation water and chemicals. U.S. Patent No. 5,246,164. September 21, 1993.

Mallawatantri, A.P. and D.J. Mulla, 1996. Uncertainties in leaching risk assessment due to field averaged transfer function parameters. Soil Sci. Society of America 60:722-726.

Mulla, D.J., C.A. Perillo and C.G. Cogger. 1996. A site-specific farm-scale GIS approach for reducing groundwater contamination by pesticides. J. of Environ. Quality. 25:419-425.

Neibling, H. and J. Gallian, 1997. Sugar Beet Irrigation: Essential in Idaho. Agricultural Irrigation. April 1997. pp22-23.

Omary, M., C. R. Camp and E. J. Sadler. 1997. Center pivot irrigation system modification to provide variable water application depths. Applied Engr. in Agric. 13 (2):235-239.

Roth, R.L. and B.R. Gardner, 1989. Modified Self-Moving Irrigation System for Water-Nitrogen Crop Production Studies. ASAE Technical Paper 89-0502. ASAE. St. Joseph, MI.

Sadler, E.J., C.R. Camp, D.E. Evans and L.J. Usrey. 1996. A site-specific center pivot irrigation system for highly-variable Coastal Plain soils. pp. 827-834. In P. C. Robert, R. H. Rust, and W. E. Larson (eds.) Proceedings of the Third International Conference on Precision Agriculture. 23-26 June, Minneapolis, MN. ASA/CSSA/SSSA, Madison, WI.

Sadler, E. J., C. R. Camp, D. E. Evans and J. A. Millen. 2002a. Spatial variation of corn response to irrigation. Trans. ASAE. 45(6):1869-1881.

Sadler, E. J., C. R. Camp., D. E. Evans and J. A. Millen. 2002b. Spatial analysis of corn response to irrigation. In Proc. 6th International Conference on Precision Agriculture, P. C. Robert, R. H. Rust, and W. E. Larsen (eds.) ASA/CSSA/SSSA, Madison, WI. (CDROM)

Optimal Site-specific Configurations for Wireless In-field Sensor-based Irrigation

by

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Abstract:
The spatial variability of agricultural fields has been addressed widely over various research papers, while difficulty remains to optimize the site-specific field configuration. Because of the complexities and time constraints involved in real-time irrigation scheduling, integrated feedback of soil water and micrometeorological sensors distributed across a field is necessary for continuous update on decision support of irrigation systems. There is a demand to improve procedures so that the minimum number of in-field sensor systems would be placed with maximum impact to the decision support.

The performance of the wireless data collection is evaluated on the experimental plot prepared with conventional irrigation schedule. Each sensor station consists of sensors for leaf temperature and humidity, soil temperature and moisture, and rain gage. Optimized sensor distribution produces cost-effective system with increased computational speed, while frequent feedback of plant-based sensors and soil water sensors minimizes drift from actual conditions.

Keywords: precision agriculture, wireless network, irrigation, real-time, sensing.

INTRODUCTION

The rapid development of sensing, computing, and information technologies has introduced new concepts on the management and control of agricultural systems. Precision agriculture is a concurrent system utilizing many technologies for site-specific management: Global Positioning System (GPS) for site-specific mapping, Geographic Information System (GIS) for decision support, ground or remote sensing for biomass formation, harvest sensors for yield mapping, and information technology for on-farm database system. The benefit of precision agriculture will be achieved by the seamless integration of all these subsystems. Wireless radio frequency has been widely applied in consumer's electronics and provided opportunities to deploy wireless data communication in agricultural systems.

A wireless in-field sensing network is proposed for sensor-based irrigation system. The system consists of in-field sensing stations, a decision support engine, and an irrigation nozzle controller. The sensing stations monitor soil and plant status across the field and are tele-metered by 915 MHz spread spectrum radio. Decision support is made out of database of all on- and off-field information and sends an application map to the irrigation controller via ethernet bridge to operate individual nozzles.

The paper describes a framework of wireless in-field sensor network for automated irrigation system and evaluate optimal site-specific configuration for the wireless sensor network. Optimized sensor distribution can produce cost-effective system with increased computational speed, while frequent feedback of plant-based sensors and soil water sensors minimizes drift from actual condition.

WIRELESS NETWORK OF IN-FIELD SENSING STATIONS

A project was established to develop wireless network of in-field sensing stations for real-time irrigation decision support by Northern Plains Agricultural Research Laboratory at USDA-ARS on early 2004. The research presented in this paper is a part of project to evaluate optimal site-specific configuration for the in-field sensor network.

Motivation

The concept of the wireless in-field sensor network for automated irrigation system was derived from managing an irrigation system quickly, accurately, inexpensively, and globally. End-users such as farmers can quickly access for irrigation control by real-time monitoring and scheduling with hands-on technical support via online knowledgebase. The direct access to the field condition is accurately supported by in-field sensor network configured based on pre-sampled soil property maps, enabling site-specific application from localized database. Rapid development and popularity of wireless technology has been reduced cost and improved the range of data communication without interference using spread spectrum radio technology. The development of online interface allows the end-users to globally access their irrigation monitoring and controlling anywhere and anytime.

Deliverables

The wireless in-field sensor network systems enable end-users to remotely access to field condition via online monitoring. The development of knowledgebase can provide for farmers real-time actions suggested to site-/time-specific application on product-identified data. From the standpoint of developers, it takes an advantage of remote access to in-field sensor stations and enables real-time manageability. The online infrastructure can provide direct link between the end-users and developers and thus enable real-time electronic-support (E-support) from GIS-identified database through secured access.

The sensor network for automated irrigation system is a user-friendly system with the promise of a future-leading technology for a precision irrigation system. The system will provide efficient irrigation management for both end-users and developers, as it becomes accessible, displayable, communicable, and supportable.

Approaches and Design

The wireless in-field sensing-based irrigation system can be achieved by a seamless integration of sensing, control, and wireless data communication. In hardware review, wireless I/O system was selected because a wired system is expensive to install and maintain. In some cases, it is difficult or impossible to install wires. A wireless system takes advantages of dynamic mobility and cost-free relocation. There are many different wireless technologies available in the market. Most of recent wireless technologies follow a standard such as 802.11, Bluetooth, or Zigbee, which adopts spread spectrum technology. Three spectrum bands (902~928 MHz, 2.4~2.48 GHz, and 5.7~5.85 GHz) were allocated for license-free spread spectrum devices (Kulkarni, 2005). The choice of wireless standard depends on how to interface: distance, data rate, compatibility, interference, and security. Major two factors are distance and speed.

The wireless in-field sensor network requires large networks that can form autonomously and operate reliably without any operator intervention for long battery life extended by solar power. Network topology is determined by a number of nodes and coverage area. A simple wireless network topology called an ad-hoc network consists of a set of wireless stations that communicate directly on peer-to-peer level without an access point, as shown in Figure 1. An infrastructure network allows more flexible configuration by bridging the wireless and wired networks via access points (Meel, 1999).

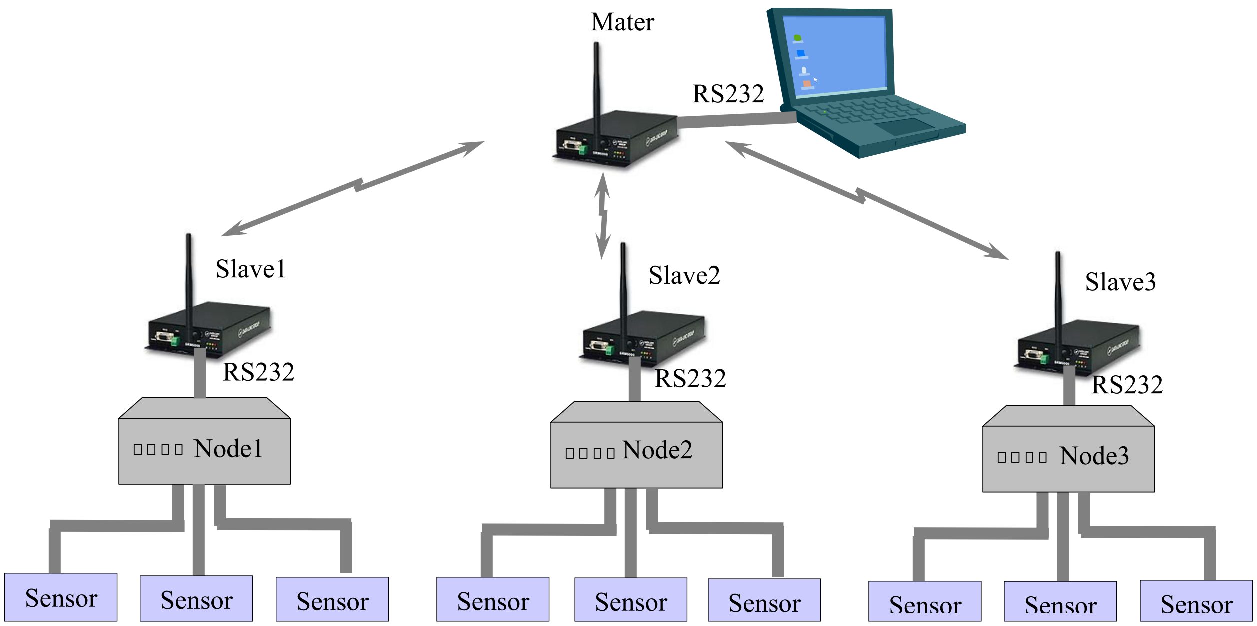

Figure 1 Ad-hoc network topology.

Data processing and management

The network infrastructure provides data communications from all available information sources. The development of microprocessors in the 1970's made it possible to realize many complex functions in a simple manner and enhanced the sensing and data processing in a unified framework. In-field information is acquired by data processing from raw data through filtering, transmitting, and fusion and sent to data management which performs decision-making, display, and diagnosis. The schematic diagram of data flow is shown in Figure 2.

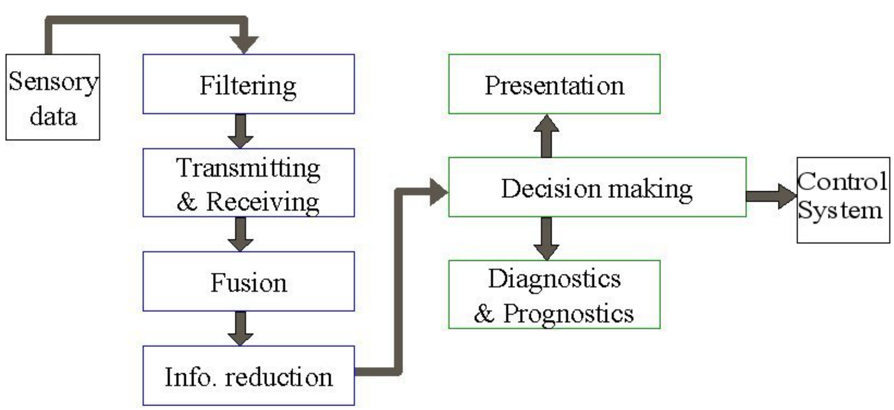

Figure 2 Schematic diagram of sensory data flow.

Data processing is a sequence of data flow from the raw sensory data to the refined data that is prepared for data management. A set of raw data are filtered to remove the noisy signals and transmitted in a suitable data format. Data fusion performs integration of low-level information provided by different kinds of sensors. The fusion of the collected data results in higher-level information that is more easily assessed by end users. Accordingly, the data fusion can provide efficiency in the decision-making process. Finally, data are screened to remove unrelated information and integrated. Refined data from the measurement system needs to be delivered to the management system. Information delivery in a timely fashion was emphasized by Harbers and Hoogenboom (2000) for their real-time database in application of dynamic web content.

Each sensory data have tolerances which relate directly to the original sensor modality and to the sensor-dependent algorithms. These tolerances may determine the overall accuracy of the system. The system will have benefits from the ability to compare the measurements of multiple sensor systems and thus provide a means of highly accurate tuning of the algorithms of all different sensor systems.

Decision making

The decision-making is a process of engineering information. A decision is made based on given information and knowledge. Integrated information system for the management in agriculture was discussed by Thiel *et al*. (2000) that used executive control center to combine the function of operative systems, decision support systems, executive information systems, and groupware systems. A correct decision is made when these two components are accurately obtained. In reality, however, the given information and knowledge often include uncertainties and also complexity arising from the dynamic nature of the underlying phenomena.

The flowchart of the dynamic decision-making process is illustrated in Figure 3. The collected information about the field condition is used to make a decision at each time frame. Field conditions are varying both independently and by the result of the previous decision. Thus, the decision is dynamically determined by the changing information from the time-variant environment just like an analogy to a medical decision making a proper treatment in time for a patient under his or her changing physical conditions over time. Similarly, decision-making in the agricultural system is to determine an optimal amount of irrigation or fertilizer with respect to various crop conditions over time and for different sites. The complexity of these problems is amplified, if information about the nature and the time of a certain situation are uncertain.

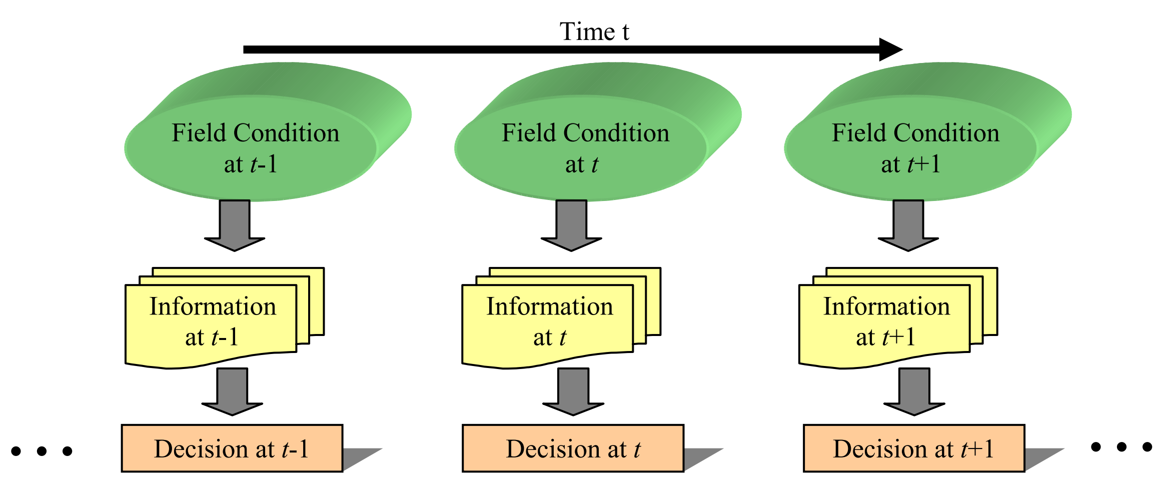

Figure 3 Flowchart of dynamic decision making process.

Information must be provided for flexible and efficient access. Visual display is useful information presentation. Descriptive information associated with processed sensory data can be represented to enable an end-user to easily access and efficiently manage the information. A communication protocol for a distributed nozzle control system may use a network bus such as Controller Area Network (CAN) which enables a huge reduction in wiring complexity with high speed, high reliability, and low cost for distributed real time control applications (Ekiz *et al*., 1996). The CAN system can provide direct feedback to the information collection and used to check the current status of each nozzle pressure. CAN bus application of distributed control to closed environments in agriculture was addressed by Alves-Serodio *et al*. (1998).

Conceptual system layout

A conceptual layout of wireless network of in-field sensing stations for real-time irrigation decision support system is illustrated in Figure 4. The wireless sensing stations monitor the in-field plant condition such as air temperature, relative humidity, soil temperature, soil moisture, and rain gage and transmit data into a base receiver connected into an office computer. A decision making is accomplished based on information given by in-field sensing stations and weather station and send outputs to an irrigation controller. The data processing and management are implemented by a computer that is bridged to internet database with secured access.

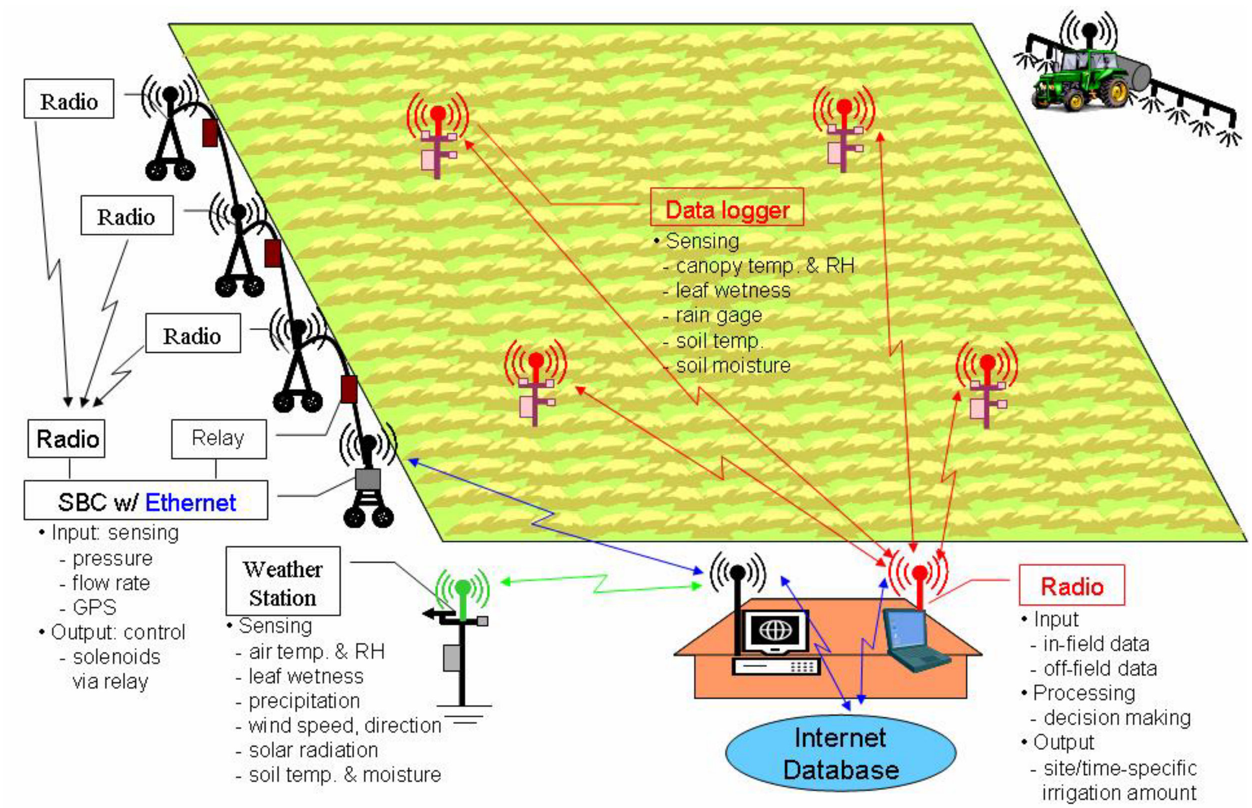

Figure 4 Conceptual layout of wireless network of in-field sensing stations for the real-time irrigation decision support system.

SITE-SPECIFIC FIELD CONFIGURATION

Agricultural fields are not homogeneous and varying across the field. The field variability continues over the time and site, affected by natural environmental impacts and human's agricultural inputs such as seeds, irrigation, fertilizers, and pesticides. The variability results in yield varying across the field. One of the major factors of field variability is the change in soil properties.

Spatial field variability

The field variability has to be taken into consideration to configure in-field sensor network. The spatial variability of agricultural fields has been studied to optimize the site-specific field configuration for wireless in-field sensor-based irrigation. The study of the field variability can provide procedure such that the minimum number of in-field sensor stations would be placed with maximum impact to the field information.

Soil property has a major impact on crop yield (Farahani, 2004). Among the many factors of field variability, soil electrical conductivity (EC) and compaction were used to map the field variability, because they are most widely used to characterize agricultural fields (Farahani, 2004 and Drummond *et al*., 2000). The EC measures the amount of salt in the soil as well as other soil properties and thus can relate to soil properties of sand, clay, and organic matter. Mapping soil EC and compaction may not identify yield variability, but provides a useful field characteristic for optimal site-specific configuration of the field variation.

A soil profiler (Veris 3000, Veris Technologies, Salina, KS) was used to map soil compaction and EC on an experimental field. The profiler is an automated system equipped with a penetrometer and soil EC probe (Fig. 5). The probe is vertically pushed into ground by a hydraulic power generated by self-contained 5.5 hp engine and measures pressure in MPa and EC in milliSiemens per meter (mS/m) at the probe tip sensed by its load sensor (Veris Technologies, 2002). The data are logged every 2 cm interval up to 92 cm in depth with geo-referenced points using DGPS (Trimble Ag132).

Figure 5 Soil profiler (Veris 3000) to measure soil EC and compaction.

Mapping spatial field variation

An experiment was conducted on a 1.4 ha field at Nesson Valley research farm located 23 miles east of Williston, North Dakota on April 14, 2005. The profiler measured soil compaction and EC at the probe tip sensed by its load sensor and associated with geo-referenced locations. A total of 134 data were collected with average 7.6 m sampling interval.

Geostatistical analysis was performed with GIS software (ArcGIS ver. 9.1, ESRI, Redlands, CA). Kriging model was used to interpolate both soil EC and compaction data and created spatial maps with five classifications by a quantile method. Figures 6 and 7 illustrate the spatial variation map of soil EC and compaction, respectively, at 30 cm soil depth. Both figures show field variations with a different trend. The soil EC in most of east area is uniform, while more variations were found in west area with highest EC in northern west area (Fig. 6).

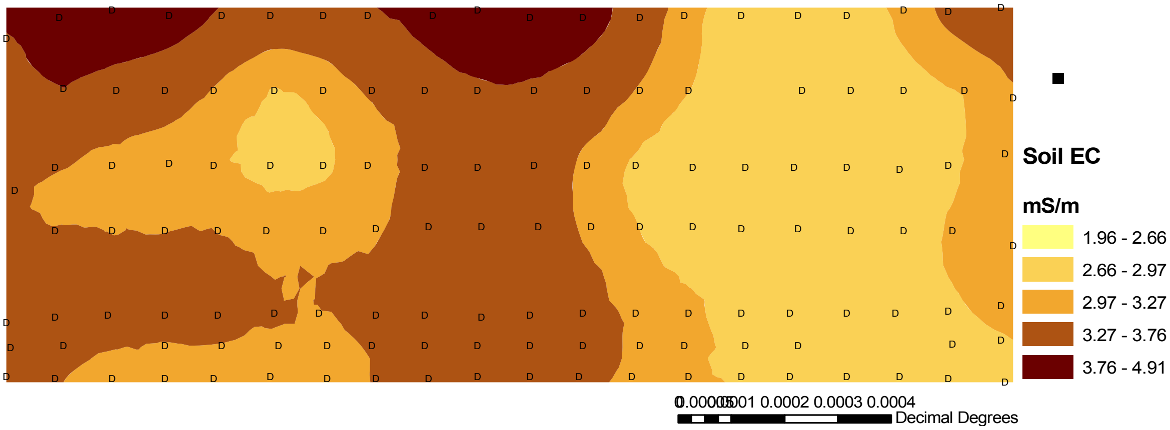

Figure 6 Spatial mapping of soil EC at 30 cm subsurface with a profiler (Veris 3000).

A spatial map of the soil compaction at 30 cm subsurface was created based on pressure reading sensed at a probe tip and displayed in figure 7. Although a few variations were found along the field edges, most of area remained uniform with the compaction of about 2 MPa. Highest compaction was located at northern east area of the field. The small scale of variation from 1.04 to 3.44 MPa indicated uniformity of the field.

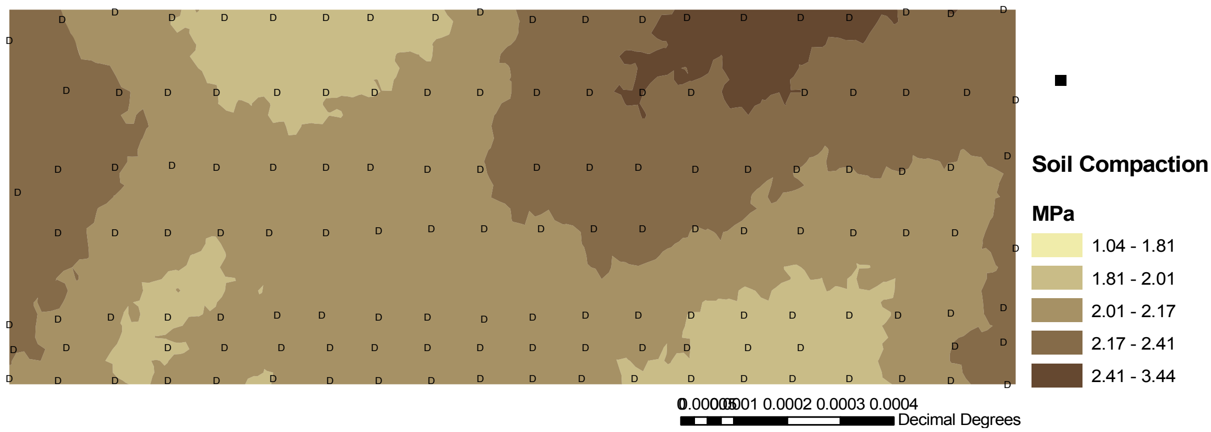

Figure 7 Spatial mapping of soil compaction at 30 cm subsurface with a profiler (Veris 3000).

CONCLUSIONS AND FUTURE WORKS

A wireless in-field sensor network for automated irrigation system was presented. The research was motivated to manage an irrigation system quickly, accurately, and inexpensively. Spread spectrum wireless technology was selected for its dynamic mobility and cost-free maintenance. Data processing and management were described from raw data to decision making through information flow.

The spatial field variability was studied on an experimental field to optimize the site-specific field configuration. Soil EC and compaction were sampled to map the field variability and geo-statistically analyzed to create spatial field variation maps. The soil compaction map resulted in minimal variation, whereas the soil EC map showed direct source to optimize network topology for site-specific field configuration,

The system framework was constructed and details on hardware interface and software will be investigated and developed. Future works include development of knowledgebase for decision making and integration of the sensor network with an irrigation controller.

BIBLIOGRAPHY

Alves-Serôdio,C. M. J., C. A. C. Couto, and J. L. Monteiro. 1998. An integrated network for agricultural management applications. *Proceedings of ISIE '98*, IEEE International Symposium on Industrial Electronics 2: 679-683.

Drummond, P. E., C. D. Christy, and E. D. Lund. 2000. Using an automated penetrometer and soil EC probe to characterize the rooting zone. *Proceedings of the 5th International Conference on Precision Agriculture*.

Ekiz, H., A. Kutlu, M. D. Baba, and E. T. Powner. 1996. Performance analysis of a CAN/CAN bridge. *International Conference on Network Protocols '96*, IEEE Computer Society and Information Processing Society of Japan, Columbus, OH. pp.181-188.

Farahani, H. J. and G. W. Buchleiter. 2004. Temporal stability of soil electrical conductivity in irrigated sandy field in Colorado. *Transaction of the ASAE*, 47(1):79-90.

Harvers, G. W. and G. Hoogenboom. 2000. The use of real-time database applications to develop dynamic web content for information delivery in time of crisis. ASAE paper No. 00-3032. ASAE, St. Joseph, MI.

Kulkarni, R. 2005. Technologies for building wireless industrial I/O systems. Online tutorial. National Instruments. Available at www.ni.com/swf/presentation/us/wireless.

Meel, J. 1999. Spread spectrum applications. Internal project note, De Nayer Institute, Belgium. Available at www.sss-mag.com/pdf/Ss_jme_denayer_appl_print.pdf.

Thiel, S., R. Helbig, and G. Schiefer. 2000. Executive control center: an internet/intranet based data warehouse solution for management support in agriculture and the food chain. ASAE paper No. 00-3031. ASAE, St. Joseph, MI.

Veris Technologies. 2002. User manual of the profiler 3000, Veris Technologies. Available at www.veristech.com.

SITE-SPECIFIC WATER AND NITROGEN MANAGEMENT FOR POTATOES WITH CENTER PIVOT IRRIGATION

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ABSTRACT

Center pivots are the most commonly used irrigation system for potato production in the Pacific Northwest and Intermountain West. Conventional irrigation management treats the field as a homogeneous unit in regards to irrigation water requirements. However, differences in irrigation water requirements often develop throughout the season within center pivot irrigated potato fields that can reduce field scale tuber yield and quality. This study investigated the potential increase in gross return from increased tuber yield and quality under site-specific versus conventional uniform irrigation management with center pivot irrigation. In 2001 and 2002, one quadrant of an 11.5 ha center pivot irrigated field was divided into eighteen arbitrary irrigation management zones. One-half of the management zones received site-specific irrigation management and the remainder received equal irrigation based on the average irrigation requirement for the nine zones. The difference between mean seasonal irrigation amounts for the treatments was less than 13 mm for both years. Total tuber yield was not significantly different ($p<0.05$) for both years. However, based on a tuber quality adjusted price structure for processing potatoes, the trend in gross receipts was approximately \$159/ha (\$64/ac) greater under site-specific water management compared to conventional uniform irrigation management for the field site. In 2004, the potential increase in gross return from conjunctive site-specific water and in-season nitrogen management was investigated. Total tuber yield was not significantly different ($p<0.05$) between treatments. The trend in gross receipts was approximately \$324/ha (\$131/ac) greater under conjunctive site-specific water and nitrogen management compared to conventional uniform water and nitrogen management. Water use efficiency was not significantly different ($p<0.05$) between treatments in any study year. However, water use efficiency trended higher under site-specific water management averaging 5% greater in study years 2001 and 2002 and 14% greater in 2004.

INTRODUCTION

Interest in site-specific irrigation management has emerged over the past decade in response to successful commercialization of other site-specific application technologies in irrigated agriculture. This interest is due partially to the desire to improve water use efficiency and partially due to the need to implement site-specific water management to complement site-specific management of other crop inputs such as nitrogen for groundwater protection. A holistic approach to site-specific crop management in irrigated agriculture includes water as one of the primary inputs. Extension of the site-specific crop management concept to irrigation follows from the fact that excessive and deficient water availability greatly impacts crop yield and quality.

Continuous-move irrigation systems provide a natural platform upon which to develop site-specific irrigation management technologies due to their current and increasing usage and high degree of automation. Control systems and hardware to implement site-specific irrigation management have been reported in the literature (e.g. Fraisse et al., 1995; King et al., 1996; Sadler et al., 1996; Evans et al., 1996; Harting, 1999; and Perry et al., 2003). However, many issues relating to reliability, management and economic viability need to be addressed before commercialization and producer adoption can be expected.

Implementation of site-specific irrigation management will require additional irrigation system hardware, labor, and information on site-specific soil and/or crop water status. Costs associated with these additional requirements will need to be covered by increased receipts from improved crop yield and quality in order for the technology to be adopted by producers. Site-specific irrigation management will not likely be an economically viable practice for all crops and all growing conditions. However, it may be universally beneficial in regards to reducing the impact of irrigated agriculture on regional water resources through improved field-scale water use efficiency and reduced localized leaching of nitrogen from the crop root zone.

The economic requirement of increased receipts to offset increased irrigation costs limits site-specific management to commodities such as potatoes where yield and quality are highly sensitive to root zone water availability (Wright and Stark, 1990) and the commodity price structure is heavily dependent upon crop quality. In Idaho, which provides more than 25% of total U.S. fall potato production, sales contracts for processing potatoes normally include a base price plus tuber quality incentives and disincentives, thus total crop receipts are strongly influenced by soil water availability throughout the growing season.

Few studies have been conducted to evaluate the profitability of site-specific water management. Studies reported in the literature often have used simulation models based on theoretical crop production functions. In each case, soil water holding capacity was considered as the only factor influencing crop yield and the basis for needing site-specific water management. In reality, many factors influence crop yield and quality besides soil water availability, although it generally has a predominant adverse affect when well outside the optimum range.

Watkins et al. (2002) used a simulation approach to evaluate the economic and environmental benefits of site-specific irrigation management for seed potatoes in Idaho. They concluded that site-specific water management was more likely to be both economically and environmentally beneficial than variable rate nitrogen application for the study conditions. Watkins et al. (2002) acknowledged that the model was not calibrated to simulate nitrogen losses and neither yield nor nitrogen loss predictions were validated. Sensitivity analysis of the results showed that a small increase in estimated costs for site-specific irrigation management over conventional uniform irrigation management costs would result in the latter being more economical.

Oliveira et al. (2004) used a simulation model to evaluate the economic return of site-specific drip irrigation management for tomatoes in Tennessee. Based on 30 years of historical climate data they found that conventional uniform irrigation management using the soil type with the lowest water holding capacity to schedule irrigations had the same economic return as site-specific irrigation management. However, uniform irrigation management required 20% more water application compared to site-specific irrigation management.

Sadler et al. (2002) conducted a three-year field study to measure the mean response of corn to irrigation and compare variation in crop response within and among soil map units. Variation in crop response to irrigation was significant both between and among soil map units. Over the three-year study, the optimum irrigation amount varied from 61% to 120% of the irrigation base rate calculated as 100% of evapotranspiration minus precipitation. One conclusion of the study was that achieving optimum site-specific irrigation management based on *a priori* information will be a significant challenge. The variation in crop response to irrigation by year, soil map unit, and within soil map unit highlighted the need to use empirically derived site-specific crop response data to adequately simulate crop growth to site-specific water management in any economic analysis.

The study of Sadler et al. (2002) represents the only known data set of empirical site-specific crop response to water. It is not feasible to develop empirical crop response relationships for all crops, conditions, and locations in order to assess the economic return from site-specific irrigation management. Thus, field experimentation of site-specific irrigation management based on real-time measurements of soil and/or crop water status will play a substantial role in evaluating the economic and environmental benefits of site-specific irrigation management.

The underlying thesis of conventional uniform irrigation management is that soil water availability must remain within an established optimum range throughout the growing season for maximum crop yield and quality. However, this does not alone ensure maximum yield and quality as many other factors can affect crop yield and quality. As a first step to field experimentation, site-specific water management, based on site-specific soil water monitoring to maintain soil water within an established optimum range throughout the growing season is the basis for the current research. The objective of field studies conducted in 2001 and 2002 were to compare site-specific water management against conventional uniform water management based on continuous soil water monitoring to evaluate potential increase in potato yield, quality, and resulting increase in crop receipts, if any. The objectives of a field study conducted in 2004 were to implement independent site-specific in-season nitrogen application and compare site-specific water and nitrogen management against conventional uniform water and nitrogen management to evaluate the potential increase in potato yield, quality, and resulting increase in crop receipts.

METHODS AND MATERIALS

The field studies were conducted at the University of Idaho Aberdeen Research and Extension Center in 2001, 2002, and 2004 using a center pivot irrigation system equipped with the variable rate irrigation control system described by King et al. (2000). Briefly, variable rate water application along the center pivot lateral is achieved using two sprinkler packages sized with application rates of 1X and 2X. Solenoid valves on each sprinkler provide ON/OFF control of each sprinkler resulting in application rates of 0X, 1X, 2X, and 3X using ON/OFF sequencing. Valve control is provided by a supervisory control and data acquisition (SCADA) system that utilizes RS-232, power line carrier, and radio frequency communication media to link system-mounted controls and in-field stationary data loggers to a master computer. The SCADA system is designed to upload logged soil moisture, water application, and environmental data from in-field sensors when the center pivot lateral is within low-power radio frequency range. The data is stored in the master computer located at the pivot point and downloaded to a portable computer for analysis and site-specific irrigation scheduling decisions.

In 2003, the center pivot system was modified to include a separate low volume chemical application system to allow independent site-specific water and nitrogen application. The chemical application system consists of a 51 mm (2 in) diameter PE pipe placed along the top of the 191-m (628-ft) center pivot lateral with an outlet at each tower. The outlet at each tower is connected to two 25 mm (1 in) diameter PE pipe manifolds equipped with microsprinklers spaced 2.7 m (8.7 ft) apart. Each microsprinkler manifold is one-half the center pivot span length to provide one-half span length radial resolution in chemical application control, equal to that of water application control. The microsprinkler manifolds are suspended below the water application sprinklers at a height of about 1.5 m (5 ft) above ground level. The microsprinklers are Nelson S10 Spinners each equipped with gray plates and a 138 kPa (20 psi) Nelson Mini Regulator and Drain Check (Nelson Irrigation Corp., Walla Walla, WA). A solenoid activated diaphragm valve is used to control flow into each microsprinkler manifold and ON/OFF pulsing is used to control chemical application rate. The microsprinkler drain check valves keep the manifold from draining when microsprinkler flow is off. A separate 3.7 kW (5 hp) centrifugal pump is used to pressurize the chemical application system. An 1890 L (500 gal) plastic tank is used to provide on-site and on-demand mixed chemical solution for the chemical application system. A fixed pipe orifice with a pressure regulated solenoid activated diaphragm valve is used to provide a known water flow rate into the mixing tank from the pressurized irrigation water source. A positive displacement chemical injection diaphragm pump is used to provide a controlled and known flow rate of chemical into the water stream entering the mixing tank. Variable rate chemical application is achieved by controlling the ON/OFF times of each chemical application microsprinkler manifold and flow rate of chemical injected into the water stream entering the mixing tank. The design application rate of the chemical application system is 0.31 L/s/ha (2 gpm/ac). The minimum uniform water application depth of the chemical application system is 0.8 mm (0.03 inch) for this particular center pivot system.

Each year one 2.9 ha (7.1 ac) quadrant of the center pivot irrigation system was divided into eighteen arbitrary irrigation management zones. Different quadrants were used in 2001 and 2002 with 2001 and 2004 being the same quadrant. Soil texture in the upper 60 cm (2 ft) of the soil profile was determined in the laboratory using the hydrometer method (Gee and Bauder, 1986) based on soil sampling of the field on a 30.5 m (100 ft) hexagonal grid. Soil texture at unsampled locations was estimated using block kriging. Soil texture ranges from a loamy sand to silty clay loam and results in a two-fold variation in water holding capacity for the field site, which is representative of many commercial potato fields in the region. The eighteen arbitrary management zones were blocked into nine groups of two according to most similar soil texture in the top 30 cm (1 ft) of the soil profile. Irrigation treatments of site-specific irrigation management (SSIM) and conventional uniform irrigation management (CUIM) were randomly assigned to the experimental units in each block. The resulting experimental design is a randomized complete block with two treatments and nine replications.

An experimental plot measuring 6.5 m by 10 m (21.3 ft by 33 ft) was established in each experimental unit located approximately three-quarters of the radial span length outward from the pivot point under a particular span. A custom data logger (King et al. 2000) recorded soil water content at two depths, soil and air temperature, relative humidity, and water application at 30-min intervals. The instrumentation was installed immediately following crop emergence. The soil water sensors (CS615, Campbell Scientific, Logan, UT) were installed in the crop row at 45° inclines to measure soil water content at depths of 2-23 cm (1-9 in) and 20-41 cm (8-16 in). The soil water sensors were placed about 5 cm (2 in) offset of the crop row and adjacent to an actively growing potato plant. An installation jig was used to ensure that the sensors were installed identically in all experimental plots.

A site-specific irrigation decision support model was used to determine the irrigation requirement of each irrigation treatment in each experimental unit. The irrigation decision model used a conventional soil water balance in combination with estimated potato evapotranspiration (ET) to compute the minimum irrigation amount needed to maintain 65% available soil moisture (ASM) in the 41 cm (16 in) soil profile until the next scheduled irrigation. Potato ET was obtained from published regional values of daily crop evapotranspiration (USBR 2004). These daily ET values are computed based on climatic parameters from a network of weather stations using a modified Penman equation (Wright, 1982). For this study, potato ET was estimated using climatic data from a weather station located within 1.6 km (1 mile) of the field site. The soil water balance was used to account for actual potato ET being less that estimated potato ET due to site-specific factors. For example, assume estimated ET is 7 mm/day (0.28 in/day) or 14 mm (0.55 in) for two days until the next scheduled irrigation. Thus, without site-specific information on soil water content, the irrigation depth would need to be 14 mm. However, if soil water data shows that 9 mm (0.35 in) is available above the lower limit (65% ASM), then only 5 mm (0.2 in) needs to be applied to sustain 65% ASM until the next scheduled irrigation. Applying this soil water balance throughout the season allows irrigation to follow actual crop ET without actually knowing the value of crop ET while assuring that sufficient water is available until the next irrigation event. However, this approach requires soil water content measurements that are representative to true field conditions. If they are biased or incorrect, excess or deficit soil water conditions will prevail. Field capacity at each site was estimated based on soil sand and clay content and in-situ field capacity tests (Cassel and Nielsen, 1986) across the field site. Permanent wilting point was estimated based on soil sand and clay content (Rawls et al., 1982). Irrigation frequency was once or twice weekly at the beginning and end of the growing season and three times weekly from mid-June through mid-August.

In 2004, site-specific nitrogen management was coupled with site-specific water management using the independent chemical application system to apply in-season N based on the potato N management guideline of maintaining a minimum 15,000 mg/kg N concentration in potato petioles (Stark and Love, 2003). Petiole samples were collected in each experimental plot on Tuesday of each week. Based on the difference between N concentration in the petioles and 15,000 mg/kg, N application on Friday of the same week in the form of Urea Ammonium Nitrate was determined using the following algorithm: difference < -3,000 mg/kg, apply 40 lb N/ac; -3,000 < difference < 0 mg/kg, apply 30 lb N/ac; 0 < difference < 3000 mg/kg, apply 20 lb N/ac; 3000 mg/kg < difference, apply 0 lb N/ac. In-season site-specific N management was applied weekly over a six-week period from 28 June through 13 August. Conventional uniform N management was coupled with uniform water application with weekly N application computed as the average of the N applications determined for the experimental units under the uniform N management treatment using the same in-season N management algorithm.

Russet Burbank potato crops were planted on 9 May 2001,1 May 2002, and 6 May 2004 with a seed piece spacing of 30 cm (12 in) and row spacing of 91 cm (36 in). Fertilizer, herbicide and fungicide were applied following University of Idaho potato production guidelines (Stark and Love, 2003). Fertilizer (2001, 2002), herbicide, and fungicide applications through the irrigation system were done uniformly using the 3X application rate with a minimum amount of water application according to label recommendations. At harvest, tuber samples from three 9.1m (30 ft) sections of crop row from each experimental unit were collected on 5 Oct. 2001, 10 Oct. 2002, and 15 Oct. 2004. Tuber samples were weighed, sized and graded within 30 days of harvest. Specific gravity was determined with the standard weight-in-air/weight-in-water method using a sub sample of U.S. No. 1 grade tubers weighing 0.170 to 0.283 kg (6 to 10 oz).

RESULTS AND DISCUSSION

In 2001, the average seasonal irrigation depth for the SSIM treatment was 503 mm (19.8 in), which is essentially equivalent to the 500 mm (19.7 in) applied to the CUIM treatment. The minimum seasonal irrigation depth applied under the SSIM treatment was 437 mm (17.2 in) and the maximum depth was 597 mm (23.5 in). In 2002, the average seasonal irrigation depth for the SSIM treatment was 432 mm (17.0 in), which is slightly less (3%) than the 445 mm (17.5 in) applied to the CUIM treatment. The minimum seasonal irrigation depth applied under the SSIM treatment was 372 mm (14.6 in) and the maximum depth was 498 mm (19.6 in). In 2004 the average seasonal irrigation depth applied to the SSIM treatment was 384 mm (15.2 in), which was 8% less than the 416 mm (16.4 in) applied to the CUIM treatment. The minimum seasonal irrigation depth applied under the SSIM treatment was 331 mm (13.0 in) and the maximum was 452 mm (17.8 in). Over the three study years, the variation in seasonal irrigation depth under the SSIM treatment ranged from 82 to 119% of the average application depth, which is within the 61 to 120% range in optimal water application depth reported by Sadler et al. (2002) for corn over 12 soil map units in South Carolina

In 2004, average seasonal N application was 210 kg/ha (187 lb/ac) for the SSIM treatment and 216 kg/ha (193 lb/ac) for the CUIM treatment. The minimum seasonal N application under the SSIM treatment was 168 kg/ha (150 lb/ac) and the maximum was 247 kg/ha (220 lb/ac).

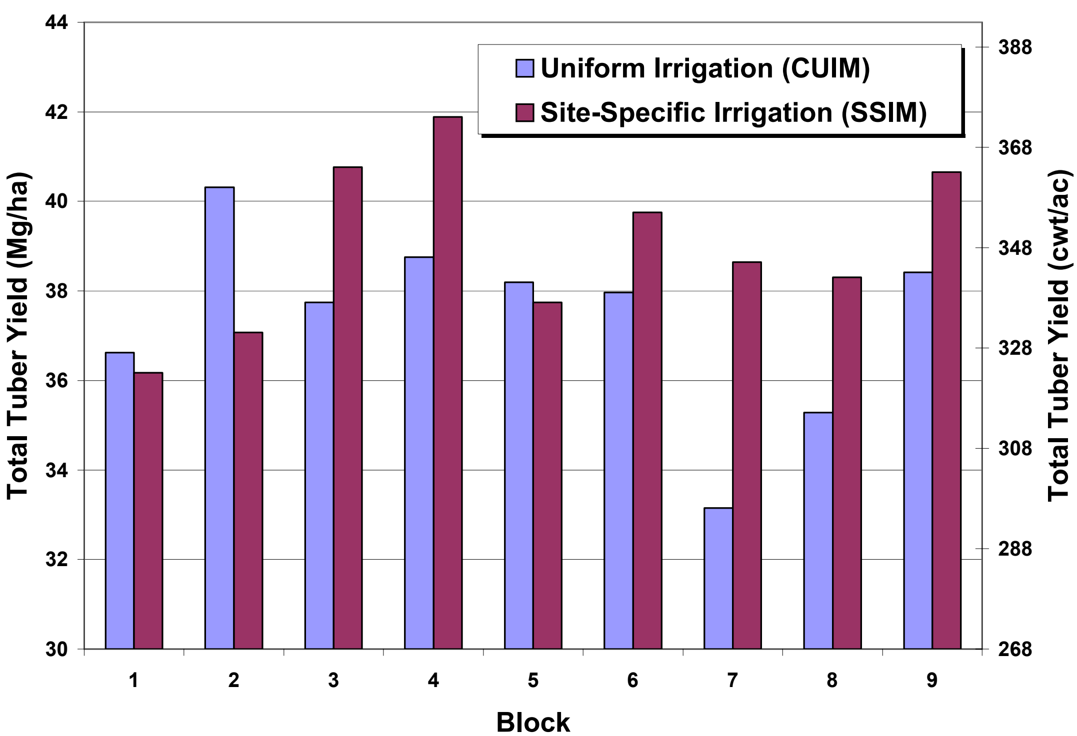

Fig. 1. Total tuber yields measured in each block of the 2001 field study.

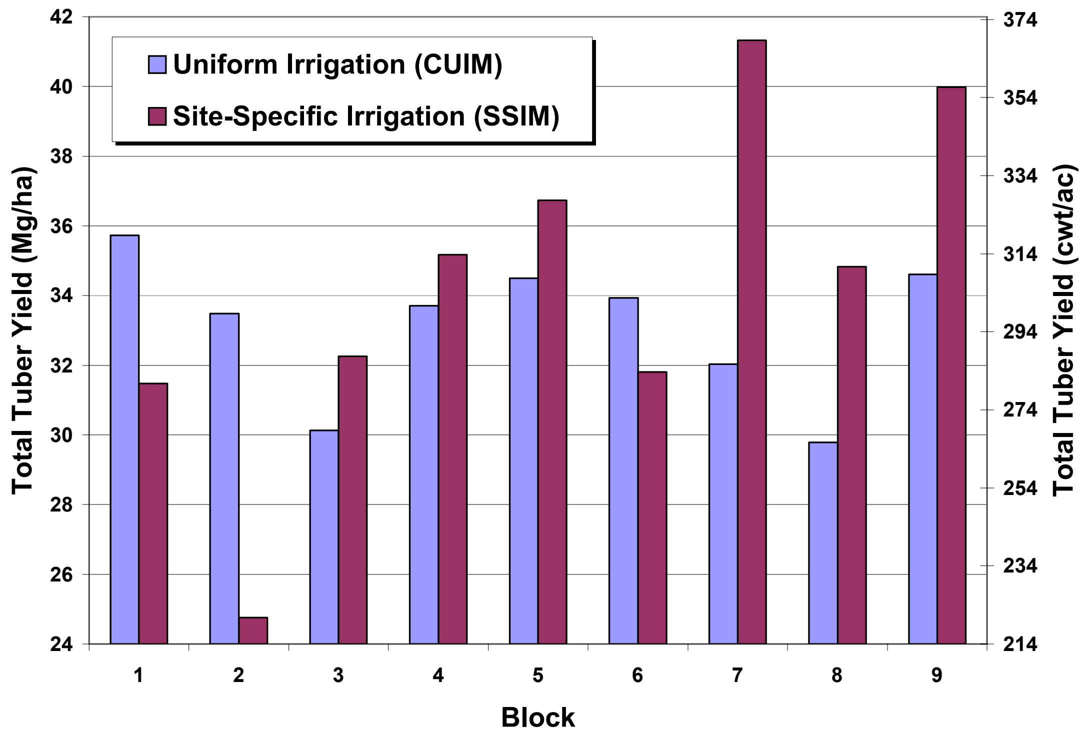

Fig. 2. Total tuber yields measured in each block of the 2002 field study.

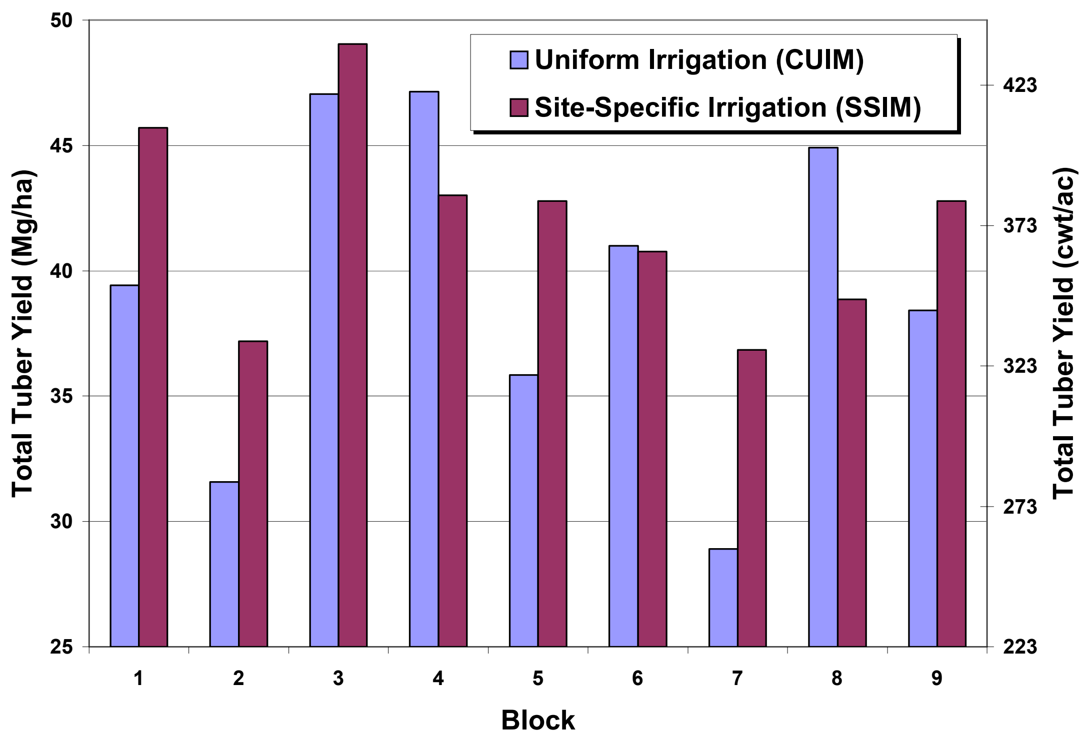

Fig. 3. Total tuber yields measured in each block of the 2004 field study.

Total tuber yields for both irrigation treatments for each block in 2001, 2002, and 2004 are shown in Figs. 1, 2 and 3, respectively. In 2001, total tuber yield was greater under the SSIM treatment in 6 of the 9 blocks. Only in block 2 was total tuber yield substantially greater under the CUIM treatment. Total tuber yield averaged across the field site was 37.4 Mg ha^{-1} (334 cwt ac^{-1}) for the CUIM treatment and 39.0 Mg ha^{-1} (348 cwt ac^{-1}) for the SSIM treatment. Total tuber yield was not significantly different between treatments at the 95% confidence level. In 2002, total tuber yield was again greater under the SSIM treatment in 6 of the 9 blocks. Total tuber yield averaged across the field site was 33.1 Mg/ha (296 cwt/ac) for the CUIM treatment and 34.3 Mg/ha (306 cwt/ac) for the SSIM treatment. However, again total tuber yield was not significantly different between treatments at the 95% confidence level. In 2004, total tuber yield was greater under the SSIM treatment in 6 of the 9 blocks. Total tuber yield averaged across the field site was 39.4 Mg/ha (351 cwt/ac) for the CUIM treatment and 41.0 Mg/ha (374 cwt/ac) for the SSIM treatment. Total tuber yield was not significantly different between treatments at the 95% confidence level.

Irrigation water use efficiency calculated as seasonal irrigation depth plus precipitation divided by total yield was 0.070 Mg/ha-mm (15.9 cwt/ac-in) and 0.073 Mg/ha-mm (16.6 cwt/ac-in) for CUIM and SSIM treatments, respectively in 2001. It was nearly equal in 2002 at 0.068 Mg/ha-mm (15.3 cwt/ac-in) and 0.071 Mg/ha-mm (16.2 cwt/ac-in) for CUIM and SSIM treatments, respectively. Irrigation water use efficiency was 0.082 Mg/ha-mm (18.6 cwt/ac-in) and 0.093 Mg/ha-mm (21.2 cwt/ac-in) for CUIM and SSIM treatments, respectively in 2004. Irrigation water use efficiency was not significantly different at the 95% confidence level in any study year. However, irrigation water use efficiency averaged over 2002 and 2003 study years trended 5% higher under the SSIM treatment and was 14% greater under the site-specific water and nitrogen treatment in 2004.

Computed gross income was calculated using a local tuber quality incentive based potato processing contract price structure. In 2001, gross income averaged across the field site was \$3690/ha (\$1494/ac) for the CUIM treatment and \$3856/ha (\$1561/ac) for the SSIM treatment, a non-significant trend difference of \$165/ha (\$67/ac) greater under SSIM. In 2002, gross income averaged across the field site was \$3283/ha (\$1329/ac) for the CUIM treatment and \$3435/ha (\$1391/ac)) for the SSIM treatment, a non-significant trend difference of \$152/ha (\$62/ac) greater under SSIM. While non-significant, demonstration of a trend showing an average increase in gross return of \$159/ha (\$65/ac) under the SSIM in the field experiment is encouraging. In 2004, gross income average across the field site was \$3544/ha (\$1435/ac) for the CUIM treatment and \$3867/ha (\$1566/ac) for a non-significant trend difference of \$324/ha (\$131/ac) in the one-year study.

SUMMARY AND CONCLUSIONS

Potato total tuber yield, gross income, and water use efficiency were increased under site-specific irrigation management relative to conventional uniform irrigation management for the study field site. However, total yield and water use efficiency were not significantly greater ($p \leq 0.05$) under site-specific irrigation management. Based on a local tuber quality adjusted potato processing contract price structure, the trend in gross income averaged across the field site for study years 2001 and 2002 was \$159/ha (\$65/ac) greater under site-specific irrigation management compared to conventional uniform irrigation management. In 2004, the non-significant trend in gross income averaged over the field site was \$324/ha (\$131/ac) greater under conjunctive site-specific water and in-season nitrogen management compared to conventional uniform water and nitrogen management. The non-significant trend in increased gross return and water use efficiency under site-specific irrigation management and conjunctive in-season nitrogen management is encouraging. Continued research and development is needed to reduce the capital and operational costs of site-specific irrigation and nitrogen management and better understand the factors leading to the development of spatially variable irrigation requirements in center pivot irrigated fields in order to realize a positive net return.

REFERENCES:

Cassel, D.K. and D.R. Nielsen. 1986. Chapter 36: Field capacity and water availability. In *Methods of Soil Analysis Part 1 – Physical and Mineralogical Methods*, 902-926. A. Klute, ed. Madison, WI.: ASA.

Evans, R.G., S. Han, M.W. Kroeger, and S.M. Schneider. 1996. Precision center pivot irrigation for efficient use of water and nitrogen. p. 75-84. *In*. P.C. Robert et al. (ed.) 3rd Int. Conf. on Precision Agriculture, Minneapolis, MN. 23-26 June 1996. ASA Madison, WI.

Fraisse, C.W., D.F. Heerman, and H.R. Duke. 1995. Simulation of variable water application with linear-move irrigation systems. Trans. ASAE 38(5):1371-1374.

Gee, G.W. and J.W. Bauder. 1986. Chapter 15: Field capacity and water availability. In *Methods of Soil Analysis Part 1 – Physical and Mineralogical Methods*, 383-409. A. Klute, ed. Madison, WI.: ASA.

Harting, G.B. 1999. As the pivot turns. Resource 6(4):13-14.

King, B.A. and J.C. Stark. 2003. Potato irrigation management. p. 285-307. *In.* J.C. Stark and S.L. Love (ed.) Potato production systems. Univ. of Idaho Cooperative Extension, Moscow, Idaho.

King, B.A., J.C. Stark, I.R. McCann, and D.T. Westermann. 1996. Spatially varied nitrogen application through a center pivot irrigation system. p. 85-94. *In*. P.C. Robert et al. (ed.) 3rd Int. Conf. on Precision Agriculture, Minneapolis, MN. 23-26 June 1996. ASA Madison, WI.

King, B.A., R.W. Wall, and L.R. Wall. 2000. Supervisory control and data acquisition system for closed-loop center pivot irrigation. ASAE Paper 00-2020. ASAE St. Joseph, MI.

Oliveiria, C., R. Yoder, and J. Larson. 2004. Evaluating the returns to site-specific irrigation. In *Proc. 7th International Conf. on Precision Agriculture*, eds. P. C. Robert, R. H. Rust, and W. E. Larson, In press. Madison, Wis.: ASA.

Perry, C., S. Pocknee and O. Hansen. 2003. Variable-rate irrigation. Resource 10(1): 11-12.

Rawls, W.J., D.L. Brakensiek and K.E. Saxton. 1982. Estimation of soil water properties. *Transactions of the ASAE* 25:1316-1320.

Sadler, E.J., C.R. Camp, D.E. Evans, and J.A. Millen. 2002. Spatial variation of corn response to irrigation. Trans. ASAE 45(5):1869-1881.

Sadler, E.J., C.R. Camp, D.E. Evans, and L.J. Ursey. 1996. A site-specific center pivot irrigation system for highly-variable coastal plain soils. p. 827-834. *In*. P.C. Robert et al. (ed.) 3rd Int. Conf. on Precision Agriculture, Minneapolis, MN. 23-26 June 1996. ASA Madison, WI.

Stark, J.C. and S.L. Love. 2003. Potato production systems. University of Idaho Extension, Moscow, ID.

USBR. 2004. AGRIMET: The Pacific Northwest cooperative agricultural weather network. Available at: www.usbr.gov/pn/agrimet/. Accessed 5 September 2004.

Watkins, K.B., Yao-Chi Lu, and Wen-Yuan Huang. 2002. A case study of economic and environmental impact of variable rate nitrogen and water application. Agricultural Engineering Journal 11(4):173-185.

Wright, J.L. 1982. New evapotranspiration crop coefficients. *J. Irrigation and Drainage Div. ASCE* 108(IR2):57-74.

Wright, J.L. and J.C. Stark. 1990. Potato. In: B.A. Stewart, D.R. Nielsen (eds.). Irrigation of Agricultural Crops. Monograph No. 30. American Society of Agronomy, Madison, WI, pp. 859-888.

Abstract #1242

Managing the Art and Science of Agricultural Irrigation Scheduling.

El Dorado Irrigation District (EID) is a water utility serving the nearly 100,000 residents in northern California's El Dorado County. A scenic drive along Highway 50 heading east from the Sacramento County line to South Lake Tahoe, takes you through the heart of EID's service area and gives you an overview of the extraordinary geographic diversity of the region.

EID was formally organized in 1925 under California's Irrigation District Law (Water Code §§ 20500 et seq.). EID hold water rights that date back to the gold rush days, and continue to work on securing and maintaining a reliable water supply to meet the growing needs of our customers. Through negotiations with the U.S. Bureau of Reclamation, EID acquired Jenkinson Lake at Sly Park in late 2003. The district has water service contracts with the Bureau and a water right for diversion from Folsom Reservoir that was awarded in 2001 by the State Water Resources Control Board. And EID's recycled water, agriculture irrigation management and water efficiency programs help our customers conserve water and thus contribute to the overall water supply.

Today, EID's facilities and delivery infrastructure for drinking water include 1,200 miles of pipeline, 40 miles of ditches, 6 treatment plants, 33 storage reservoirs and 21 pumping stations. The wastewater treatment system operates 58 lift stations, 300 miles of pipeline and 5 treatment facilities. The El Dorado Hills and Deer Creek wastewater treatment plants produce 2,500 acre-feet of recycled water each year — water that is used to irrigate front and back yards at 1,700 homes as well as commercial and public landscapes. EID estimate these numbers will more than double in the coming decade.

EID customer needs are as broad ranging as the area's diversity. The district provides drinking water for homes, schools and businesses and recycled water from wastewater treatment plants to irrigate front and backyards and public landscapes. EID operate a hydroelectric power project that includes dams, reservoirs and 23 miles of flumes, canals, siphons and tunnels. Further, EID owns and manage several outdoor recreation sites, including Sly Park Recreation Area near Pollock Pines and a 48-unit campground at Silver Lake. In all EID does, the district strive to meet or exceed federal and state standards for water quality, environmental protection and wildlife habitat.

EID's agricultural customers farm over 3,500 acres. Topography limits the size of the commercial planting which range in size from 0.25 acres to over 25 acres. Nearly all of the holdings are family managed ventures. The Apple Hill Growers Association is located in the middle of the EID. Commodities grown in the area include, but not limited to, citrus, avocadoes, stone fruit, pome fruit, hay, grapes and Christmas trees. Irrigation water requirements for the various commodities range from 48 inches per acre for peaches grown at low elevation on south slopes to 6 inches for Christmas trees grown at higher elevation on north slopes.

California experienced a severe drought in 1976 and 1977. Nearly one half of Jenkinson Lake's holding capacity was consumed during the summer of 1976. As a result the United States Bureau of Reclamation (USBR) required EID to implement a water conservation program. Thus the EID Irrigation Management Service (IMS) was developed.

The IMS program (the first of its kind in California) was developed through a collaboration that included EID, USBR, University of California, Davis, Soil Conservation Service, UC Cooperative Extension, El Dorado County Farm Advisor Office and Grower Associations. The IMS program was developed to answer the questions "How often do I irrigate" and "How much water do I apply." To answer these questions the three basic functions of the program were determined to be: 1) Sprinkler evaluations to determine the time required to replace depleted water, 2) Determine the amount of water required to refill the soil profile at any time and 3) Provide irrigation scheduling.

In 1977 a study was initiated to determine the growing practices and needs for commercial agriculture customers found within the EID service district. Three growing seasons were spent determining the evapotranspiration (ET) rates of all commodities, cover crop practices and evaluating irrigation systems. From these studies a multiple commodity irrigation scheduling program was developed to achieve more crop per drop.

In 1984 a report was filed with the California Department of Water Resources. This report documented the annual conservation of >2,000 acre feet of water through the IMS program. The report further showed that the irrigation efficiency went from 50% to over 80% and the average irrigation dropped from 6 inches to 4 inches. Overall the IMS program saved 2 irrigations per growing season. In addition the growers noticed the reduction or absence of tail waters as well as the disappearance of a few springs.

Irrigation scheduling in the Sierra Nevada Foothill is very complex problem. This is due to multiple microclimates, soil types, irrigation techniques and commodities. Multiple microclimates are the result of slope, exposure, elevation and wind patterns. An example of this is seen in the precipitation amounts which range from 25 inches per year at the west edge of the county to over 50 inches per year near Pollock Pines. This requires site specific ET rates to be developed from weather information and site specific crop curves.

Commercial crops are currently being grown on 38 soils types as classified by the Soil Conservation Service for El Dorado County. This results in different field capacities and refill points. This combination produces different Allowable Depletion for the various commodities. Therefore a site specific Managed Allowable Depletions (MAD) is required.

Irrigation techniques used are as varied as the growers using them. Practices include overhead (200 gallons per hour, gph), undertree, portable, microspray and drip (<1 gph). In addition practices change over time as new techniques are developed. This requires site specific sprinkler evaluations to allow run time predictions to achieve refill.

Further crop management goals must be known to help the grower achieve the quality of fruit required for his buyer. At the initial stages of the IMS program most of the crops were pome fruits (apples and pears) with a constant MAD through the growing season. Since then the growers have diversified to include stone fruits, nut crops, blueberries, nursery stock and wine grapes. Current practices for wine grapes include deficit irrigation to improve quality. Deficit irrigation practices require changes in the MAD depending on the development stage of the berry. The result is changes in the run times for the predicted irrigation events.

Initially there were over 90 growers participating in the program with over 300 sites being monitored on a weekly basis. It was determined that the only way to handle all of the data was to make this program effect was to utilize a computer program Initially the WMC (Water Management and Conservation) computer program from USBR was used for the irrigation scheduling prediction. The program was contained on two 5.25" floppy and run on an Apple IIE computer. Weather data had to be entered as well as the weekly water depletion. The program was limited to predicting the water depletion for the next two weeks. This program was used effectively for over 20 years.

EID determined that the prediction software needed to be updated before the start of the 2005 growing season. A survey of the current software revealed that all of the programs could meet only part of the IMS needs. TruePoint Solutions was contracted to produce new prediction software to meet EID's needs. Within two months EID went live with True Irrigation Scheduling Management (TrueISM).

The goal for TrueISM is to promote and advance effective agricultural water management. The program was developed to provide the mechanics of scientific irrigation management in a straightforward and easy to use package. TrueISM is deployed on the service oriented architecture platform utilizing the most current .NET technology that delivers interoperability, scalability and flexibility.

Initially site specific crop curve and sprinkler efficiency are entered into the program. Weekly soil moisture levels are entered into the program. The program then utilizes a variety of data collected from weather stations, tensiometer, neutron probes and individual site details (crop type, soil type, etc) to measure the soil-water content and predict irrigation schedules. The program will generate irrigation reports that can be automatically sent to the participating growers. The report contains site specific information (historical weather, predicted ET, soil-moisture inspections, irrigation events and irrigation schedules) for each site that the grower is monitoring.

A majority of the TrueISM functions are automated which reduces the amount of time need to update the program. This includes daily weather station data. The weather data can be viewed in either a tabular form or a graph form. In addition, the weather data is color coded to quickly identify any quality control flags associated with the data. The EID program is utilizing data from Station #13 of the California Irrigation Management Information System (CIMIS) to provide daily ET calculations. With this data the program automatically updates the prediction schedule. Currently all of the predicted irrigation events are calculated through the 2016 growing season.

TrueISM stores an unlimited amount of irrigation history that can be used for historical trending and analysis. This historical data will help EID plan water needs for the future years. This data can then be used for drought year(s) irrigation needs and potential water sales to other utilities during wet abundance.

Currently there are 91 growers with 291 sites participating in the IMS program and TrueISM has greatly increased the effectiveness and efficiency of the program. Initially the IMS program was developed as a water conservation program, but it has matured into irrigation water efficiency program. The implementation of the TrueISM program will assist EID to increase the efficiency of irrigation management to everyone's benefit.

Practical and Effective Water Use Efficiency Measurement and Management Methods for the Australian Cotton Industry

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Irrigation consultants and the National Centre for Engineering in Agriculture at the University of Southern Queensland have been working with Australian Irrigated Cotton Growers to improve their water use efficiency. This collaboration has seen the development of a collection of revolutionary techniques which have taken the theories behind evaporation and seepage and allowed for the practical measurement and mitigation of these losses for both commercial and environmental benefits. Main areas of work have included a farm water balance that can at any time in the season separate out how much water has been used in each area of the farm. Secondly consultants have been using surface simulation modeling to make irrigation performance precise and a highly accurate depth sensor coupled with weather data to partition evaporation and seepage losses throughout the system. This technique is also used to measure the effectiveness of various innovative mitigation strategies including damcovers and monolayers.

Using water auditing to assess irrigation efficiency: a comparative assessment of trickle, sprinkler and rain-guns for potato production in the UK

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Abstract

In the UK, supplemental irrigation is an essential component in the production of high value crops, such as potatoes, where continuous and reliable supplies of premium quality produce are demanded by the major supermarkets. However, the rising demand for water is exerting acute pressure on water supplies with many river basins (catchments) now considered to be over-licensed and/or over-abstracted. Promoting efficient use of water has become a major priority for the government and the regulatory authority responsible for water resource planning and allocation.

New legislation in England and Wales requires irrigators to demonstrate efficient use as part of renewing their water abstraction licence (permit). As a result, defining and measuring irrigation efficiency is the subject of national debate within and between the irrigation industry and water regulatory authority. This paper describes the role of water auditing as a tool for assessing the financial benefits (value) of irrigation water as a surrogate for quantifying irrigation efficiency.

Using selected farm sites, an analysis of water use, crop productivity and irrigation costs and benefits for three contrasting systems (trickle, sprinkler and rain-guns) has been completed. The study focuses on potatoes, the most important irrigated crop in the UK. A brief description of the rationale, methodological approaches and implications of the research are outlined.

Keywords: auditing; efficiency; irrigation; potato; rain-gun; sprinkler; trickle.

1. Introduction

Internationally, the rising demand for water, most notably for irrigated agriculture, is exerting acute pressure on water resources. This supply-demand imbalance is unsustainable, particularly if targets for environmental protection are to be achieved. As a consequence, there is an increasing scarcity in freshwater supplies, not only in arid and drought prone areas of the world, but also in more temperate climates where rainfall is abundant. A typical example is in England and Wales, where recent droughts have highlighted the fragile balance that exists between the needs of the water environment and those of abstractors (e.g. Gowing and Ejieji, 2001). Although irrigation is supplemental to rainfall, it is essential for the production of high value crops, such as potatoes, where continuous and reliable supplies of premium quality are demanded by the major processors and supermarkets. As a consequence, the demand for irrigation water in England and Wales is rising steadily, at an underlying rate of 3% per annum (Weatherhead and Knox, 1999). This has contributed to a situation that is considered environmentally unsustainable in many catchments (EA, 2001).

The European Water Framework Directive (2000/60/EC) requires Member States to establish controls over the abstraction (withdrawal) of fresh surface and groundwater, including a register of water abstractions. Almost all water abstractions in England and Wales therefore require an abstraction licence (permit) from the regulatory authority, the Environment Agency (EA). There are currently about 48000 licences in force of which approximately a quarter are for irrigation. Historically, licenses were issued on a first-come first-served basis and allocated in perpetuity (Weatherhead *et al*., 1997). However, all new licenses are now time-limited and subject to renewal conditions. The seasonal volume of water allocated on a new licence now reflects the water required by the farmer in a 'design' dry year, equivalent to the 80% probability of non-exceedance, that is meeting demand in 80 years in 100 (Knox *et al*., 2005). In addition to this seasonal restriction, conditions in a licence can restrict peak rates of water use (e.g. daily, monthly), particularly where an abstraction is from environmentally sensitive water source.

As part of a broader project investigating the role of irrigation water auditing and benchmarking, this paper reports on a study that combines fieldwork (water metering and hydraulic performance assessment) with computer analyses (agronomic and economic) to assess the relative "efficiency" of irrigation under three contrasting systems (trickle, sprinkler and travelling rain-gun). The study is focussed on potatoes, the most important irrigated crop in the UK. A brief overview of potato irrigation in the UK is provided. The research approaches, fieldwork and proposed cost-benefit analyses are then described.

At the time of writing this paper (September 2005) the irrigation season was still underway; the final results from the study are not therefore included here but will be presented at the 2005 US Irrigation Association Conference and made available on the author's website.

2. Potato irrigation in the UK

Irrigation accounts for less than 2% of total water abstraction in England and Wales, but can nevertheless be environmentally damaging, because it is a consumptive use, concentrated in the driest catchments and in the driest months. During peak periods it can account for up to 70% of total abstraction in intensively irrigated areas. It is mostly used for the production of high value vegetables and potatoes (Knox *et al.*, 1996). Nationally, in 2001, potatoes accounted for 52% of the total irrigated area and 58% of the total volume of water applied (Weatherhead and Danert, 2002). For many farm businesses, irrigation of potatoes is the economic driving force behind investment in irrigation. The main financial benefits of irrigation relate to the value of extra yield and improved quality, less any additional production costs. In the UK, it is often the quality assurance benefits of irrigation that are most significant. These are gained on the whole crop, not just the extra yield from irrigation. In general, the extra net margin per m^3 of water applied is highest for soft fruit (e.g. strawberries), vegetables, potatoes and orchard fruit, and lowest for grass, cereals and sugar beet. For potatoes, irrigation is crucial to minimise skin quality problems caused by common scab (*Streptomyces scabies*). Optimising size, shape and skin finish are also important criteria in irrigation management. Indeed, quality criteria are specified as a condition of producer contracts and supermarket grower protocols. Failure to meet these quality standards often leads to large price reductions and possibly rejection.

Most UK potato irrigation relies on hose-reel systems (travelling guns). These are acknowledged to be inaccurate and inefficient in water and energy use. However, they are robust, versatile, and fit well into typical UK mechanised arable farms (Weatherhead *et al*., 1997), particularly where irrigation has to follow the crop rotation around the farm, often with non-standard field sizes (typically irrigated potatoes are grown in a rotation including non-irrigated cereal crops). However, changes in technology choice are being driven by industry and regulatory pressures for more accurate and efficient irrigation particularly since water is becoming scarce and highly valued. As a consequence, there has been significant growth in the use of trickle irrigation, helped by product improvements and a reduction in the cost of disposable drip tape. In 2003 there were estimated to be 2500 ha of potatoes under trickle irrigation in England and Wales (Knox and Weatherhead, 2005), although this area is small compared to the national total irrigated area (approximately 150,000 ha). Farmer experiences with trickle on potatoes have been mixed, with many finding that their soil conditions make it difficult to achieve sufficient lateral soil wetting, particularly on beds in sandy soils. Many have subsequently reverted back to overhead systems, choosing hose reels fitted with booms in preference to rain-guns. Some are trialling the use of solid set micro-sprinkler systems, which are an economic alternative where frequent applications are required, and well suited to small areas or irregular shape fields that are difficult for mechanized systems.

3. Methodology

In this project, a comparative assessment of water use under trickle, sprinkler and hose-reel (rain-gun) irrigation has been conducted at contrasting agroclimatic sites across the UK. The sites were located on commercial farms involved in the production of high value maincrop potatoes. In summary, the pattern of water use at each site was monitored during the 2005 irrigation season (April to September). The water audit data were then combined with information relating to crop production (yield, prices, labour and management costs) and irrigation (capital (equipment) and operating (energy, labour, water) costs) to assess irrigation water use efficiency (t ha^{-1} mm^{-1}) and the marginal value of water (£/m^3) for each irrigation system. The study involved three main components:

1. An audit of water use under each irrigation system (trickle, permanent set sprinklers, hose-reel fitted with rain gun) during the season;

2. A comparative assessment of the in-field performance of each irrigation system, and;

3. An evaluation of the financial costs and benefits associated with crop production under each irrigation system. This involved a comparison of crop water use and productivity for each irrigated crop against an equivalent non-irrigated (rain-fed) potato crop.

A brief description of each stage is given below:

3.1 Irrigation water audit

The purpose of the water audit was to record the date of each irrigation event, the scheduled depth (mm) of water applied and the volume (m^3) of water diverted (pumped) to each field site during the course of the irrigation season. Water meters were installed at the field hydrant in each field site. A reading was taken at the start and end of each irrigation event. Each farmer was provided with a water audit proforma to record the necessary information. A weather station was used to record local weather data, mainly rainfall and the parameters required to derive reference evapotranspiration (ETo) at each site. A Sentek EnviroSCAN™ was used to monitor changes in soil moisture within the field sites during the season, to assess the relative impact of the timing and frequency of each irrigation event on soil moisture deficits.

Using information relating to local soil, climate and cropping practices (husbandry), the actual irrigation applications (depths of water applied) during the season were compared against simulated applications using an irrigation scheduling water balance model, and assuming the farmer was following best management practice for irrigation scheduling.. The model (Hess, 1996), estimates the daily soil water balance for the potato crop and local soil type, working from daily rainfall and reference evapotranspiration (ETo) data. The model outputs information on the crop water use, the amounts of irrigation water applied and the proportional yield loss due to any water stress. This provides a useful comparison between the theoretical irrigation water requirements (mm) against the actual irrigation applications.

3.2 Irrigation system performance (uniformity)

In addition to measuring water use, it is also important to consider how uniformly the water is distributed across a crop. Non-uniform application inevitably leads to over or under-irrigation in some parts of the field, leading to inadequate or inefficient irrigation, resulting in uneven yield and quality. For the trickle irrigated field site, a hydraulic evaluation was undertaken based on a methodology defined by the American Society of Agricultural Engineers (ASAE, 1999) to evaluate micro-irrigation systems. This included an assessment of irrigation uniformity within selected irrigation blocks, using mini catch-cans to collect the discharge from a series of randomly selected emitters, evaluation of the uniformity along a complete lateral and measurement of pressure variations within the block (header, midpoint and tail-end). For the sprinkler and hose-reel irrigation systems, a procedure defined by ISO (1990) was followed, using catchcans between static sprinklers and across gun travel lanes. Two uniformity indicators were calculated, namely the Christiansen (1941) coefficient of uniformity (CU) and the distribution uniformity (DU) defined as the ratio between the average depth in the lowest quartile and the overall average.

3.3 Irrigation cost-benefit and irrigation water use efficiency

Farmers are generally most interested in maximising their economic returns. Where water is the scarce (limiting) resource, these should be maximised per unit of water applied (£/m^3). The irrigation cost-benefit analysis was based on a methodology developed by Morris *et al*. (1997), but updated for current prices. A comparison of irrigation benefits less costs (expressed as £/m^3 of irrigation water applied) provides the farmer and water regulator with indicative values of water for that enterprise, and hence best economic use. This is probably the most rational indicator to compare different uses of water from an economic viewpoint. The efficiencies of irrigation management and equipment are implicitly included in the appraisal of the value of water. This approach also enables a comparison of the value of water between different crops (e.g. potatoes, strawberries) and sectors to be undertaken (e.g. horticulture versus sports-turf irrigation).

For each crop, the irrigation water use efficiency (IWUE, tonnes per hectare per mm of water, t ha^{-1} mm^{-1}) was also estimated. This is defined as the ratio between the additional crop produced and the irrigation water applied. IWUE is considered one of a useful range of measures to evaluate irrigation system performance (Ayars *et al*., 1999). However, IWUE ignores the role that irrigation plays in attaining premium crop quality, which is particularly important under supplemental irrigation conditions such as in the UK. Price differentials of circa 30% between premium grade potatoes for the pre-pack markets and processing potatoes illustrates the financial benefit of irrigating for quality. Nevertheless, IWUE can be a useful indicator to compare irrigation productivity between individual irrigation systems, assuming they are all scheduled correctly.

In order to estimate the marginal value of water and IWUE for each crop at each site, information on a range of parameters were collected (Table 1).

Table 1. Components of crop production used to assess the performance of each irrigation system.

Indicator	**Description and units of measurement**
Crop husbandry and production	Cropped areas (ha). Crop configuration (planting depth, ridge spacing, plant spacing) Crop growth (planting, establishment and harvest dates) Other costs of production (e.g. fertilizer application) Farm labour inputs for irrigation management (hours) Yields (t/ha) for irrigated and un-irrigated crops. Crop prices (£/t).
Irrigation system and water use	Irrigation system design and capital cost (£/ha) Annualised in-field costs (£/ha/year) for each system, comprising the capital costs amortised over their estimated useful lives, together with estimated in-field running costs (i.e. labour, fuel, water and repairs). Water sources, costs and volumes abstracted (m^3)

4. Results

Unfortunately, at the time of preparation of this paper (September 2005) the irrigation season was still underway. A complete set of results cannot therefore be produced. The results will be presented at the US Irrigation Association Conference (November 2005) and reported on the authors website and in a scientific irrigation journal in due course.

5. Discussion

A brief discussion of the rationale for evaluating irrigation efficiency and the implications for improving water resource management is given below.

In many countries where water resources are under pressure, improving irrigation efficiency has become the main objective of irrigated agricultural production. In the UK, rising demands for water, increased competition between sectors and the longer-term threat of climate change are also highlighting the limitations on available supplies for irrigation. Improving irrigation efficiency has therefore become the focus of significant industry and regulatory attention. However, despite broad acceptance of the overall concepts of making best use of water, improving crop productivity and obtaining more crop per drop, the term "irrigation efficiency" has been very loosely used, often without clear definition, including in the new Water Act (2003). Clarifying its interpretation has become particularly important since new water regulation came into force whereby abstractors may have to demonstrate "efficiency" at licence (water permit) renewal. Whilst this might sound straightforward in practice, there is currently widespread confusion due to the many definitions of "efficiency".

In order to compare irrigation systems, a range of indicators that provide an assessment of performance has been widely used internationally. These have generally been termed *efficiencies,* for intuitive appeal (Burt *et al*., 1997). Unfortunately, in many cases, the same term *irrigation efficiency* has been used, but each time assuming a slightly different technical definition. This has led to widespread confusion. To exacerbate the problem, another criterion, *irrigation uniformity*, has also been widely used; in many cases the terms have been used interchangeably without recognising their fundamental differences (Burt *et al*., 1997). A seminal paper by the on–farm irrigation committee of the American Society of Civil Engineers (ASCE, 1978) defined *irrigation efficiency* as the ratio of the average depth (or volume) of irrigation water which is beneficially used, to the average depth (or volume) of irrigation water applied. But estimating irrigation efficiency is not straightforward. It requires a detailed consideration of the various hydrological inputs and outputs through an irrigation water balance, clear definition of the study area boundaries (e.g. field, farm or catchment) and quantification of the fate of the various fractions of the irrigation water that is applied. Failure to define these scale and boundary issues has led to problems in comparing efficiency values for different systems (Clemmens and Burt, 1997). Furthermore, efficient systems by some definitions can be very poor performers by other definitions (Rogers *et al*., 1997). Use of the term efficiency to assess individual systems and to set benchmarks for comparison between different methods is therefore likely to be misleading. Indeed, its misuse has been noted to occur most often when adopted as synonymous of irrigation performance (Pereira *et al*., 2002).

Whilst there is a significant volume of published research that deals with the efficiency of individual irrigation systems for a wide range of crops, there is very little published information on studies that specifically compare trickle with rain-gun irrigation on crops under UK weather conditions (low evapotranspiration and significant rainfall). Most studies identified relate to the USA and for crops not grown in the UK (e.g. cotton, sorghum). Many of the papers focussed on comparing trickle with either sprinklers or more usually surface (furrow) irrigation. This reflects the dominance of surface irrigation internationally. The findings confirm that the levels of efficiency attained in practice depend more on the suitability of that crop to a particular irrigation method rather than the method of application *per se*.

In the UK, trickle irrigation has been widely described as being more efficient. On this basis there have been suggestions that the government should encourage or even require irrigators to use trickle irrigation, and/or should exempt trickle from abstraction licensing. For this reason, trickle irrigation is being heavily promoted, often by regulators and governments as well as the trickle industry. Compared to traditional surface or overhead methods, trickle irrigation offers the potential for greater water use efficiency and has often been reported to produce crops of higher yield and quality (Knox and Weatherhead, 2003). Despite its higher costs, these characteristics make trickle an attractive option in regions where irrigation water resources are scarce and/or expensive. Our initial findings confirm that trickle irrigation is potentially more efficient than overhead irrigation. However, in practice its *actual* efficiency depends as much on the level of on-farm water management being practised and on the crop being grown. Another problem interpreting on-farm trial data is in distinguishing between water savings directly due to the use of trickle irrigation, from that due to better scheduling and more intense management. Whether water savings will persist once a trial is less closely monitored is unknown.

A number of field-scale farm trials using trickle on potato crops have been undertaken in the UK. None were scientifically replicated or fully instrumented, but they usefully identified field-scale issues and problems. None reported on direct water savings or increased irrigation efficiencies attributable to trickle. A major problem in interpreting findings from all trials is in distinguishing between any water savings (efficiencies) arising directly due to the use of trickle irrigation, and those due to better scheduling and more intense management during the trial. Although figures of 90% efficiency are often quoted from research and demonstration plots, the *actual* efficiency of trickle under field conditions as evidenced in this study suggest the values significantly below this figure, depending on the level of on-farm water conservation being practised.

A number of farm trials have also been reported in Australia where trickle has been compared against other irrigation methods for use on various crops including potatoes, tomatoes and cotton. For potatoes, farmer experiences are broadly similar to those experienced by many UK growers. Greater responses to irrigation have been shown giving improved water use efficiency as well as crop quality benefits. However, few of the studies have reported direct water savings attributable to trickle. On one comparative study of trickle on tomatoes, it was reported that it was the skills of the grower that had the most impact on yield and water use efficiency. Whilst some crops have shown spectacular increases in yield when irrigated using trickle, this does not seem to be the case for potatoes; yields appear to be similar to those from fully irrigated sprinkler plots. However, there is evidence of increase in yield and quality when compared to hose-reel-gun irrigation, probably related to poor uniformity and inadequate irrigation under the hose-reel (Weatherhead *et al*., 1997).

Finally, there are policy implications for promoting water efficiency. Water can generate very high financial returns where supplementary irrigation assures first class quality high value crops. The profitability of irrigation depends considerably on the price differentials offered for quality produce in the market. In situations where water is limiting and returns per m^3 of water are high, as they are in the case of potatoes, previous research (Morris *et al*., 2003) suggests rationing water through increased water prices could have a major impact on farm incomes before it substantially changes water use behaviour. In such situations restrictions on abstraction licences may be a more effective and equitable mechanism to achieve beneficial change. Some increase in abstraction charges, however, could help fund water resource management initiatives by the regulatory agency. For example, further research into the impacts of irrigation non-uniformity on crop yield and quality and the development of precision irrigation application systems to increase water use efficiency, constitute two areas that might help to deliver additional improvements in efficiency and water savings.

6. Conclusions

Water auditing studies have been undertaken to compare and assess the water use efficiency and value of water under contrasting irrigation systems (overhead and trickle). The research is helping to improve levels of understanding of irrigation system performance for the industry and water regulator. Clearly, if meaningful comparisons between different irrigation systems (e.g. trickle versus sprinkler) are be made, it is essential that those who undertake such work and the stakeholders for whom the results will be relevant (e.g. government, regulatory authorities, irrigation industry and farmers) understand and agree from the outset the various definitions and their appropriateness. This will enable more rational assessments of actual farm irrigation practices to be made and referenced against recognised industry and government benchmarks.

The study so far has confirmed there are practical difficulties in assessing application efficiency, and risks in using it as an indicator of best use. If efficiency assessments are required legally for abstraction licensing control, then it is suggested they should be more closely related to the marginal IWUE and/or the economic benefits (value) of the water being used. However, these definitions can themselves become subjective in defining costs and benefits, and still omit non-economic issues, such as rural development and fairness.

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8. References

ASCE (1978). Describing irrigation efficiency and uniformity. *Journal of the Irrigation and Drainage Division* 104 (IR1):35-41.

ASAE (1999). Field evaluation of mirco-irrigation systems. ASAE EP458 December 1999. American Society of Agricultural Engineers.

Burt, C.M., Clemmens, A.J., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardy, L.A., Howell, T.A., and Eisenhauer, D.E. (1997). Irrigation performance measures: efficiency and uniformity. *Journal of Irrigation and Drainage Engineering* 125(6):423-442.

Christiansen, J.E. (1941). The uniformity of application of water by sprinkler systems. *Agric Eng*. 22: 89-92.

Clemmens, A.J. and Burt, C.M. (1997). Accuracy of irrigation efficiency estimates. *Journal of Irrigation and Drainage Engineering* 123(6):443-453.

EA (2001). Water Resources for the future: A Strategy for England and Wales. Environment Agency. Bristol.

Gowing, J.W., and Ejieji, C.J. (2001). Real-time scheduling of supplemental irrigation for potatoes using a decision model and short-term weather forecasts. *Agricultural Water Management* 47: 137-153.

Hess, T.M. (1996). A microcomputer scheduling program for supplementary irrigation. Computers and Electronics in Agriculture 15: 233-43.

Knox, J.W., Weatherhead, E.K., and Bradley, R.I. (1996). Mapping the spatial distribution of volumetric irrigation water requirements for maincrop potatoes in England and Wales. *Agricultural Water Management* 31; 1-15.

Knox, J.W. and Weatherhead, E.K. (2003). Trickle Irrigation in England and Wales. Technical Report. Water Resources R&D Project W6-070/TR. Environment Agency.

Knox, J.W., Weatherhead, E.K., and Ioris, A.A.R. (2005). Allocation and control of water for irrigated agriculture in Scotland. *Water International*, *Journal of the International Water Resources Association* (in press).

Knox, J.W., and Weatherhead, E.K. (2005). The growth of trickle irrigation in England and Wales; data, regulation and water resource impacts. *Irrigation and Drainage* 54:135-143.

ISO (1990). Irrigation equipment – rotating sprinklers. Part 2: Uniformity of distribution and test methods. ISO 7749-2: 1990(E).

Morris, J., Weatherhead, E. K., Mills, J., Dunderdale, J.A.L., Hess, T.M., Gowing, D.J.G., Sanders, C.L., and Knox, J.W. (1997). Spray Irrigation Cost Benefit Study. Final Report to Environment Agency. Cranfield University.

Morris, J., Vasileiou, K., Weatherhead, E.K., Knox, J.W., and Leiva-Baron, F. (2003). The Sustainability of Irrigation in England and the Impact of Water Pricing and Regulation Policy Options. Proceedings: of International Conference in Advances in Water Supply Management, Imperial College, London, UK, 15 - 17 September.

Pereira, L.S., Oweis, T., and Zairi, A. (2002). Irrigation management under water scarcity. *Agricultural Water Management* 57: 175-206.

Rogers, D.H., Lamm, F.R., Alam, M., Trooien, T.P., Clark, G.A., Barnes, P.L., Mankin, K.(1997). Efficiencies and losses of irrigation systems. Irrigation Management Series. MF-2243. Kansas State University. Manhattten.

Weatherhead, E.K., Knox, J.W., Morris, J., Hess., Bradley, R.I., Sanders, C.L. (1997). Irrigation Demand and On-farm Water Conservation in England and Wales. Final Report to Ministry of Agriculture, Fisheries and Food. MAFF Project OC9219. Cranfield University, Bedford.

Weatherhead, E.K. and Knox, J.W. (1999). Predicting and mapping the future demand for irrigation water in England and Wales. *Agricultural Water Management* 43: 203-218.

Weatherhead, E.K. and Danert, K. (2002). 2001 Survey of Irrigation of Outdoor Crops in England. Cranfield University, Bedford.

The Use of Low-Cost, Differentially-Corrected GPS for Reporting Field Position of Self-Propelled Irrigation Systems[1].

R. Troy Peters[2], Dale F. Heermann[3], Kristine M. Stahl[3]

Abstract

Precision irrigation and chemigation using center pivots and lateral move systems requires precise knowledge of the field position of the moving irrigation system. This kind of precision is not possible with typical methods of reporting angular position of center pivots. Lateral move systems do not have a readily-available, low-cost method of reporting field position. The decreasing costs and increased precision of differentially corrected GPS receivers make them a possible solution to this problem. Low-cost GPS units were tested at stationary positions in Bushland Texas and in Fort Collins, Colorado. Tests on a moving center pivot were performed in Fort Collins. Outlying errors from the reported GPS positions can be mitigated by averaging the GPS positions. Two different averaging methods were evaluated and an algorithm for combining these averaging methods with dead reckoning for reporting real-time position using recent historical data is presented. Various time periods for averaging GPS points were evaluated. Averaging time periods from 10 to 30 minutes bring in the outlying errors sufficiently without having to apply dead reckoning across long times and distances. There was good agreement on the moving pivot between GPS calculated angular data when compared with measured reference points. The position estimates improved by averaging over greater time periods. Averaging GPS points to calculate angular velocity decreases the variability of velocity estimates. Averaging times of 5 to 10 minutes appeared adequate to give good estimates of angular velocity.

Introduction

Along with increased accuracy, the cost of differentially corrected GPS receivers has been decreasing, making possible their use in many additional applications. One such application includes precision farming where GPS systems are used to guide tractors, and collect position and yield data to create yield maps. There has been additional interest in using GPS technology for center-pivot or lateral-move positioning with precision or site-specific irrigation and/or chemigation.

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[1] Contribution from USDA-Agricultural Research Service, Conservation and Production Research, Bushland, TX and Water Management Research, Fort Collins, CO. The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation or exclusion by USDA – Agricultural Research Service.

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Most modern center pivots use either a resolver or an optical encoder located at the pivot point to report angular position. However, these are often subject to errors and can only report the position of the first tower from the center point. Since the pivot end tower on an electrical drive pivot typically moves much more frequently than the first tower and there may be a bow in the pivot alignment, the reported angular position of the first tower may not translate into an accurate representation of the position of the end tower. Other site-specific irrigation research has found errors in the pivot position angle reported by the control panel and identified correction algorithms to get accurate field positions (e.g. Sadler et al., 2002; Peters and Evett, 2005a). Though these position errors are not a cause for concern for most irrigators, accurate, real-time knowledge of pivot position is required for site-specific irrigation. A low cost GPS receiver mounted near the end of the pivot has the potential to provide a more accurate representation of the pivot's position (Peters and Evett, 2005a). Most lateral-move control systems do not have an accurate, low-cost mechanism for reporting field position. Heermann et al. (1997) discussed the position reporting alternatives and concluded that GPS was the most viable method for determining field position for lateral-move systems.

Heermann et al. (1997) investigated non-differentially corrected GPS positioning on a lateral-move irrigation system for site-specific irrigation work. They determined potential position with dead reckoning based on travel speed and known initial position. This was then corrected with an averaging algorithm applied to the GPS receiver reported positions. The demonstrated accuracy was within plus or minus 7 m. Kostrzewski et al. (2002) briefly described a lateral-move system with a differentially corrected GPS unit mounted on one end for reporting system position. In this experiment the position accuracy was described by fitting a regression curve to the measured points from a moving system and the variance from the regression was discussed. Reinke Manufacturing Inc. (Deshler, Nebraska) has applied for a patent (Barker, 2004) for a GPS control system for mechanized irrigation systems. GPS units are being tested on cornering systems (Robinson, 2003). Peters and Evett (2005a) investigated the accuracy of low-cost GPS units as applied to center pivots or lateral-move irrigation systems and found that significant improvement of angular position reporting was possible. The tested low-cost receiver was accurate to within 2.1 m 95% of the time. However, the remaining 5% of points had errors as large as 6.6 m (Peters and Evett; 2005a). Peters and Evett (2005b) also investigated the use of a second, similar GPS receiver in a known location (like the pivot center point) to correct for the errors of the moving receiver (mounted on the pivot end point) and discovered that there was very little correlation between the errors of the two receivers. Although GPS has much better accuracy than traditional methods of reporting field position of self-propelled irrigation systems, their application for center pivot or lateral move positioning is hindered by large outlying errors and the fact that the reported position tends to fluctuate in time. These errors can be mitigated by using average position locations instead of single, real-time-reported locations from the receiver. The objective of this research is to evaluate the effectiveness of averaging algorithms for controlling these outlying errors and to present methods of using averaged positions with dead reckoning for more precise position estimates of moving, self-propelled irrigation systems.

Materials and Methods

Bushland, TX Data Collection

A low-cost, differentially-corrected GPS receiver (Garmin 16HVS; Garmin International; Olathe, KS), was mounted past the end tower on a center pivot with a 127 m (417 ft) radius located at the Conservation and Production Research Laboratory of the USDA, Agricultural Research Service (ARS) in Bushland, Texas. The GPS receiver was wired into a Campbell Scientific datalogger (CR10X). The datalogger recorded data from the GPS output NMEA (National Marine Electronics Association) sentence ($GPGGA), which used the RS-232 protocol, every second and logged the one minute averages of the sensed location. The pivot was left in a stationary location for three different extended time periods of five days or greater on days of year (DOY) 194-199 (132 hours), 215-221 (131 hours), and 224-232 (183 hours). Since the sensors were not on a known benchmark, precision was calculated instead of accuracy and the relative position to the mean was evaluated.

The reported positions in longitude and latitude were translated into X-Y positions on a theoretical grid using a series of equations described by Carlson (1999). These equations used the WGS-84 (World Geodetic Survey 1984) reference datum to determine the earth's spheroid model. The average position of the receiver was set as the axis origin and the variations of the individual measurements from the mean were calculated. The pivot's known location is used with the reported end location to calculate the center pivot's angular position.

Fort Collins, CO Data Collection

A similar, low-cost, differentially-corrected GPS receiver (Garmin GPS 17N; Garmin International; Olathe, KS) was also mounted both at a stationary position and one foot beyond the center pivot end tower with radius of 79 m (260 ft) located at the Agricultural Engineering Research Center, Colorado State University, Fort Collins, Colorado. The data were collected on a laptop computer at three second intervals. The processing was similar to the procedure at Bushland above. A long term data set (approximately 68 hours) was collected at a stationary position. Data were also collected from the moving center pivot with the percent timer setting of 50 and 100%. Seven reference stakes were placed just outside of the outer tower and the times of the pivot passing each stake were recorded. The moving data were analyzed in terms of errors in both radius and angle of rotation. The angle, θ, is the only unknown since the radius is a constant when mounted on a pivot. However, since the radius is known, the error in measuring this length with the GPS provides an insight as to the accuracy expected when the pivot is stationary or moving.

Averaging Algorithms and Dead Reckoning

Peters and Evett (2005a; 2005b) and others have shown that although differentially corrected GPS is quite good at providing an accurate estimate of position, the observed large outlying errors are a cause for concern for applications in precision irrigation. It was hypothesized that averaging the reported positions over various time intervals could reduce these errors. Determining the real-time position using averaged sensed GPS positions on a moving center pivot requires a method of estimating the current position from past positions. Development of an algorithm combining dead reckoning and GPS measurements is possible.

Dead reckoning is defined as the use of a known beginning point, velocity and direction of travel to determine the ending location. When used on a pivot, the beginning reference position is the latest averaged GPS position. Average GPS positions can be determined in two ways. The first is to take the average position during specific time intervals such as between every five minute mark. This is termed a *time-period average*. The other is a *rolling average*. With a rolling average, all reported locations within a specified time interval are held in memory. Each new point is included in the average as it comes in and the oldest point is excluded such that the number of averaged points remains constant. Both methods (time-period, and rolling averages) can be taken over various time intervals. The time intervals of 3 seconds data, and 1, 5, 10, 30 and 60 minutes averages were tested to determine which would be most ideal for accurate center pivot position reporting. An advantage of rolling averages is that dead reckoning is applied across a time only half as long as the chosen time interval for averaging. For example if a rolling average was taken on a 60 minute time interval then dead reckoning must be applied from the average point forwards 30 minutes. However, with time-period averages dead reckoning must be applied across longer times from 0.5 to 1.5 times the averaging interval. For example if a 60 minute time interval is used then at the extreme, dead reckoning must be applied across a 90 minute time interval before the next 60 minute average is updated. Applying dead reckoning across longer times and distances may be an added source of uncertainty. Taking rolling averages has the distinct disadvantage, however, of requiring the retention of all of the data points and their order in memory so that the oldest point may be dropped when the newest point is included in the average. This may complicate programming and increase memory requirements considerably.

The other unknowns for dead reckoning are travel speed and direction. Pivot travel speed can be determined from the commonly known time that the pivot takes to make a complete 360 degree revolution (t_{rev}) at the 100% setting, or traveling as fast as possible. The travel speed in degrees/minute can be calculated using this time as:

$$\Delta\theta / \Delta t = \frac{Pcnt}{100} \bullet \frac{360}{t_{rev}} \qquad (1)$$

where $\Delta\theta/\Delta t$ is the travel speed in degrees per minute, and *Pcnt* is the pivot timer's percent setting which is available from the pivot's electronic control panel. This method of calculating $\Delta\theta/\Delta t$ will not be able to identify slippage or unplanned changes in velocity. $\Delta\theta/\Delta t$ can also be calculated using GPS data from the recent past. This is as simple as choosing a time interval (Δt) and measuring the change in angular position over this time interval ($\Delta\theta$) and calculating $\Delta\theta/\Delta t$. The analysis of error with different averaging times would provide an estimate of any changes in $\Delta\theta/\Delta t$ for calculating the angle θ.

Averaged GPS positions from a moving center pivot or lateral move can be combined with dead reckoning using *time-period averages* as:

$$X_{new} = \overline{X} + \left(\frac{t}{2} + t_{now} - t_{LastEnd} \right) \bullet \Delta\theta / \Delta t \qquad (2)$$

where X_{new} is the new real-time angular position of the pivot, $\overline{X}$ is the averaged GPS position, and t is the time period over which the GPS position is averaged in minutes, t_{now} is the current time, and $t_{LastEnd}$ is the time that the last time-period average was updated. Position can be reported as an angular position for center pivots, or a position from starting point for lateral move systems. The same calculation using *rolling averages* is computed as:

$$X_{new} = \overline{X} + \frac{t}{2} \bullet \Delta\theta / \Delta t \, . \qquad (3)$$

Results and Discussion

The overall results from using the one-minute averages for the three different trials at Bushland are given in Figure 1. Although most position estimates are within 1 – 2 meters of the mean, there are a few outlying points that go far beyond this.

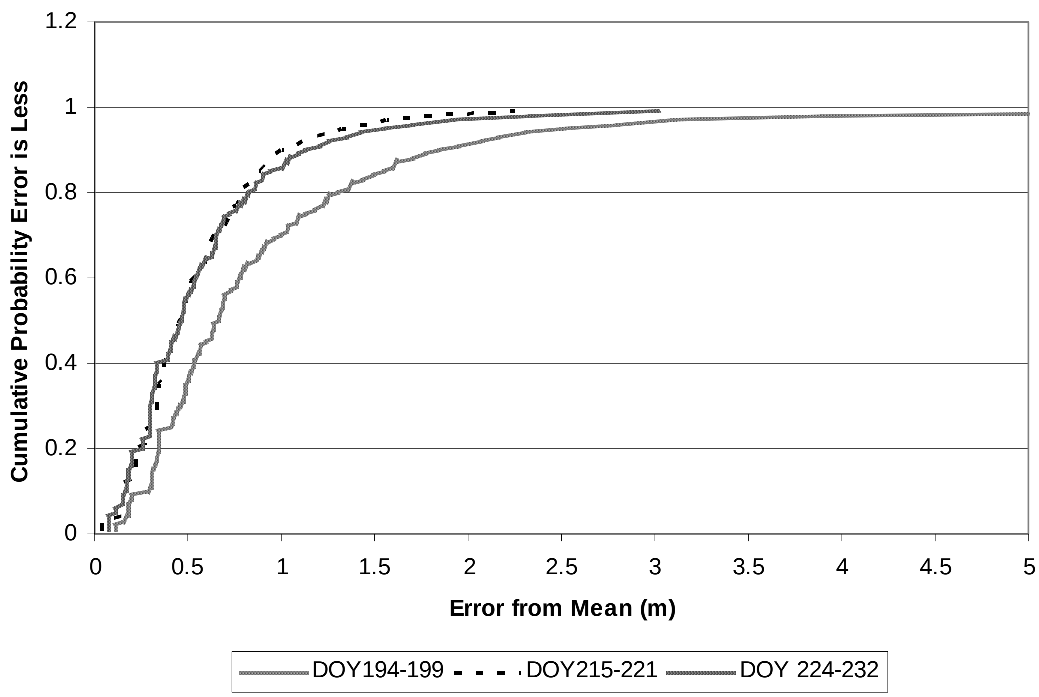

Figure 1. Cumulative probability that the error is less than the given distance from the mean for the three different extended time periods.

The one minute average position for the DOY 194-199 time period is plotted in Figure 2. This shows the large amount of variability, and especially the outlying points. To show the effect of averaging, the 10 minute and 60 minute average positions (time-period averages) for the same time period are plotted in Figures 3 and 4. The effect that averaging has on bringing in the outlying points is dramatic.

Although it is clear that averaging bring in outlying points, they do not have much effect on the average deviation from the mean. Table 1 gives the descriptive statistics for the errors (distance from the mean) of the three Bushland trials using time-period averages. Table 2 gives the same statistics for the errors of the stationary trial in Fort Collins. Although the maximum error is reigned in significantly and the root mean squared error is decreased slightly, the other error terms are only slightly affected. The 50^{th} and 90^{th} percentile of the distribution sometimes actually increase when more points are included in the average. This may be due to the fact that some errors are not random, but effected by things which change slowly over time such as the atmospheric influences on the signal speed from the satellites. It is not clear why the errors from the data collected on DOY 194-199 are so much higher than the other days.

For comparison rolling averages using the same time intervals were taken with the same data from Bushland (Table 3). The errors of these rolling averages for the same time interval are generally larger than for the time-period averages (Tables 1 and 2). Again this may be due to the slowly changing atmospheric conditions which would cause the errors to follow each other around.

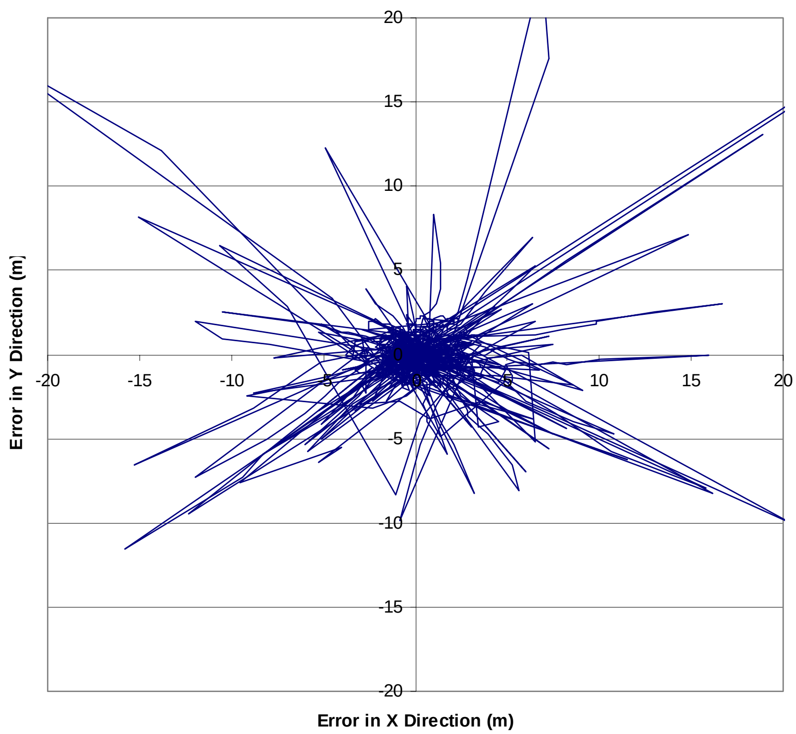

Figure 2. 1 minute averages for the DOY 194-199 time period.

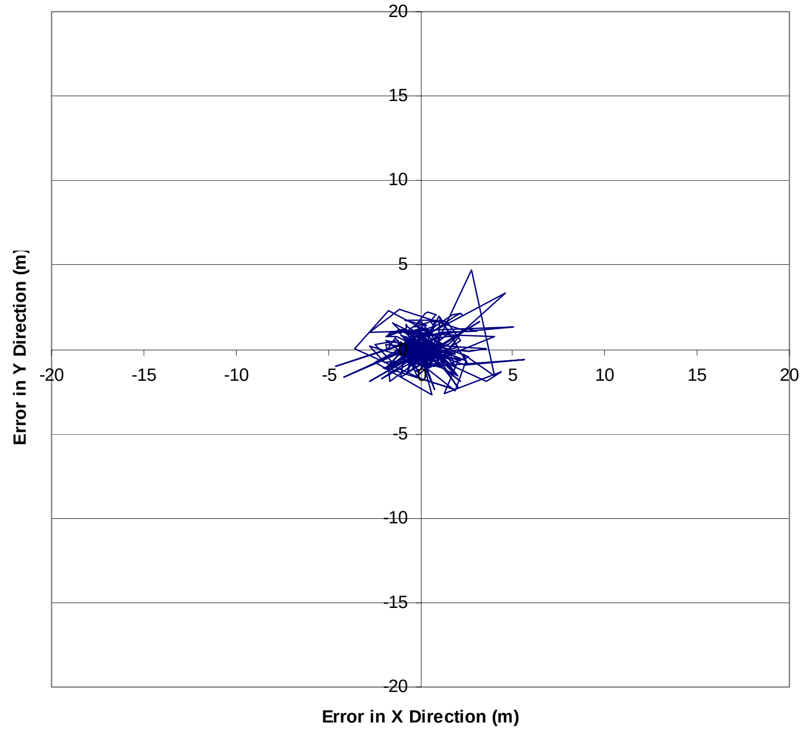

Figure 3. 10 minute averages for the DOY 194-199 time period.

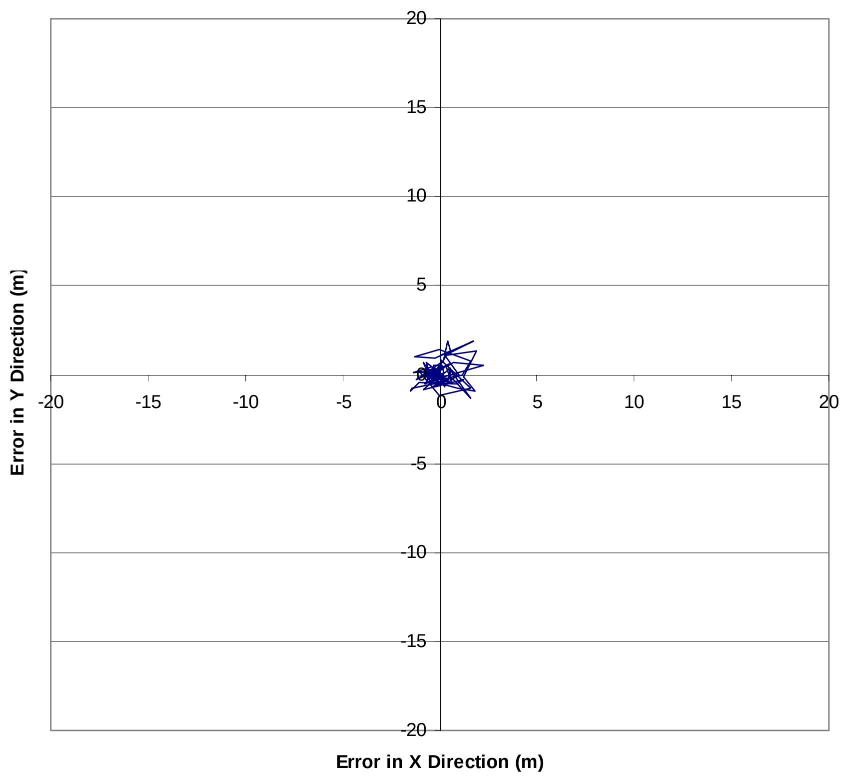

Figure 4. 60 minute averages for the DOY 194-199 time period.

Table 1. Time-period averages of three different extended data collection periods in a stationary location in 2005 from DOYs 194-199, 215-221, and 224-232 in Bushland, TX. The averages were taken on 1, 5, 10, 30, and 60-minute time intervals. Statistics on the error (distance from the mean, m) include the mean, the root mean square error (RMSE), the 50% (median) and 95% distribution, the maximum error, the standard deviation, and the number of points included (N).

		1 min	5 min	10 min	30 min	60 min
DOY 224-232	**Mean**	0.60	0.60	0.60	0.60	0.61
	RMSE	0.83	0.76	0.73	0.69	0.67
	50%	0.47	0.48	0.50	0.55	0.60
	95%	1.56	1.52	1.42	1.18	1.10
	Max	9.27	4.97	3.38	2.33	1.73
	StDev	0.57	0.47	0.41	0.33	0.28
	N	10663	2134	1068	358	180
DOY 215-221	**Mean**	0.56	0.56	0.56	0.56	0.56
	RMSE	0.73	0.69	0.67	0.64	0.62
	50%	0.45	0.46	0.47	0.49	0.53
	95%	1.33	1.30	1.26	1.12	1.02
	Max	11.42	4.68	2.99	2.17	1.49
	StDev	0.47	0.40	0.37	0.31	0.26
	N	7885	1577	789	264	132
DOY 194-199	**Mean**	0.99	0.99	0.99	0.99	0.99
	RMSE	1.86	1.49	1.38	1.26	1.21
	50%	0.67	0.68	0.69	0.72	0.75
	95%	2.51	2.70	2.74	2.67	2.43
	Max	72.89	18.09	9.26	4.36	3.72
	StDev	1.57	1.12	0.95	0.78	0.70
	N	7897	1581	791	265	133

Table 2. Time-period averages of a 68 hour data collection period in a stationary location for 2002, DOY 262-265 in Fort Collins, CO. The data were collected on 3 second intervals, and averages were taken on 1, 5, 10, 30 and 60-minute timer intervals. Statistics on the error (distance from the mean, m) are shown include the mean, the root mean square error (RMSE), the 50% (median) and the 95% distribution points, the maximum error, the standard deviation, and the number of points included (N).

		3 sec	1 min	5 min	10 min	30 min	60 min
DOY 262-265	**Mean**	0.82	0.80	0.71	0.64	0.51	0.40
	RMSE	0.98	0.96	0.85	0.76	0.60	0.46
	Std Dev	0.53	0.52	0.47	0.42	0.30	0.24
	50%	0.73	0.69	0.61	0.54	0.47	0.34
	0.95	1.87	1.84	1.62	1.46	1.12	0.84
	Max	5.20	4.89	3.66	2.69	1.54	1.14
	N	81444	4072	814	407	135	67

Table 3. Rolling averages of three different extended data collection periods in a stationary location in 2005 from DOY 194-199, 215-221, and 224-232 in Bushland, TX. The rolling averages were taken on 1, 5, 10, 30, and 60-minute time intervals. Statistics on the error (distance from the mean, m) include the mean, the root mean square error (RMSE), the 50% (median) and 95% distribution, the maximum error, the standard deviation, and the number of points included (N).

		1 min	5 min	10 min	30 min	60 min
DOY 224-232	**Mean**	0.60	0.60	0.60	0.60	0.60
	RMSE	0.83	0.76	0.73	0.68	0.66
	50%	0.47	0.48	0.50	0.55	0.58
	95%	1.56	1.52	1.42	1.18	1.07
	Max	9.27	4.97	3.65	2.37	1.82
	StDev	0.57	0.47	0.41	0.33	0.27
	N	10663	10659	10654	10634	10604
DOY 215-221	**Mean**	0.56	0.56	0.56	0.56	0.56
	RMSE	0.73	0.69	0.67	0.64	0.62
	50%	0.45	0.46	0.47	0.50	0.52
	95%	1.33	1.30	1.26	1.13	1.04
	Max	11.42	4.98	3.25	2.45	1.80
	StDev	0.47	0.40	0.36	0.30	0.26
	N	7885	7881	7876	7856	7826
DOY 194-199	**Mean**	0.99	0.99	0.99	0.99	0.99
	RMSE	1.86	1.50	1.39	1.27	1.22
	50%	0.67	0.67	0.69	0.73	0.75
	95%	2.51	2.73	2.76	2.59	2.48
	Max	72.89	20.26	12.54	6.08	4.25
	StDev	1.57	1.12	0.98	0.80	0.70
	N	7897	7893	7888	7868	7838

A graphical representation of the maximum error and the root mean squared error data for the different trials are given in Figures 5 and 6. Again, the advantages of averaging are clear. Figures 5 and 6 also show that the differences between time-period averaging and rolling averages are not very large. Both methods give very similar precision and there is no clear advantage of one method over the other. Based on these figures it would make sense to choose a time period of between 10 and 30 minutes for averaging GPS points. Time intervals beyond this do not improve the precision while significantly increasing the time and distance across which dead reckoning must be applied. This lack of precision is particularly true if actual speed changes, with a constant timer setting, may be caused by field conditions.

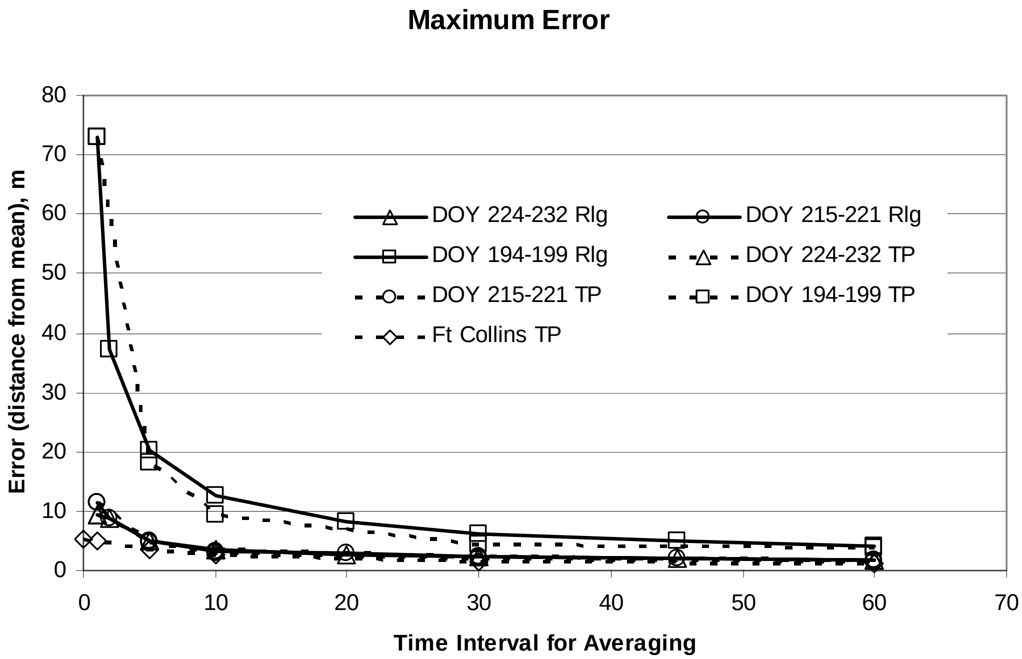

Figure 5. Graphical representation of the maximum error from the mean for the three different stationary time trials in Bushland and the one from Ft. Collins. Rolling averages (Rlg; solid lines) and time-period averages (TP; dashed lines) are included for comparison.

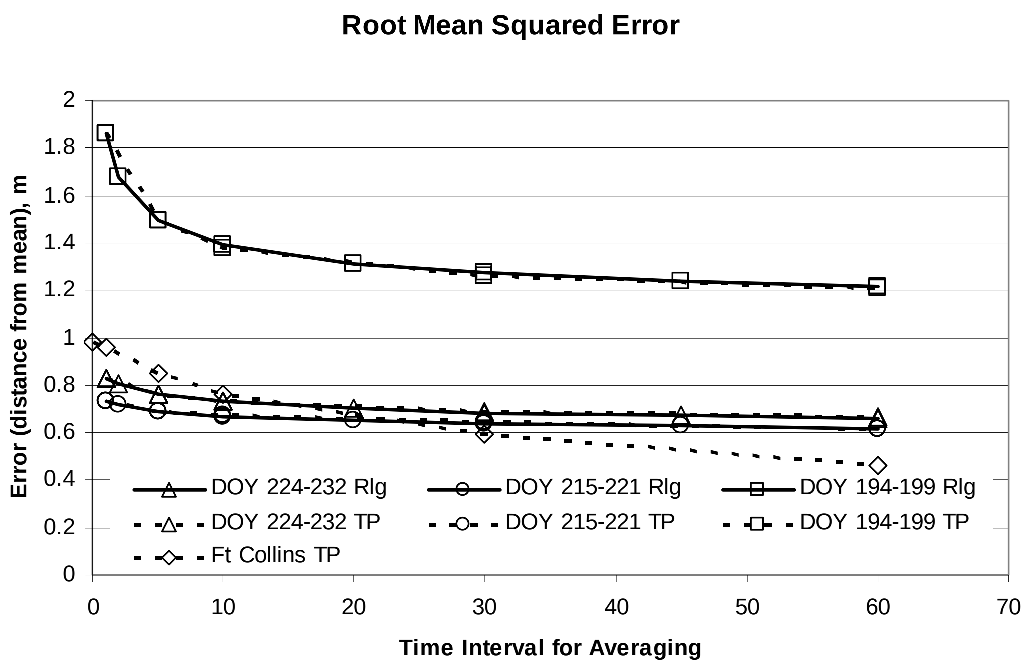

Figure 6. Graphical representation of the root mean squared error from the mean point for the three different stationary time trials in Bushland and one from Ft. Collins. Rolling averages (Rlg; solid lines) and time-period averages (TP; dashed lines) are included for comparison.

The first moving test, run at the Ft. Collins site, was 2 hours in length, with the system stationary for the first hour. The system was run in the reverse direction until it reached the first reference point and then run in the forward direction for 50 minutes. The three second data are connected with a linear line (Figure 7). The 1,5 and 10 minute average data for both the radius and angle are shown. At the maximum the radius exceeds the mean of 79.6 m by 1.2 m and is less than the mean by 1.1 m. This is equal to about ± 2 standard deviations of the stationary data. The data in Figure 7 shows quite good agreement between measured angular data when compared with the reference points.

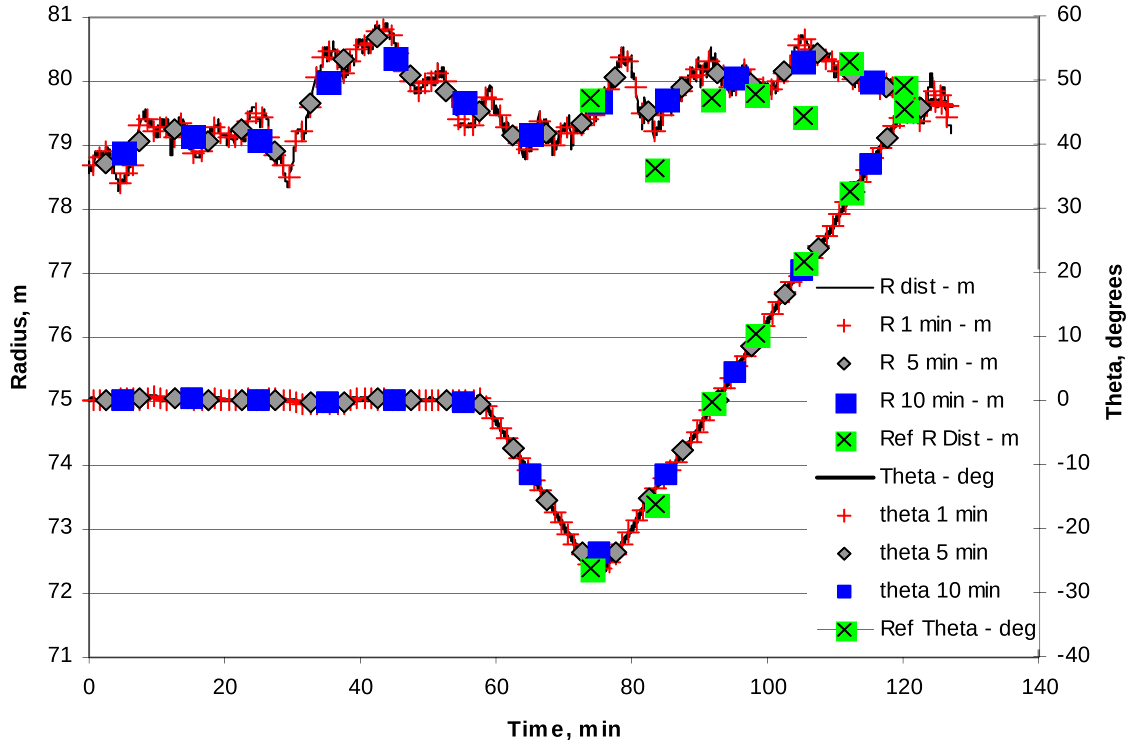

Figure 7. Fort Collins center pivot system with GPS mounted near outer tower, stationary for approximately 1 hour, followed by moving in reverse direction for 27˚, and then moving forward 72˚. The timer setting for speed control was 100%. The calculated radius (R) and angular position (theta; θ) are shown for all of the data (3 second time interval), and for 1-minute, 5-minute, and 10-minute averages. The measured reference points are also shown for comparison.

The second moving example (Figure 8) had a similar maximum deviation of ± 1.2 m from the actual radius to the GPS measured radius. This would be approximately equal to an angle difference of 0.9˚. The change in θ at approximately 100 minutes is closely coupled to the change in estimated radius at the same time. An analysis of the change in θ and its change with time is better illustrated in Figure 9 and 10. The 3 second data has considerable variation from one point to another. When connecting the data points the entire figure is a series of up and down lines. This is likely due to the rapid change seen in the GPS estimated radius caused by the limited precision of the receiver. The averaging process results with small changes in Δθ/Δt but both the 5 and 10 minute averages are quite constant. Table 4 is a summary of the mean and standard deviation of the Δθ/Δt for the 75-120 minute period for the 100 % timer and for the 20-115 minute period for the 50% timer setting. The mean angular velocity is almost the same for all averaging times. However, the standard deviation is less for both the 5 and 10 minute averaging times. It would appear that either would be a reasonable time for use in estimating the velocity for dead reckoning estimates of position corrected by GPS data. The shorter average time would be more sensitive to changes in velocity due to field conditions. The pivot's % timer is quite accurate and could be used for dead reckoning. The GPS would then account for changes in velocity due to slippage or velocity changes due to going up or down hill.

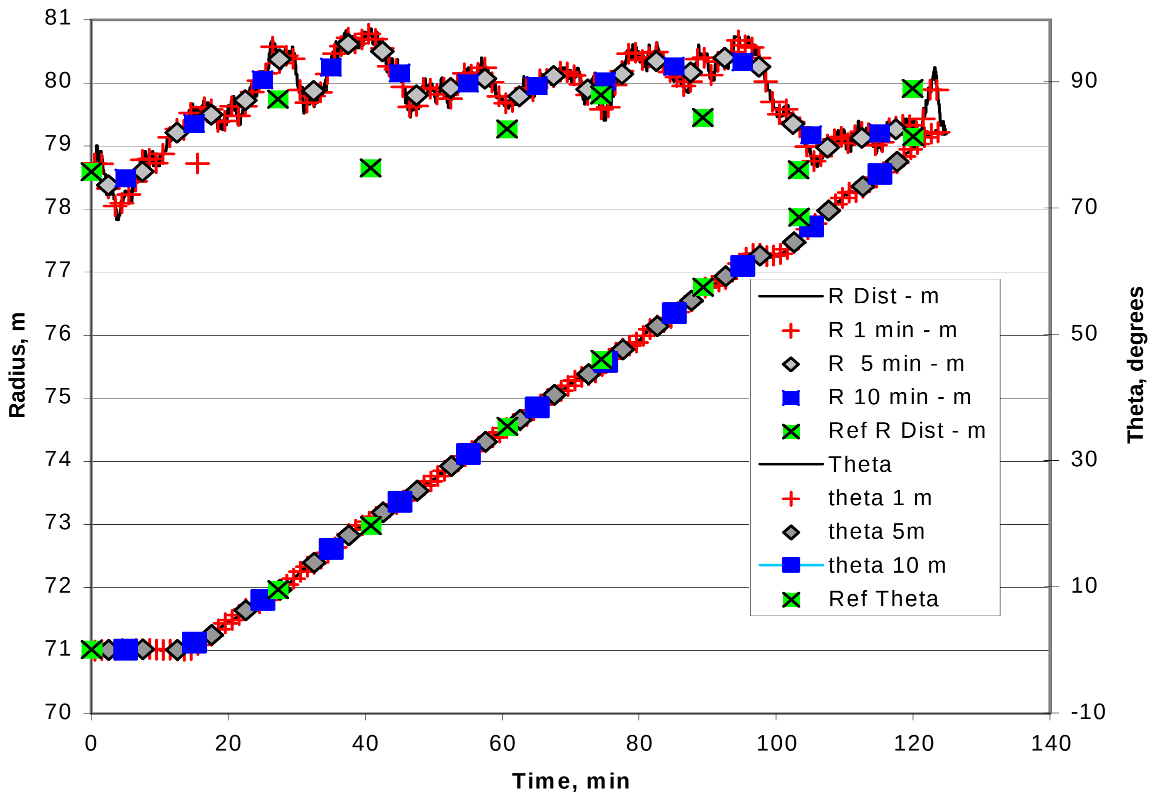

Figure 8. Center pivot system with GPS mounted near outer tower, stationary for approximately 15 minutes, followed by moving in forward for 80˚. The timer setting for speed control was 50%. The calculated radius (R) and angular position (theta; θ) are shown for all of the data (3 second time interval), and for 1-minute, 5-minute, and 10-minute averages. The measured reference points are also shown for comparison.

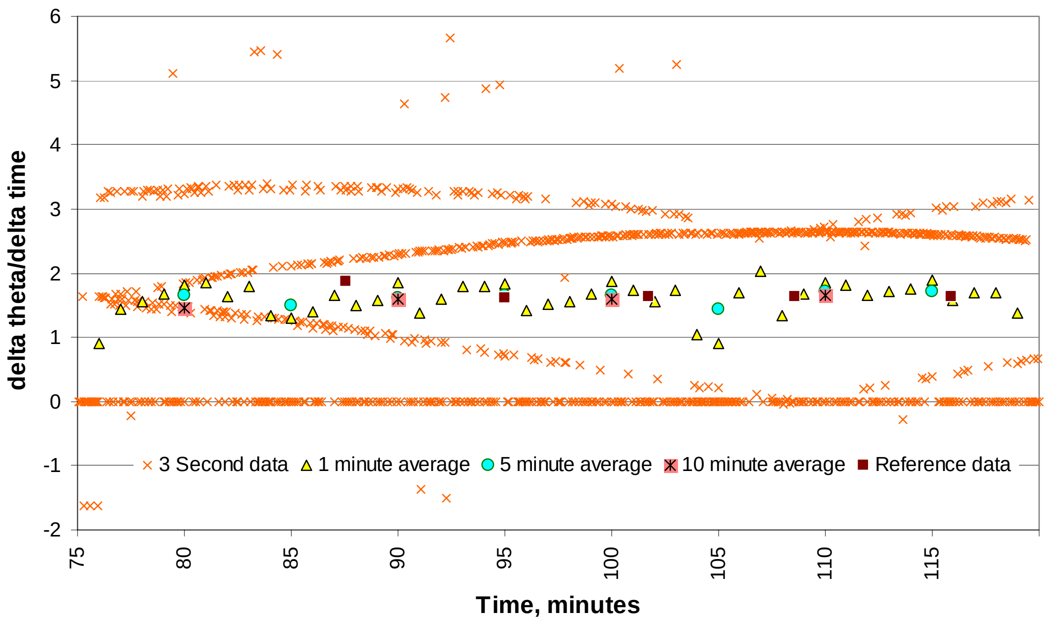

Figure 9. Center pivot system with GPS mounted near outer tower, stationary for approximately 1 hour, followed by moving in reverse direction for 27^{o}, and then moving forward 72^{o}. The timer setting for speed control was 100%..

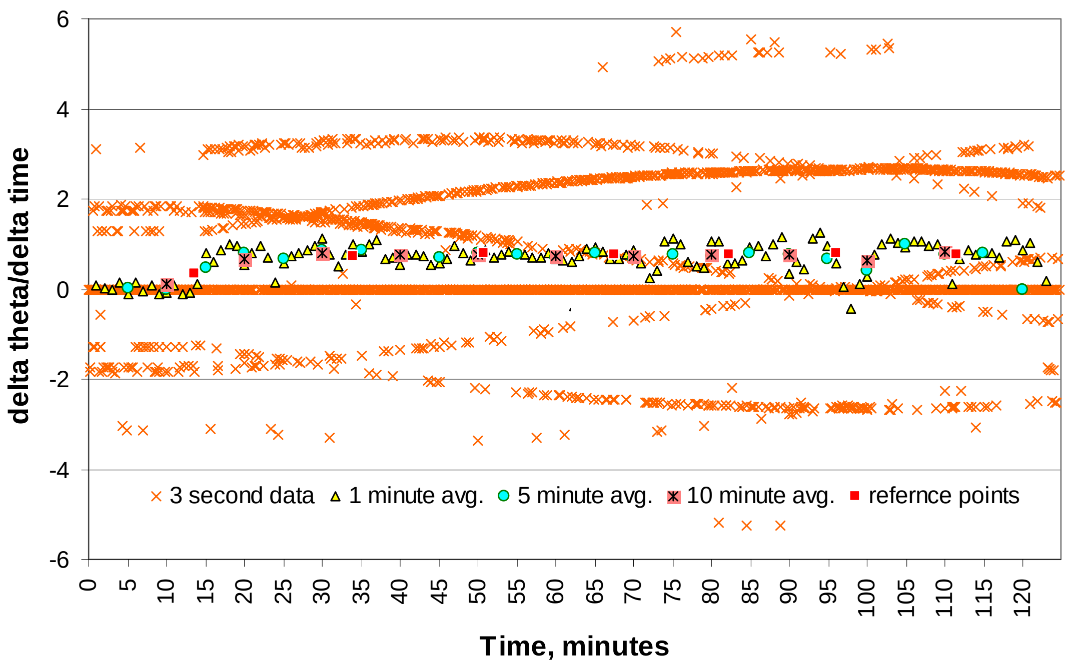

Figure 10. Center pivot system with GPS mounted near outer tower, stationary for approximately 15 minutes, followed by moving in forward for 80^{o}. The timer setting for speed control was 50%.

Table 4. Summary statistics for the estimation of $\Delta\theta/\Delta t$ and standard deviation for the different averaging times. The reference is included for comparison.

75 – 120 minutes 100% Timer					
average t	3 seconds	1 minute	5 minute	10 minute	reference
$\Delta\theta/\Delta t$	1.57	1.60	1.62	1.51	1.68
Std. Dev.	1.34	0.248	0.100	0.205	0.108
20 – 115 minutes 50% timer					
average t	3 seconds	1 minute	5 minute	10 minute	reference
$\Delta\theta/\Delta t$	0.75	0.74	0.75	0.74	0.77
Std. Dev.	1.65	0.271	0.112	0.060	0.017

Additional studies with more variability in velocity would be needed to develop and test the algorithm for estimating the position of a center pivot or linear move system. The error in estimating the angular position for a center pivot would decrease as the length of the pivot increased. As was indicated, a 1.2 m variation in determining the position of a point has almost one degree error with a center pivot lateral length of 79 m. The same 1.2 m variation with a lateral length of 105 m would have less than 0.2 degree error. Precision irrigation applications with the longer laterals can be made within the expected tolerances of treatment areas.

Conclusion

Although differentially corrected GPS receivers report positions fairly accurately outlying position estimates are a cause for concern in precision irrigation or chemigation applications. Low-cost, differentially corrected GPS units were tested at stationary locations in Bushland Texas and in Fort Collins, Colorado. Tests on a moving center pivot were performed in Fort Collins. It was demonstrated that outlying errors from the reported GPS positions can be mitigated by averaging the reported GPS positions. Time-period averages and rolling averages were evaluated and compared and it was found that there were not large differences between the two methods. An algorithm was presented for combining averaged GPS positions from a moving irrigation system with dead reckoning for reporting real-time position. Various time periods for averaging GPS points were compared and it was found that 10 to 30 minute averages bring in the outlying errors sufficiently without having to apply dead reckoning across long times and distances. There was good agreement on the moving pivot between GPS calculated angular data when compared with measured reference points. Averaging GPS points over greater time periods to calculate angular velocity decreased the variability of velocity estimates. For estimating angular velocity averaging times of 5 to 10 minutes appeared to be adequate.

References

Barker, L.J. 2004. GPS-based control system and method for controlling mechanized irrigation systems. United States Patent 20,040,117,070. July 17, 2004.

Carlson, C.G. 1999. What do latitude and longitude readings from a DGPS receiver mean? Available online at: http://www.abs.sdstate.edu/abs/precisionfarm/EARTHMO1.html. Accessed Oct. 2003.

Heermann, D. F., G.W. Buchleiter, W.C. Bausch, and K. Stahl. 1997. Nondifferential GPS for use on moving irrigation systems. Proceedings of 1st European Conference on Precision Agriculture. Sept. 8-10, 1997. V(II):567-574.

Kostrzewski, M., P. Waller, P. Guertin, J. Haberland, P. Colaizzi, E. Barnes, T. Thompson, T. Clarke, E. Riley, and C Choi. 2002. Ground-based remote sensing of water and nitrogen stress. Trans. ASAE. 46(1):29-38

Peters, R.T, and S.R Evett. 2005a. Using low-cost GPS receivers for determining field position of mechanized irrigation systems. App. Eng. in Ag. In Press.

Peters, R.T. and S.R. Evett. 2005b. Mechanized irrigation system positioning using two inexpensive GPS receivers. In: Proceedings of the ASAE/CSAE Annual International Meeting. July 17-20, 2005, Tampa, Florida. CDROM

Robinson, E. 2003. GPS-guided center pivot eliminates need for buried wire. Southwest Farm Press. April 17, 2003.

Sadler, E.J., C.R. Camp, D.E. Evans, and J.A. Millen. 2002. Corn canopy temperatures measured with a moving infrared thermometer array. Trans. ASAE. 45(3): 531-591

Advances in Using Center Pivots for Resource Management
By
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Summary: Significant changes have occurred in how irrigators are using center pivots and their expectations. In addition constraints on available water are beginning to change irrigators' management processes. This paper will focus on changes within the center pivot industry to meet both wants and needs of irrigators to provide optimum resource management. Data will be presented on some specific examples of how irrigators are using new center pivot technology to minimize input of labor and variable expenses and additionally improve their quality of life. Generalized costs associated with center pivot options for resource management will be compared with potential annual savings. Finally the paper will contain a brief discussion of the direction commercial center pivot technology is moving.

Objective: To discuss specific examples of advances in center pivot irrigation for providing better resource management options for operators.

Introduction: Since the early 1980's center pivots have seen a dramatic increase in improved irrigation efficiencies with changes in the sprinkler packages, pipeline diameters and structural design while little has been done to address farmers' needs for integrated resource management tools.

Besides the irrigation water, resources requiring management consideration include but are not limited to power to pump the water, labor, equipment to management such as a pickup truck, fertilizer, seed and herbicide. With the rising costs of capital purchases and operation, more consideration is being given to tools to help manage these resources. This coupled with farm consolidation has made a dramatic change in the costs for an irrigator to manage their operation efficiently and effectively. In addition, many irrigated farm operations need to be able to rapidly adjust their cropping strategy due to changing commodity prices, available water and production costs which requires maximum flexibility in resource management.

To help address the labor required to monitor, center pivot manufacturers have offered some tools for remote communication such as phone communication or VHF and UHF radios either for direct or base station applications. These tools have been offered for over ten years but have met with limited acceptance with 5% or less of growers using them. Part of the reason for limited acceptance has been the cost, reliability and durability. Plus in most cases the communications devices provided only limited monitoring or control information without providing an integrated platform for resource management. Lastly many of the products offered did not work on older 'orphan' center pivots.

With energy costs rising for both the pumping plant and for vehicles to check the center pivot and consolidation of farms – more center pivots being operated by single operations, the need and want for improved monitor and control is rapidly increasing.

Discussion: Recent changes in technology have facilitated improvements in the tools being offered for resource management. These changes include improved design and construction of automated control panels such as the TLC Pivot Manager™, RAMS 2000™, GrowSmart FieldBOSS™ and cams Pro2™, improved cellular communications options such as Field Sentry and the cams Tracker, data instead of voice radios for Base Stations and a variety of sensors along with the software to provide expanded monitoring and control capabilities.

Today, reliable tools are available to monitor specific functions of the center pivot such as position, pressure, voltage, safety circuit, direction, water on/off and others. In addition, monitoring of a variety of environmental sensors has become common place. These include but are not limited to water pressure, water flowrate, water volume, temperature, rainfall, wind speed, wind direction and soil moisture. Data is consolidated at the center pivot control panel and/or sent via state of the art communication devices to cell phones, direct to the farm's computer or the internet.

Let us look at some generalized scenarios that may not reflect actual situations but are designed to be instructive. In each case the costs for the monitoring and communications is spread over a three year life.

Scenario 1 – Grower owns two center pivots and is renting three more for row crop production and farms 2,500 acres more dryland. These pivots are scattered with ten miles (16 km) between them and the farthest being twelve miles (19km) from the farm house. The grower's pumping cost (natural gas) is running about $275/day/pivot (August 2005). While rainfall is limited, rainfall events do occur during the growing season. He estimates the cost (labor and pickup fuel) to check the pivots at $60 per trip not including wear and tear on his pickup. Typically he will operate the pivots about 1,800 hours and make about 100 trips to check the pivots.

Situation 1 – The resource concern is labor and energy costs. If it rains, did all or some of his pivots receive rain and was the rain sufficient that he can stop the pump for a period of time. Does he stop his activity and drive to check each of the pivots? To check the pivots costs about $60 but it is also costing $57/hour to run all of the pivots. If he could shut them all down for one day, he could save $1,375.

Solution 1a – By adding a rain shutoff, the pivot can be set to stop at a set amount of rainfall, stop the pump and a remote monitoring device will call and alert the farmer when the pivot has stopped. Depending on the device, he will only know that the pivot and pump have stopped and not specifically why.

Costs 1a - Basic rain shutoff and remote monitoring only - $525 annual (costs spread over three years).

Payback 1a – If he can save two days of pumping for a pivot plus two trips to the field, this will more than cover his costs for the monitoring package.

Solution 1b - His other alternative is to have a complete Base Station package which will provide monitoring, control and reporting of what is happening in the field.

Costs 1b - Complete monitor, control and report package, VHF radio - $1,600 annual (costs spread over three years).

Payback 1b – While this package cost more in initial investment, its more advanced capabilities providing more information such as specific pivot status may also well be worth consideration. By reducing trips to check the pivots by 20 could save about $1,200 plus if he can save operating the pivots five days, will more than payback his investment. This also does not consider any wear and tear on the equipment to check the irrigation equipment and his ability to control the irrigation equipemtn.

Scenario 2 – Grower owns two center pivots for row crop production and farms another 4,000 acres. These pivots are scattered with five miles (8km) between them and the farthest being six miles (9km) from the farm house. The grower’s pumping cost (electric) is running about $61/day/pivot (August 2005). His monthly demand charge is $750/pivot. He is in an area of supplemental irrigation with rainfall events occurring during the growing season. He estimates the cost (labor and pickup fuel) to check the pivots at $40.

Situation 2 - The primary resource concern is cost of the demand charge when he will not have a chance to operate sufficient hours to use power to offset the demand charge. In the early and late part of the season, it is difficult to decide if he should irrigate or not. It is quite expensive to apply one inch due to the demand charge. Does he stop his activity on the other fields and spend time walking the pivots to determine soil moisture? Often in the fall, he is already into harvest on some of his crops. To check one pivot's soil moisture status costs him more time than he is willing to give up but not applying one more irrigation can impact his crop quality. If he has to start the pivot to apply one more irrigation, it will cost him $750 per pivot.

Solution 2 - By adding a moisture monitoring device integrated into the control panel, he can go to the pivot point and immediately have a good idea of the current moisture status without taking the time to scout the field. In addition he can see the changes in soil moisture over a period of time and know if the area of the soil moisture sensor is becoming wetter or dryer. Based on this information he can make a decision as to how critical one more irrigation would be.

Costs 2 - Soil moisture monitoring package - $950 annual (costs spread over three years).

Payback 2 - If he can save the demand charge both in the spring and fall, it will more than pay for the cost of soil moisture monitoring plus the added benefit of using the soil moisture monitoring to help him determine during the growing season if irrigation is required.

Scenario 3 - Grower owns five center pivots for forage production and runs a large dairy. His pivots are about three miles (5km) away from his milkhouse. The grower's pumping cost (electric) is running about $125/day/pivot (August 2005). He is in an area that is water limited with some rainfall events occurring during the growing season. He estimates the cost (labor and pickup fuel) to check the pivots at $97 due to the high cost of labor. He runs forage crops continuously under the pivots and contracts his harvest. Typically the pivots run about 2,500 hours per year. With checking the pivots and changes during harvest he figures he makes about 250 trips per year.

Situation 3 – His primary resource management concern is labor and water is also important. His focus is the dairy and does not believe he has a sufficient number of pivots to justify someone to operate and watch just them. Often when harvest is in progress he needs to be moving the pivots out of the way as the custom harvester does not want the responsibility of operating the pivots. Does he stop his activity in the dairy to run out and check the pivots and move them out of the way? Also the pivots need to be running as soon as harvest is complete to maximize his yields.

Solution 3 - His solution is a complete Base Station package which will provide monitoring, control and reporting of what is happening in the field. At a glance in the milkhouse, he can see the location of the pivots on his computer screen, maintain notes on cropping and harvest status and control what pivots are irrigating where without having to be in the field all of the time.

Costs 3 - Complete Base Station package for monitor, control and reporting, VHF radio - $ 1,600 annual (costs spread over three years).

Payback 3 – Quickly by looking at a computer screen he knows what is happening and with a few mouse clicks he can be moving his pivots, changing directions and applications depths. By reducing his trips to the field by a third (80) would save him $7,760 plus help him maintain focus on the dairy and allow more timely irrigations behind the harvest. Certainly within three years he has more than saved what the cost of the Base Station system is and this also does not consider any wear and tear on the equipment to check the irrigation equipment.

Conclusion: In many more cases than farmers and growers realize, an investment in remote monitoring, control and/or reporting for their center pivot can have a very rapid payback. Traditionally less than 5% of growers considered any type of ancillary equipment other than just the center pivot for resource management.

Each of the above scenarios is built around specific customer situations.

All of the major manufacturers are moving to more and better integrated control packages to meet the changing needs of agriculture. With the automated control panels, functions specific to the operation of the center pivot such as position, pressure, safety circuit, direction, water on/off and others are included. In addition, monitoring of a variety of environmental sensors is becoming common place. These include but are not limited to water pressure, water flowrate, water volume, temperature, rainfall, wind speed, wind direction and soil moisture. Information is collected at the center pivot control panel and stored for review or sent via state of the art communication devices to cell phones, direct to the farm’s computer or the internet.

With rapidly rising energy costs, the challenges of finding adequate labor and general changes in cropping strategies, the need is here now and is being met by the center pivot manufacturers.

Reliability and durability have been addressed and the challenges of the 1990’s have been overcome to offer products meeting most grower situations. Today due to changes in design and manufacture in many cases the maintenance costs for an automated panel are similar to a manual panel.

As shown by the three examples above in many cases farmers can see a very rapid payback, less than two or three years, for the additional investment in equipment offered by the center pivot manufacturers for resource management. In many cases, it is justified to upgrade existing center panels and add ancillary hardware to better manage their available water resource and fertilizer.

An area requiring more work is helping farmers and growers recognize the advantages of the newer resource management tools for center pivots. Also ‘selling’ farmers on the reliability and durability of the new tools will require effort by manufacturers.

It is anticipated we will continue to see more integrated monitoring, control and reporting packages available utilizing the latest communication options available to help farmers best manage their resources at a cost providing excellent value.

Also the center pivot manufacturers are moving to providing better and more economical precision application solutions to address better resource management within a particular field by crop, soils or topography.

As water resources for food, fiber and forage production continues to be a world concern and available time growers have to manage their resources is a challenge, more will move to mechanical move irrigation and integrated monitoring, control and reporting packages to provide the flexibility they require. Other irrigation technologies may offer water savings but do not allow cost effective operation as growers move to more closely manage their fields and cropping strategies.

References: The author would like to thank farmers across the United States for their comments and input, which have been collected at grower meetings and farm shows over the last three years.

The author also would like to thank the other center pivot manufacturers, Lindsay, Reinke and T-L for providing general information and data to help develop this discussion.

Instrumentation for Variable-Rate Lateral Irrigation System

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Crops in the Southern United States are generally produced in fields which are known to have a high degree of variability in soil type, topography, water holding capacity and other major factors which affect crop production. A variable-rate lateral irrigation system was developed for site-specific application of water to match crop needs. A GPS receiver is used to determine the position of the lateral irrigation system in the field. A variable speed control system allows the lateral to move quickly over wet spots and slow down over dry spots. The lateral system is controlled by the nozzle-pulsing technique for variable-rate water application. The nozzle pulsing technique to adjust irrigation rate worked very well. The average water application rate error was less than 2%. There was a strong correlation between soil electrical conductivity (EC) and soil water holding capacity. Therefore, the EC measurements could be used for irrigation scheduling decisions.

FIELD PERFORMANCE TESTING OF IN-CANOPY CENTER PIVOT NOZZLE PACKAGES IN KANSAS

Danny H. Rogers, Gary A. Clark, Mahbub Alam, Kent Shaw[1]

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Abstract: Traditional performance evaluation procedures of center pivot nozzle packages involved placement of catch cans under the nozzles. An accurate catch requires at least three feet of separation between the top of the can and the nozzle outlet. In the Ogallala irrigated regions of western Kansas, the majority of the nozzle packages are in-canopy systems that preclude a catch can type performance evaluation. An in-canopy nozzle package testing procedure was proposed, using individual nozzle pressure and flow readings at prescribed locations along the center pivot lateral to compare to design specifications. The goal is to develop a streamlined protocol to allow individuals, consultants, and/or agency personal to evaluate systems in a timely and efficient matter. Such evaluations would allow independently gathered flow and pressure reading to verify on-site monitoring equipment readings, add to the information data base on nozzle package performance under various operating conditions and help producers track performance and help them decide when a nozzle package upgrade or change is needed. The evaluation procedure and testing are being conducted as part of the Mobile Irrigation Lab (MIL) project. MIL software and information are available on the MIL website (http://www.oznet.ksu.edu/mil/).

Introduction

The Mobile Irrigation Lab (MIL) project is an educational and technical assistance program focused on enhancing the irrigation water management practices of Kansas irrigators (Clark et. al., 2002 and Rogers et. al., 2002). The MIL has two parts: one part emphasizes irrigation software development and hands-on computer training for producers; the second part has emphasis on field activities, which has included on-farm irrigation demonstrations and center pivot performance evaluations. Center pivot nozzle package evaluations have used catch can data to calculate a distribution uniformity coefficient (Figures 1 and 2). However in the Ogallala irrigated areas of western Kansas, the most commonly utilized center pivot nozzle package is an in-canopy placement of the nozzles, which can not be tested using the catch can procedure. The development of a testing procedure for these types of systems that can be done in a time efficient manner would help producers evaluate systems and make adjustments as needed to keep the system distributing irrigation water and chemicals effectively and allow for good irrigation water management.

In-canopy Nozzle Package Testing

Unlike an above canopy nozzle package, where the uniformity of water distribution is dependent on non-

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interference by the crop canopy, the in-canopy nozzle package almost always has the water streams from the nozzle being intercepted and/or redirected by the crop stocks and leaves. The primary exception to this would be a LEPA system utilizing circularly planted rows and bubble mode nozzles or drag tubes. Few of these types of system are utilized in Kansas. However, even these types of systems would have non-uniform water distribution if the design flow rate and pressure conditions are not met. Above-canopy testing experience revealed that some package uniformity problems were related to the package design conditions not being met. This could be caused due to a variety of reasons, including mis-communication between the designer and the installer, errors in measuring or estimating well yield, changes in well capability due to water declines or wear, and monitoring equipment errors resulting in incorrect operation flow and pressure setting. Another package error discovered was improper installation, the most common of which was the reversal of pivot span nozzles. This latter error could be more easily be discovered and corrected for an in-canopy package than for most above canopy systems, since access to the nozzles for size reading and changing is convenient.

The concept of the in-canopy test was to develop a protocol to minimize data collection from a system that would still allow a determination of whether design and operating conditions matched. The intent was to take a number of pressure and flow readings from nozzles along the center pivot lateral and measure total flow and pivot point pressure and compare this information to the design sheet specifications. It was thought that eventually only readings of a few nozzles at the beginning and end of the pivot lateral would be sufficient to verify the system performance in terms of water distribution along the center pivot lateral.

Since the nozzles are near the ground and many are mounted on a flexible drop tube, it was thought that installation of a pressure shunt could be done by crimping off the water flow to an individual nozzle and installing the pressure shunt to determine the nozzle pressure. The flow rate could be determined by volume flow measurement and a stop watch. However before testing began, several small digital flow meters (F-1000-RB flow rate meters from Blue-White Industries[2]) were purchased and configured with the pressure shunt as shown in Figure 3.

Most irrigation wells are metered in Kansas and flow meter readings were accepted for use in the previous above-canopy evaluations. However, several of the systems that were evaluated had poor performance ratings for no apparent reason. One reason might have been improper flow or pressure at the pivot point. However input flow and pressure readings were not independently verified, so this could not be proven. One of the systems was retested at a later date and the performance rating was good and both input flow and pressure were verified independently. To allow this to routinely occur, a non-intrusive flow meter was obtained.

The digital flow meters were lab tested and worked well over the specified flow range. However, during field tests, we have had some difficulty with moisture accumulation in the LED display to the degree that the display can not be read. Although the instrument specifications indicate they can be used in a wet environment, the instruments would also shut down after several readings presumably due to the moisture condensation within the body of the instrument. The instrument bodies can be opened to allow drying without apparent effect on accuracy. Several ideas to prevent condensation have been tried without much success, so this remains an issue for these particular instruments. The back up method for obtaining flow readings is the bucket and stop watch.

Data collection as not been as easily obtained as hoped for. A minimum of two individuals are needed on-site, although three can be efficiently used. One “dry” individual is needed to record the data.

[2][2] No criticism or endorsement is intended by the use of commercial name. The use is only for clarity of the presentation.

Example Test Results

Test results from the first in-canopy pivot analysis are shown in Table 1. Most of the measurements were taken adjacent to a pivot tower. The test was conducted early in the irrigation season. The center pivot was 1305 feet long and equipped with 251 Senninger LDN nozzles using concave grooved by chemigation pads with 6 and 10 psi pressure regulators. The design flow rate was 350 gpm with a top of pivot pressure of 14 psi.

Figure 4 shows the field measured pressure distribution and the design pipe pressure. The field pressures were measured at approximately the nozzle height of 3 feet from the ground. The design pipe pressure would be at an elevation of approximately 12.5 feet, for about a 4 psi pressure differential. The measured values appear to be slightly higher than the design values. However, all nozzles are pressure regulated, so much of the pressure differential would be dampened out through the regulators.

Figure 5 shows measured flow rates and design flow rates. Measured observations appeared to be slightly higher at the end of the center pivot than design values. The test was conducted before the start of the general irrigation season, which could mean the well yield was higher than what it might be after long term pumping. However flow measurements at the beginning of the pivot lateral were matched very closely to the design values. Overall, it appears this system's performance was satisfactory.

Future Activities

The obvious improvements needed for the in-canopy test procedure are 1) reliable measurement of the pivot point flow rate and pressure, 2) either a different nozzle flow measurement instrument or a method to better seal the existing instrument, and 3) a standardized data collection routine. The latter comes with multiple testing and analysis. Items one and two are being addressed. In addition to moisture condensation or accumulation within the instrument, the instruments also shut down completely after a number of uses. This was originally thought to be due to the moisture exposure, but an additional suggestion that exposure to cold ground water may be having an effect on the instrument. This will be tested in the lab. During the test, the instruments are not exposed to direct spray from other nozzles, but do get wet from handling.

Center pivot irrigation systems are the dominate type of irrigation system in Kansas. The most common type of nozzle package uses an in-canopy configuration. The goal of developing a method to allow a cost effective verification of the nozzle package performance will help irrigators management the irrigation water resources to the highest degree possible.

Acknowledgment:

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References:

Clark, G.A., D.H. Rogers, M. Alam, D. Fjell, R. Stratton, and S. Briggeman. 2002. A Mobile Irrigation Lab for Water Conservation: I. Physical and Electronic Tools. In proceedings of Irrigation Association International Irrigation Technical Conference, October 24-26, 2002, New Orleans, LA, available from I.A., Falls Church, VA.

Rogers, D.H., G. A. Clark, M. Alam, R. Stratton, and S. Briggeman. 2002. A Mobile Irrigation Lab for Water Conservation: II Education Programs and Field Data. In proceedings of Irrigation Association International Irrigation Technical Conference, October 24-26, 2002, New Orleans, LA, available from I.A., Falls Church, VA.

Figure 1. Series of IrriGages being positioned prior to an above canopy nozzle package evaluation.

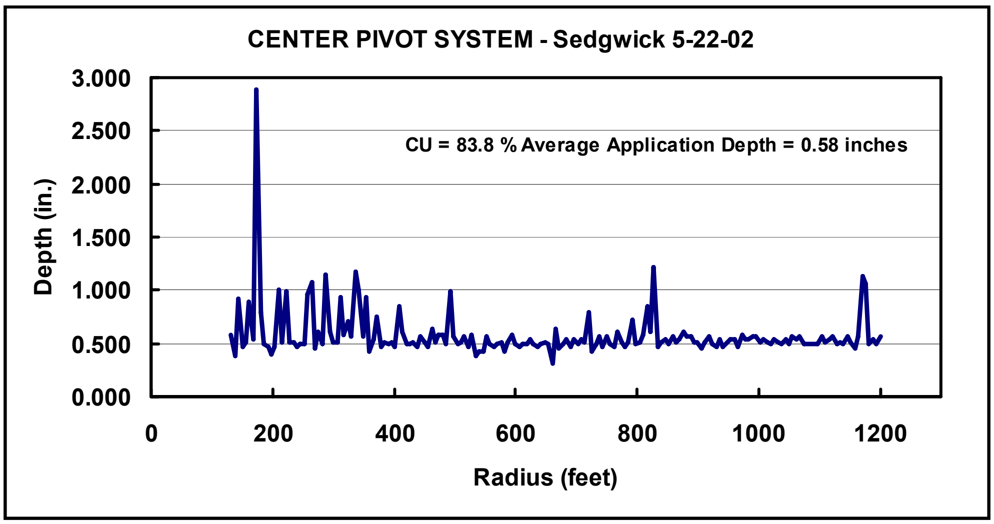

Figure 2. MIL uniformity test results for a center pivot equipped with an above canopy nozzle package of

rotator nozzles.

Figure 3: Digital flow meter and pressure shunt apparatus used for in-canopy performance evaluation**.**

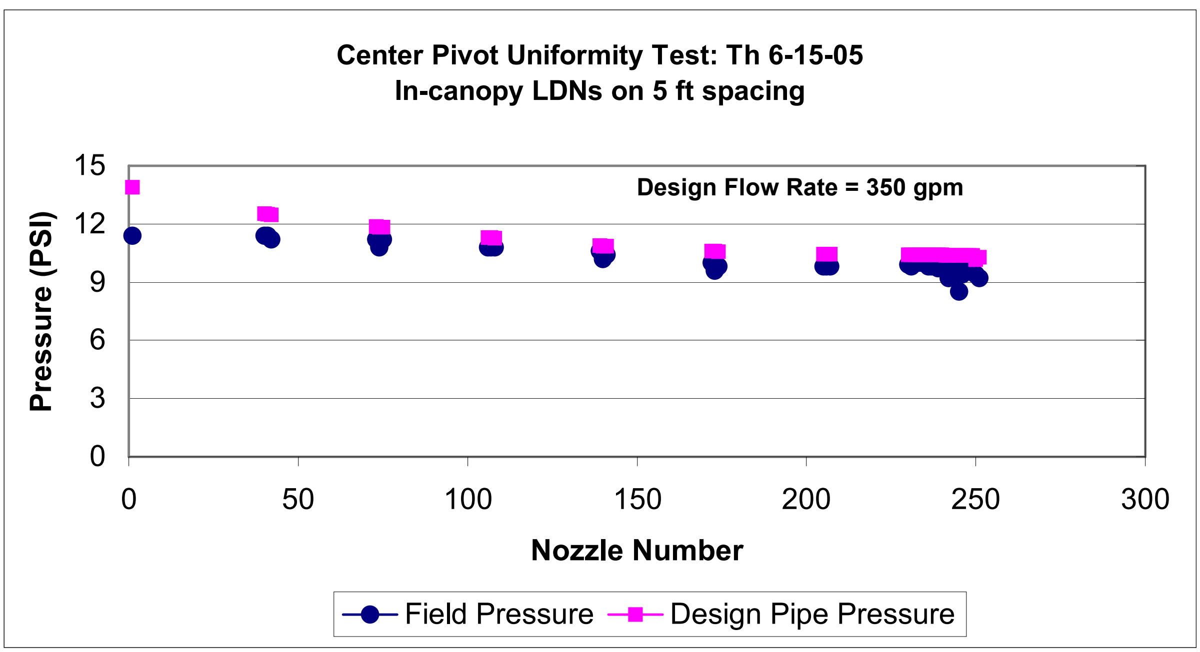

Figure 4: Field measured verses design pressure from an in-canopy center pivot evaluation.

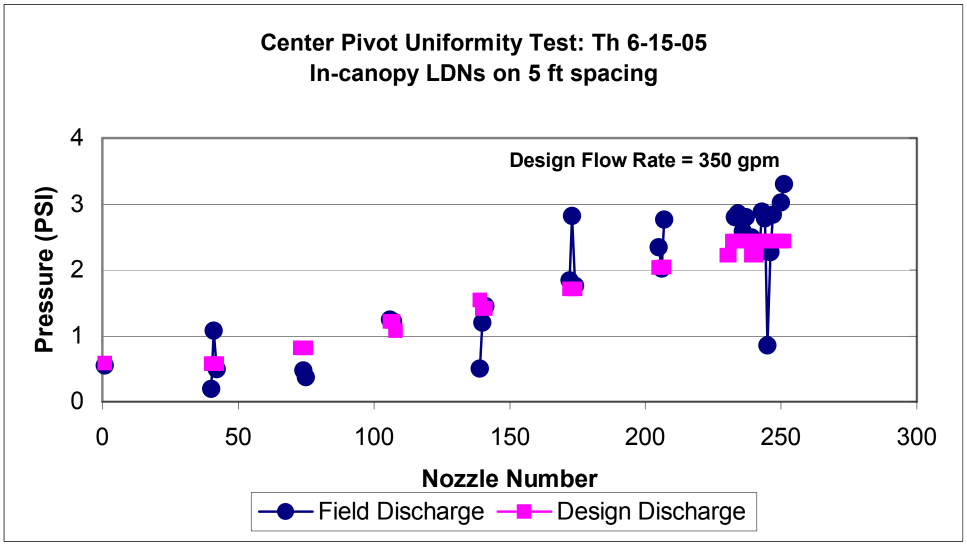

Figure 5: Field measured verses design nozzle flow rates from an in-canopy center pivot evaluation.

Table 1: Field Observed and Design Pipe Pressures and Nozzle Flow Rates from an In-canopy Center Pivot Nozzle Package in Thomas County, Kansas.

Nozzle number	Field psi	Design psi	Field gpm	Design gpm
251	9.2	10.3	3.3	2.44
250	9.4	10.15	3.02	2.44
247	9.8	10.39	2.84	2.44
246	9.4	10.39	2.27	2.44
245	8.5	10.39	0.86	2.44
244	9.8	10.39	2.78	2.44
243	9.8	10.39	2.88	2.44
242	9.2	10.39	2.27	2.44
240	9.8	10.4		2.23
239	9.7	10.4	2.49	2.22
238	10	10.4		2.44
237	9.8	10.4	2.8	2.44
236	9.8	10.4	2.59	2.44
234	10	10.4	2.86	2.44
233	10	10.4	2.8	2.44
231	9.8	10.4		2.22
230	9.9	10.4		2.22
207	9.8	10.44	2.76	2.05
206	9.8	10.44	2.02	2.04
205	9.8	10.44	2.34	2.04
174	9.8	10.58	1.76	1.71
173	9.6	10.59	2.82	1.71
172	10	10.59	1.84	1.71
141	10.4	10.86	1.45	1.41
140	10.2	10.87	1.2	1.41
139	10.6	10.88	0.5	1.54
108	10.8	11.27		1.08
107	10.8	11.29	1.22	1.22
106	10.8	11.3	1.25	1.22
75	11.2	11.82	0.37	0.82
74	10.8	11.84	0.47	0.82
73	11.2	11.86		0.82
42	11.2	12.48	0.49	0.58
41	11.4	12.5	1.08	0.58
40	11.4	12.52	0.2	0.58
1	11.4	13.9	0.55	0.59

2005 Irrigation Association Technical Conference
Phoenix, AZ

Center Pivot Sprinkler
Instantaneous Application Area, Droplet Size and Soil Infiltration

Presented by: James Burks / Senninger Irrigation, Inc.

Objective:

Provoke thought, research and the development of improved methodology in analyzing the effects of sprinkler system application intensity as it pertains to instantaneous uniformity and droplet size. Promote the development of standards and procedures in the quantification of system application efficiency and potential soil property degradation.

Note: For the purpose of this presentation, the term sprinkler is often used to refer to any type of water emission device used in center pivot irrigation (impact-driven sprinkler, fixed-plate spray nozzles, moving-plate applicators, etc).

Intro:

The modeling of sprinkler application patterns provides valuable information necessary in designing irrigation systems that will uniformly apply our valuable water resource. Good designers rely on this information to help determine the optimum spacing, elevation and operating pressure of a selected sprinkler. The most commonly used model is arguably the single ray profile which can be described as the "fingerprint" of a sprinkler's performance at a specified pressure, flow rate and elevation. Our industry has benefited greatly from software packages currently being used to calculate system application uniformity and/or estimate potential run-off. These applications depend heavily on the single ray profile model.

While the quantification of system application uniformity is achieved with reasonable accuracy through conventional analytical methods, the ability to accurately predict application efficiency and the potential negative effects a system design may have on soil structure remains elusive. Scientists and irrigators have hypothesized on many ideas and concepts that could lead to great improvements in this area yet improved procedures and firm solutions have not yet solidified.

The remainder of this presentation will focus on some ideas that have improved our understanding of the interface between the irrigation system and the soil or crop. An isolated look at what occurs at the critical moment water is delivered to the soil and the benefits and detriments in the process. Without standardized methods of quantifying many of the sprinkler application aspects being discussed, observations and comparisons must be based on relativity.

Conventional methods and thought:

Application Intensity or Instantaneous Application Rate:

The term IAR (<u>Instantaneous Application Rate</u>) has been used for several years in discussions relating to the system-to-soil interface, most frequently when considering potential detrimental effects to the soil such as structural degradation, surface compaction and run-off. <u>Application Intensity</u> may be a better term as there has been some confusion in our industry between the definitions of System Application Rate and Instantaneous Application Rate.

It is generally understood that the term System Application Rate (can be stated in GPM/Acre) is the total system flow rate divided by the entire wetted area of the system.

SAR = System Flow / Total Area of Coverage

Example: A center pivot system with a flow rate of 750 gpm and a length of 1,300 ft equipped with sprinklers (fixed-plate spray nozzles) having an average wetted diameter of 80 ft. Total area of coverage in acres is calculated by 1,300 ft multiplied by 40 ft and the product divided by 43,560 ft^2 per acre.

SAR = 750 gpm / 1.2 Acres = 625 GPM/Acre

In the estimation of how the system's application may impact the soil, using SAR can be characterized as a two dimensional view of the system-to-soil interface where a three dimensional view, using IAR, could provide additional detail for a more accurate analysis. With SAR as our only gauge for application intensity, we are making two very errant assumptions. First we are assuming that the total wetted area is receiving a perfectly uniform application and secondly that this uniform application is instantaneous and continuous in time.

-Assumption #1 – Total Uniformity

The single ray profile model again proves useful in revealing that the different types of sprinklers available today have varying application rates at varying distances from the sprinkler location out to the edge of the wetted area. While some sprinkler types do have a more even distribution profile than others, none of them offer perfect uniformity throughout the profile.

Duly noted: This is not to say that a sprinkler distributing an uneven profile is necessarily bad. When properly selected, spaced and designed, many sprinklers that individually produce an uneven profile have very good distribution uniformity as a collective package on a mechanical move system. These types of sprinklers may offer other advantages over those with more even profiles such as application efficiency and/or low pressure operation.

-Assumption #2 – Instantaneous Application

As mentioned before, a standard for measuring a sprinkler's instantaneous application area has not yet been determined. This is the most important factor to analyze when considering an irrigation system's potential impact on soil and is the greater contributor, of the two assumptions, to an inaccurate analysis based on the SAR formula. Even without a standard, comparing different sprinklers through observation has proven useful. Focusing on application intensity, an observer can look at the relativity among various sprinklers in the total surface area of soil that is being impacted at any given second of the sprinkler's operation. How much surface area of the soil is being wetted instantaneously?

It is easier at this point to explain the difference between SAR and IAR, and the two dimensional versus three dimensional view concept. Referencing the previous example of the SAR calculation we can modify the formula to an IAR calculation.

IAR = System Flow / Instantaneous Area of Coverage

The difficulty comes in quantifying the "Instantaneous Area of Coverage" without a standard method of testing and quantification. At this point we must default to estimates via observation. For the purpose of this example, it is reasonably safe to say that a fixed-plate spray nozzle providing a 40 ft diameter of coverage is instantaneously applying water to only 25% or less of the total area that it covers. Allowing this assumption through observation, we would adjust our Total Area of Coverage accordingly, producing an IAR calculation as follows.

IAR = 750 gpm / 0.3 Acres = 2500 GPM/Acre

The potential impact a system's application may have on the soil surface becomes much more apparent when we are seeing a more accurate picture, in this case we might say a magnitude of four times more accurate. It is important to again mention that there are many aspects to consider in evaluating a sprinkler package. Spray nozzles inherently have a greater application intensity than some other devices but when applied in the proper areas can offer benefits that lower intensity sprinklers may not.

The concept of lowering application intensity is not new and can also be further achieved in various ways of opening up the total sprinkler package wetted area through specialized mounting hardware such as "boom-backs" and truss-rod mounting systems. With the growing recognition of the benefits in lower application intensity, our industry needs to support this movement through research and further development. Standardized methodology and procedures that could incorporate an "Application Intensity" factor into new or existing formulation of estimating run-off potential or soil structure degradation is necessary for truly accurate forecasting.

-Intensity and Droplet Size:

Droplet size is another common topic when irrigators discuss potential soil structure degradation. The physical truth of *energy equals mass multiplied by velocity²* has held up too long to argue. Yet even with this strong physical understanding, field observations have sometimes shown that soil structure degradation occurs with small droplets when larger droplets have lesser impact. This was difficult to explain until the application intensity issue was brought into the equation. With certain soil conditions it has been demonstrated that smaller droplets delivered at high intensity have a much greater negative impact on soil structure than larger droplets at low intensity. Research in the area of what specific soil characteristics contribute to a soil being either more droplet size sensitive or more application intensity sensitive would bring tremendous insight to sprinkler selection and design.

-Benefits of maximizing droplet size:

When maximizing sprinkler system efficiency, a great rule of thumb regarding droplet size is to select a sprinkler and pressure that generate the largest droplet possible without adverse effects on the soil or crop. This rule of thumb covers three major design points:

1) Promotes efficiency by minimizing wind drift and evaporative loss.
2) Larger droplets are generally associated with lower operating pressures. Lowering system operating pressure has become a very successful strategy in conserving energy and enhancing profitability.
3) Design spacing and elevation are typically selected through single ray profile analysis. Industry standards and repeatability dictate that the data for these profiles be gathered in no-wind conditions. Larger drops contribute to better "pattern integrity" which means the performance illustrated in a single ray profile will be closer to field conditions with a wind element. System application uniformity is likely to be negatively affected if a pattern does not have strong integrity.

Conclusion:
Sprinkler technology has advanced greatly over recent years resulting in an ability to yield very high performance in uniformity and efficiency while reaping the benefits of energy savings through lower system operating pressures. Focusing on performance aspects such as application intensity and droplet size are critical in providing solutions to ongoing center pivot irrigation concerns such as surface soil compaction, run-off and wheel tracking. Further research and support to our industry is crucial to leverage the potential of our advancing technology.

Low Pressure Drip Irrigation - Alternative Irrigation System to Flood/Furrow Irrigation in California – "Water Savings with No Increase in Energy Useage"

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California irrigators have been cautioned regarding the adoption drip or micro irrigation. A recent state funded study concluded that the adoption or conversion from flood/furrow to drip or micro irrigation may result in some water savings but will increase overall energy usage. The study found that when farmers converted from flood/furrow to drip or micro irrigation they ultimately used more energy per acre due to the higher system operating pressures and the switch, in many cases, from surface water to ground water. The savings of one limited resource, water, may increase the use of another –energy.

Dr. Claude J. Phene's Paper #1060 detailed a new concept of Low Pressure Systems (LPS). LPS provides the water saving benefits of drip or micro irrigation and does not increase the system operating pressure since it operates at the same field inlet pressure as flood/furrow systems. LPS is a solution to California's water/energy dilemma.

Evaluation of Phosphate Fertilizer Type on Plugging of Drip Irrigation Tape

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Phosphate fertilizers have a widely held reputation for reacting with other materials including the dissolved salts in irrigation water to form solids that can plug drip emitters and tapes. Phosphates can combine with many common cations in water to form precipitates with very low solubility. The propensity for phosphates to precipitate with Calcium, Magnesium and other metallic ions that occur in irrigation water is the basis for the commonly issued warning to avoid the use of phosphate fertilizers in chemigation programs. The undeniable advantages of drip systems for applying fertilizers with the same precision as the water applications have not been extended to fertilizer programs where phosphates are needed by the crop. Phosphate nutrition, unlike many other essential plant nutrients, is a matter of constant need throughout the growing season and is proportional to the size and vigor of the plant. Ideally, they should be available to the crop in steadily increasing amounts for the whole the growing season. Typically, phosphates are applied as a dry material, in one large dose, often prior to planting. Uptake of phosphate by the plant from the root zone competes with a variety of chemical and mineralogical reactions that can significantly reduce the availability of the nutrients over time. Frequent small applications of phosphate as in chemigation through a drip system would allow for a much more efficient application program and better utilization by the crop. Unfortunately fears of permanent plugging of the drip system by chemical precipitates prevents the use of this potentially effective method of phosphate fertilizer application.

A contributing factor to the problem of chemigation with phosphate is the fact that there are only a few common forms of the fertilizer and each has the potential to react with Calcium in the irrigation water. Nitrogen, Potassium and most micro-nutrient fertilizers are available in a variety of formulations many of which have high solubility. That is not the case for the phosphates. Liquid forms of phosphate fertilizers are limited to Phosphoric acid (0-54-0) and Ammonium Phosphate solution (10-34-0). Phosphoric acid is usually very expensive and 10-34-0 is commonly assumed to form precipitates with even a small amount of Calcium in the irrigation water. Recently, the CSU Fresno – Center for Irrigation Technology was approached by the manufacturer of an organic based liquid phosphate fertilizer. The possibility that an organic complex containing the phosphate might be less likely to react with Calcium in the water suggested this new form of phosphate fertilizer might be more successful in a chemigation program.

A testing program was devised to compare the organic-phosphate material along with the two common inorganic forms in drip tape using poor quality, high Calcium irrigation water. The testing program was designed to evaluate the plugging potential of the fertilizers under conditions at least as extreme as those encountered in the field. A very high application rate of phosphate was used in both new and used tapes and with water sources selected for high salinity and Calcium content. A combination with other fertilizers containing Calcium was also part of the test. The results were somewhat surprising and, while the organic phosphate material did appear to be less of a plugging problem, the most interesting conclusion from this evaluation was the fact that each of the drip tapes tested maintained a normal delivery under conditions that were initially expected to cause serious plugging. While this simple series of tests should not be construed as conclusive proof that phosphates can be applied through drip tapes without any danger of plugging, it does indicate the fact that the ability of modern drip tapes to handle poor quality water and solids has been considerably underestimated.

Methodology

The effects of adding three fertilizer materials, (10-34-0 liquid ammonium phosphate, 0-54-0 phosphoric acid, and a organic based phosphorus fertilizer) on drip tape flows were evaluated with various water sources. A system traditionally used to test plugging of drip tape by sand particles from media filters was used for the tests. The system entails a pump, pressure regulation system, heat exchanger, and two 25 ft. runs of drip tape used to test plugging or reduced flow rates (Fig. 1). Once water and fertilizer was emitted from the drip tape it was re-circulated through the system continually. Flow rates were recorded periodically during the test.

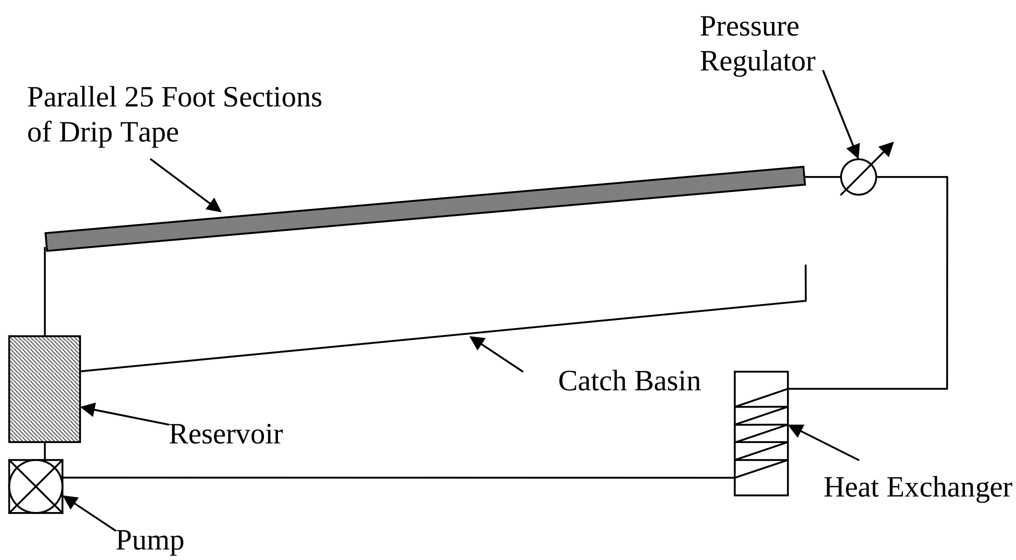

Fig. 1 Schematic of drip testing apparatus

Flow rates of individual emitters were recorded with volumetric cylinders over a two minute period and converted to gallons per hour. Initials tests of the study were run for a time period of four hours but latter tests were extended in time to induce more plugging. The initial tests included five readings for each test. Reading #1 before addition of fertilizer, reading #2 thirty minutes after addition of fertilizer, reading #3 two hours after the addition of fertilizer, reading #5 four hours after addition of fertilizer, and reading #6 after flush of system with test water. Fertilizers were added to the system by pouring a stock solution into the reservoir. The extended tests were similar to the shorter test but additional readings were made every two hours until late in the day approximately fifteen hours after the start of the test they system was shut-down for the night. The testing system was restarted the next morning, allowed to run for thirty minutes, after which flow rates were recorded. Depending on severity of plugging a flush with clean test water or phosphoric acid (0-54-0) was done after which additional flow rates were recorded. Table 1. is an example the type of data created with the extended test.

Table 1. Table of data produced from extended test

Drip Tape Plugging Test Results - Drip Tape Flow Rates									
	Fertilizer		Test Water		Drip Tape				
	Organic		Coastal		Salinas Valley				
Sample Time	745	910	1040	1240	1530	1830	2130	1245	1400
Sample Description	Test Water	Fert + 0.5 h	Fert + 2 h	Fert + 4 h	Fert + 7 h	Fert + 10 h	Fert + 13 h	Fert + 28 h	Post Flush
Reading #	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5	Reading 6	Reading 7	Reading 8	Reading 9
GPH/Emitter	0.22	0.23	0.23	0.23	0.22	0.22	0.21	0.22	0.23
% of Initial Flow Rate	100%	101%	101%	101%	100%	97%	94%	100%	104%

The testing conditions were a simulation of two extreme situations in California where phosphate fertilizer could be used in vegetable production irrigated with drip tape. In each case, a typical drip tape and a poor quality water from each simulated location was used. Testing with a high quality water was also done for calibration of the testing equipment and procedures. Three types of water were used as test water for evaluation. Fresno State campus water was used to represent high quality water, tile drain water from southern Kings County with high levels of calcium and magnesium was used to represent low quality, Central Valley water, and well water from northern Monterey County with high levels of calcium was used to represent low quality Salinas Valley water.

Two types of drip tape were chosen to match the different test waters. A 6” spacing tape (Toro Aqua-Traxx EAXxx0667) typical of those used in the coastal vegetable growing regions was used for the Salinas Valley simulation and a 12’’ tape (T-Tape TSX 7XX-12-220) typical for vegetable and field crop production in the southern San Joaquin Valley was used with the tile drain water source. Both tapes were obtained from the growers who supplied the water samples. The tape was new in each case but some of the Central Valley testing was duplicated with similar tape recovered from the field after three seasons and no differences in results were apparent. The fertilizers were all applied at a rate of 150 lbs./A of P_2O_5 which is a very high rate but one that could be required for a high value vegetable crop in either location.

The original testing procedure did not result in any plugging with any tape, water source or fertilizer combination. The four hour period with the fertilizer in the tape was apparently insufficient time to allow the chemical precipitation to form. The test procedure was modified to increase the time and add a second cycle to simulate a second irrigation with the fertilizer remaining in the tape between irrigations. Plugging was observed with this longer test procedure. Figure 2 and Table 2 show the Salinas Valley test with 10-34-0 and the tape was almost completely plugged by the end of the first run and did not recover at the beginning of the second irrigation cycle. The test equipment failed during the second cycle so the flushing with acid to test the recovery from the plugging could not be completed. Table 3 and Figure 3 show the same fertilizer with good water and the Central Valley tape. The results were similar to those in Table 2 in that complete plugging occurred at the end of the first irrigation and the interval before the second. In this case, flushing with acid was able to restore about 40% of the emitters to nearly their original flow rate. The organic based phosphate fertilizer caused some reduction in flow rate under the same conditions but the loss was about 10% compared to nearly 100%

plugging with the 10-34-0. Recovery after flushing with water in the second irrigation restored the original flow rate of the tape for both the Salinas Valley simulation, Table 4 and Figure 4 and the Central Valley simulation, Table 5 and Figure 5.

These simulations, while intentionally extreme, are not intended to be proof that phosphate fertilizers can be safely applied through drip tape. The chemical precipitates can still form and plug the tape under field conditions similar to these. The interesting results found in the tests were these:

1. The chemical precipitation may require several hours to form and cause plugging. Short irrigation periods and short chemical applications within those short irrigations may be safer than long runs.
2. Phosphate fertilizer remaining in the tape because of insufficient post-application flushing can be responsible for additional plugging problems.
3. Some forms of phosphate fertilizers may produce significantly less chemical precipitate than other forms.
4. Tapes in current use are capable of being flushed after partial plugging with phosphate fertilizers to restore some, and perhaps all of the original performance.

It would appear that the "fatal plugging" by fertilizers of drip tape and emitters that was observed in the first years of the use of drip irrigation is not as big a problem as it once was. The use of phosphate and other low solubility fertilizers may be considered for chemigation programs with appropriate testing and careful monitoring, flushing and maintenance of the system.

Table 2 Table summarizing data evaluating 10-34-0, coastal water, and Salinas Valley drip tape

Drip Tape Plugging Test Results - Drip Tape Flow Rates			
Fertilizer	Test Water	Drip Tape	
10-34-0	Coastal	Salinas Valley	
Sample Time	715	2200	800
Sample Description	Test Water	Fert + 14 h	Fert + 24 h
Reading #	Reading 1	Reading 8	Reading 9
GPH/Emitter	0.23	0.02	0.01
% of Initial Flow Rate	100%	9%	6%

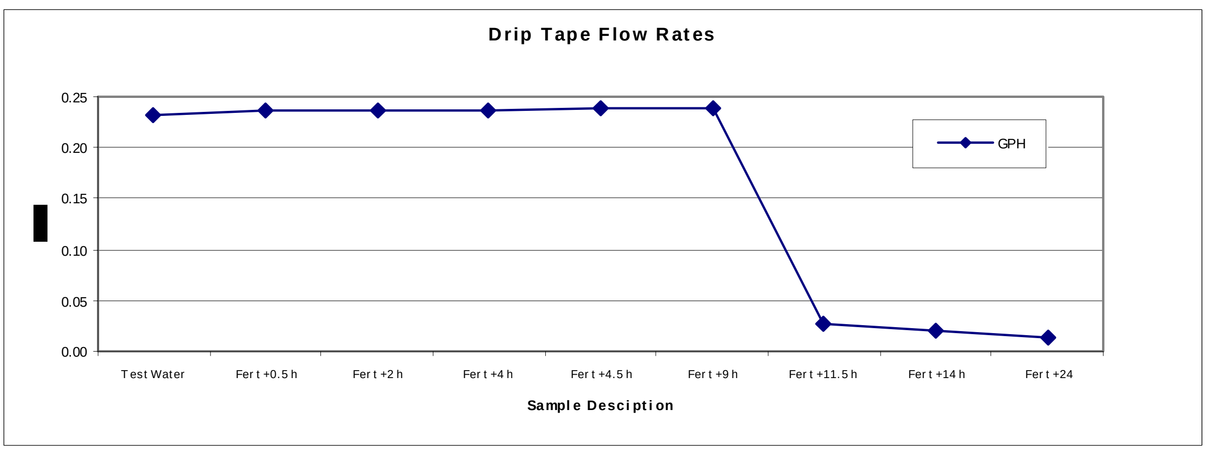

Fig. 2 Graph illustrating reduction of drip tape flow rates when running 10-34-0 and coastal water through Salinas Valley drip tape

Table 3 Table summarizing data evaluating 10-34-0, campus water, and Central Valley drip tape

Drip Tape Plugging Test Results - Drip Tape Flow Rates			
Fertilizer	Test Water	Drip Tape	
10-34-0	Campus	Central Valley	
Sample Time	640	2200	850
Sample Description	Test Water	Fert + 15 h	Post Acid + Flush
Reading #	Reading 1	Reading 8	Reading 11
GPH/Emitter	0.17	0.00	0.07
% of Initial Flow Rate	100%	0%	40%

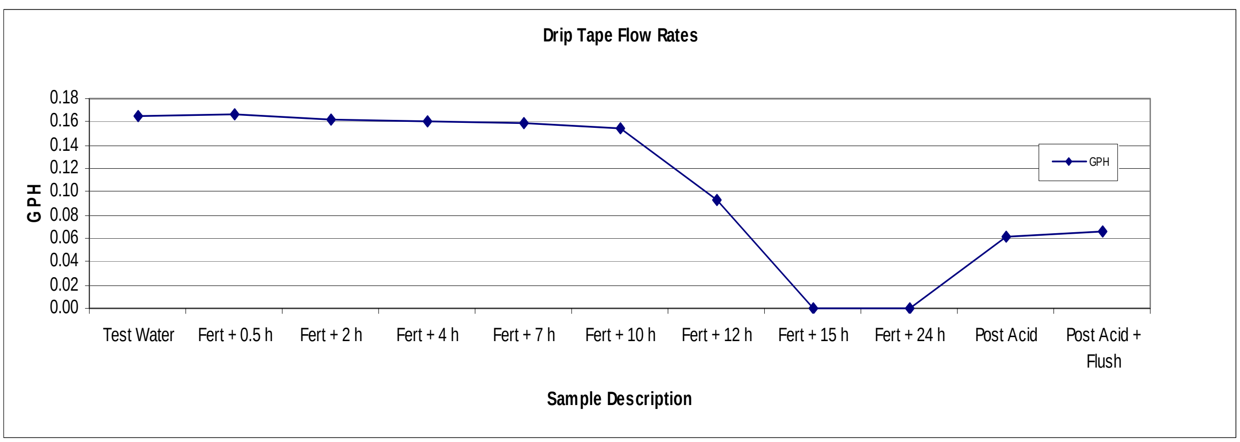

Fig. 3 Reduction in flow rates of drip tape after several hours or running 10-34-0 and campus water in Central Valley drip tape

Table 4 Table summarizing data evaluating an organic fertilizer, coastal water, and Salinas Valley drip tape.

Drip Tape Plugging Test Results - Drip Tape Flow Rates			
Fertilizer	Test Water	Drip Tape	
Organic	Coastal	Salinas Valley	
Sample Time	745	2130	1400
Sample Description	Test Water	Fert + 13 h	Post Flush
Reading #	Reading 1	Reading 7	Reading 9
GPH/Emitter	0.22	0.21	0.23
% of Initial Flow Rate	100%	94%	104%

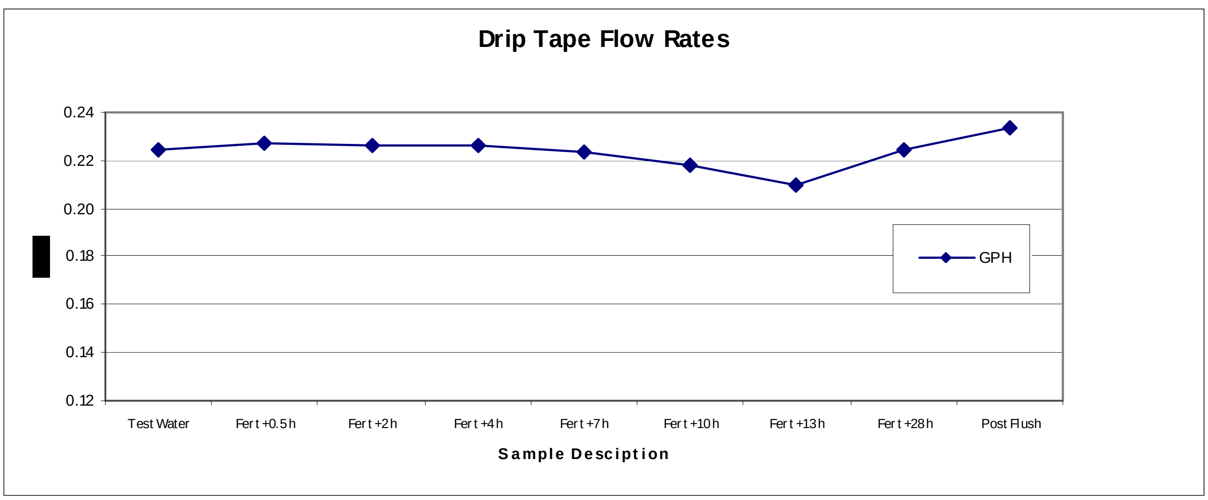

Fig. 4 Drip tape flow rates slightly decreased when running an organic fertilizer and coastal water through a Salinas Valley drip tape.

Table 5 Table summarizing data evaluating an organic fertilizer and drainage water ran through Central Valley drip tape.

Drip Tape Plugging Test Results - Drip Tape Flow Rates			
Fertilizer	Test Water	Drip Tape	
Organic	Drainage	Central Valley	
Sample Time	640	2200	900
Sample Description	Test Water	Fert + 15 h	Post Flush
Reading #	Reading 1	Reading 8	Reading 10
GPH/Emitter	0.16	0.15	0.16
% of Initial Flow Rate	100%	92%	99%

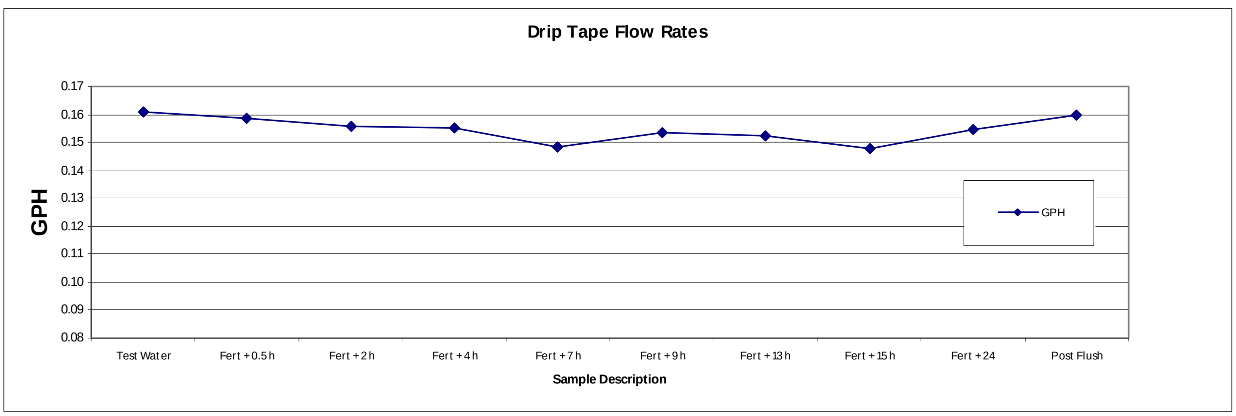

Fig. 5 Drip tape flow rates decreasing slightly when running an organic fertilizer and drainage water through Central Valley drip tape

OPTIMIZING WATER ALLOCATIONS AND CROP SELECTIONS FOR LIMITED IRRIGATION

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ABSTRACT Irrigators are facing challenges with declining well yields or reduced allocations from water districts. To make reductions in water use, irrigators are considering shifts in cropping patterns that earn better net economic returns. A cropping season planning tool, the Crop Water Allocator (CWA), available at www.oznet.ksu.edu/mil , has been developed to find optimum net returns from combinations of crops, irrigation amounts, and land allocations (crop rotations) that program users choose to examine. Because personal computers can bring solutions to complex questions, this program can be used by individual irrigators at their workplace. The model uses yield-irrigation relationships for 280-530 mm of rainfall in western Kansas. The user can customize the program with crop localized crop production costs or rely on default values from typical western Kansas farming operations. Irrigators are able to plan for the optimum economic use of their limited water supply by testing their options with CWA.

Groundwater declines and dwindling surface water deliveries are normal rather than infrequent. Record energy costs are driving irrigators to fewer applications or crops that require less water. Irrigators have adjusted by turning to more efficient irrigation application techniques and water-conserving cropping practices. All of these measures have given incremental improvement to the use and effectiveness of water at the farm level.

Irrigators choose crops on the basis of production capabilities, economic returns, crop adaptability to the area, government programs, crop water use, and their preferences. When full crop evapotranspiration demand cannot be met, yield-irrigation relationships and production costs become even more important inputs for management decisions. Under full irrigation, crop selection is driven by the prevailing economics and production patterns of the region. Crops that respond well to water, return profitably in the marketplace and/or receive favorable government subsidies are usually selected. These crops can still under perform in limited irrigation systems, but management decisions arise as water is limited: should fully watered cops continue to be used; should other crops be considered; what proportions of land should be devoted to each crop; and finally, how much water should be apportioned to each crop? The final outcome of these questions is returning the optimal net gain for the available inputs.

Determining the relative importance of the factors that influence the outcome of limited-irrigation management decisions can become complex. Commodity prices and government programs can fluctuate and change advantages for one crop relative to another. Water availability, determined by governmental policy or by irrigation system capacity, may also change with time. Precipitation probabilities influence the level of risk the producer is willing to assume. Production costs give competitive advantage or disadvantage to the crops under consideration.

With computationally powerful personal computers becoming common on the desks of irrigators during the last 5 years, mathematical models for decision tools can be given to managers at their work place. The objective of this project has been to create a decision tool with user interaction to examine crop mixes and limited water allocations within land allocation constraints to find optimum net economic returns from these combinations. This decision aid is for intended producers with limited water supplies to allocate their seasonal water resource among a mix of crops. But, it may be used by others interested in decisions concerning allocating limited water to crops. Decisions are intended as a planning tool for crop selection and season allocations of land and water to crop rotations.

BACKGROUND

Net economic return occurs is calculated for all combinations of crops selected and the water allocated. Subsequent model executions of land-split (crop rotation) scenarios can lead to more comparisons. The land split options are: 50-50; 25-75; 33-33-33; 25-25-50; 25-25-25-25. Irrigation system parameters, production costs, commodity prices, yield maximums, annual rainfall, and water allocation were also held constant for each model execution, but can be changed by the user in subsequent executions. The number of crops eligible for consideration in the crop rotation could be equal to, or greater than, the number of land splits under consideration. Optimum outcomes may recommend fewer crops than selected land splits. Fallow is considered as a crop (cropping system selection) because a valid option is to idle part of a field or farm.

The model examines each possible combination of crops selected for every possible combination of water allocation by 10% increments of the gross allocation. The model has an option for larger water iteration increments to save computing time. For all iterations, net return to land, management, and irrigation equipment is calculated:

Net return = (commodity price) X (yield) – (irrigation cost + production cost)
(1)
where:

commodity prices determined from user inputs,
crop yields calculated from yield-irrigation relationships derived from a simulation model based on field research,
irrigation costs calculated from lift, water flow, water pressure, fuel cost, pumping hours, repair, maintenance, and labor for irrigation, and
production costs calculated from user inputs or default values derived from Kansas State University projected crop budgets.

All of the resulting calculations of net return are sorted from maximum to minimum and several of the top scenarios are summarized and presented to the user.

One of the features of CWA is that the user can choose among five land splits or fixed configurations of dividing the land resource (50-50; 25-75; 33-33-33; 25-25-50; 25-25-25-25). These splits reflect the most probable crop-rotation patterns in western Kansas. The user can examine the results of each one of the land splits in sequential executions of the model, but the algorithm treats land split as a constant during an individual scenario. Producers divide their fields into discrete parcels, and rotate their crops in this same pattern, which led to this simplifying assumption and to the possibility of an iterative solution of the model.

The grain yield-irrigation relationship forms the basis for calculating the gross income from the crop Irrigation translates into grain yield, which combines with price to determine income. Grain yields for corn, grain sorghum, sunflower, and winter wheat were estimated by using the “KS Water Budget v. T1” software. Software development and use are described in Stone et al. (1995), Khan (1996), and Khan et al. (1996). Yield for each crop was estimated from relationships with irrigation amount for annual rainfall and silt loam soils with loess origins derived from research in the High Plains of western Kansas and eastern Colorado. The resulting yield-irrigation relationship for grain sorghum (fig. 1) shows a convergence to a maximum yield of 10.7 Mg/ ha (159 bu/ac) from the various combinations of rainfall and irrigation. A diminishing-return relationship of yield with irrigation applied was typical for all crops. Each broken line represents normal annual rainfall for an area.

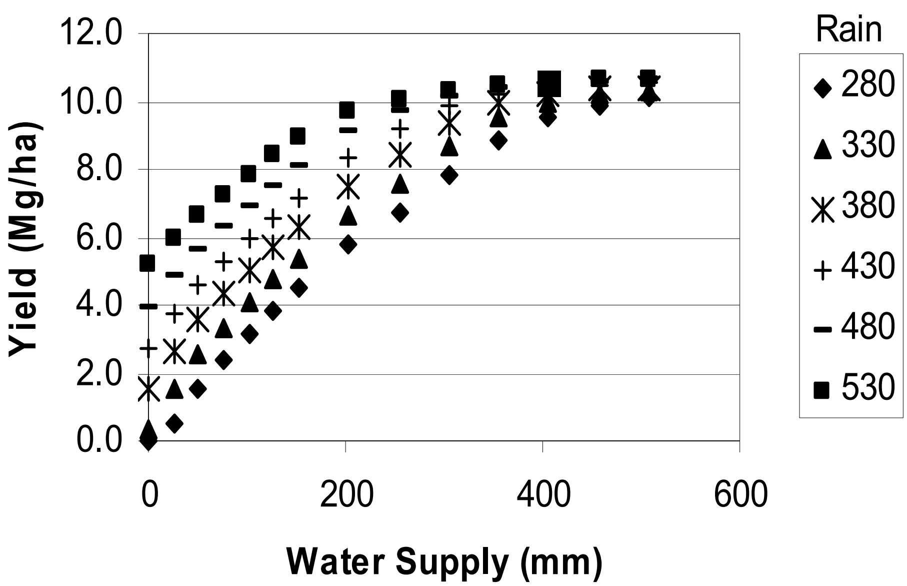

Figure 1. Yield-irrigation relationship for grain sorghum with annual rainfall from 280-530 mm (11-21 in).

The crop production budgets are the foundation for default production costs used in CWA. Program users can input their own costs or bring up default costs to make comparisons. For western Kansas, cost-return budgets for center-pivot irrigation of crops (Dumler and Thompson,

2004) provided the basis for default production-cost values for CWA. Results can be sensitive to production costs, which require realistic production inputs.

The program was designed with user-friendly, customized interface screens with discrete input information cells or keyed actions. The input cells have drop-down choices, where appropriate, and direct links to help information. A help library is also available that serves a technical guide for the program. Information inputs are categorized into general, irrigation, and crop production, according to the input screens receiving the data. Each crop has a separate production-cost screen. User inputs including water supply, irrigation costs, crop production costs, commodity prices, and maximum crop yields can be tailored to user circumstances. These inputs directly influence the selection of the optimum crop rotation, water allocation among those crops, and ultimate net return of the cropping system. The Crop Water Allocator can be found at: www.oznet.ksu.edu\mil

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REFERENCES

Dumler, T.J. and C.R. Thompson. 2004. Center-pivot-irrigated cost-return budgets in western Kansas. Kansas Farm Management Guides. Kansas State University Agricultural Experiment Station and Cooperative Extension Service, Manhattan, KS.

Kansas State University. 2004. Crop Water Allocator (CWA): KSU Mobile Irrigation Lab. Available at: www.oznet.ksu.edu/mil ,Accessed 25 April 2005
.

Khan, A.H. 1996. KS Water Budget: Educational software for illustration of drainage, ET, and crop yield. Ph.D. diss. Kansas State Univ., Manhattan (Diss. Abstr. 96-29047).

Khan, A.H., L.R. Stone, O.H. Buller, A.J. Schlegel, M.C. Knapp, J.-I. Perng, H.L. Manges, and D.H. Rogers. 1996. Educational software for illustration of drainage, evapotranspiration, and crop yield. J. Nat. Resour. Life Sci. Educ. 25:170-174.

Stone, L.R., O.H. Buller, A.J. Schlegel, M.C. Knapp, J.-I. Perng, A.H. Khan, H.L. Manges, and D.H. Rogers. 1995. Description and use of KS Water Budget v. T1 software. Resource Manual, Dep. of Agron., Kansas State Univ., Manhattan, KS.

Improved irrigation through technology and community engagement

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Abstract

While many irrigators are aware that improved technology can increase their control of water, the implementation of these improvements is often limited by external supply and regulatory systems. In a study of a large irrigated area of south eastern Australia, it was evident that significant improvement in water productivity and irrigation efficiency came when irrigated communities were able to combine improved delivery systems and on-farm irrigated practice. The study brought together the bio-physical and socio-economic information that illustrates the use of resources, the water productivity and the differences in performance of different regions. From this analysis it was possible to identify where new opportunities might be available and how irrigation might adapt to an increasingly variable resource and market environment. Further improvement in water productivity will be possible when the introduction of more control technology is combined with improvements in water delivery systems, institutional arrangements and learning support.

The irrigated areas of inland, south eastern Australia are largely associated with two large, connected river systems, the Murray and Murrumbidgee. These rivers arise in the catchments of the eastern and southern highlands and then generally run in a westerly direction through 1000 km of semi arid country. Water from these rivers and their associated storages is used in extensive surface irrigated areas on the flat riverine areas in the east, while in the downstream, westerly regions irrigation occurs in quite narrow ribbon developments along either side of the river. Almost all of these irrigated developments are less than 100 years old, several are less than 50 years old but all areas are actively upgrading and refurbishing the water delivery infrastructure.

Irrigated regions in the Murray and Murrumbidgee Basins

For this study the irrigated areas of the Murray and Murrumbidgee Basins were grouped into ten regions as illustrated in Figure 1.

Within the study regions, the total area irrigated grew by 21% between 1996/97 to 2000/01 to reach 1,243,000 ha. This accounted for 49% of the total irrigated area of Australia.

These regions diverted 8,608 GL[1] of water for irrigation which is about half the total water used for irrigation in Australia. Of the water diverted, 6,656 GL (77%)

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[1] GL = Gigalitre = 10^6 m^3 = 1000 Megalitres (ML) = 10^9 litres

was recorded as being delivered to farms. Recent collation of runoff and inflow to the storages and tributaries of these major rivers indicates that, on average just more than 50% of this inflow is diverted for irrigation.

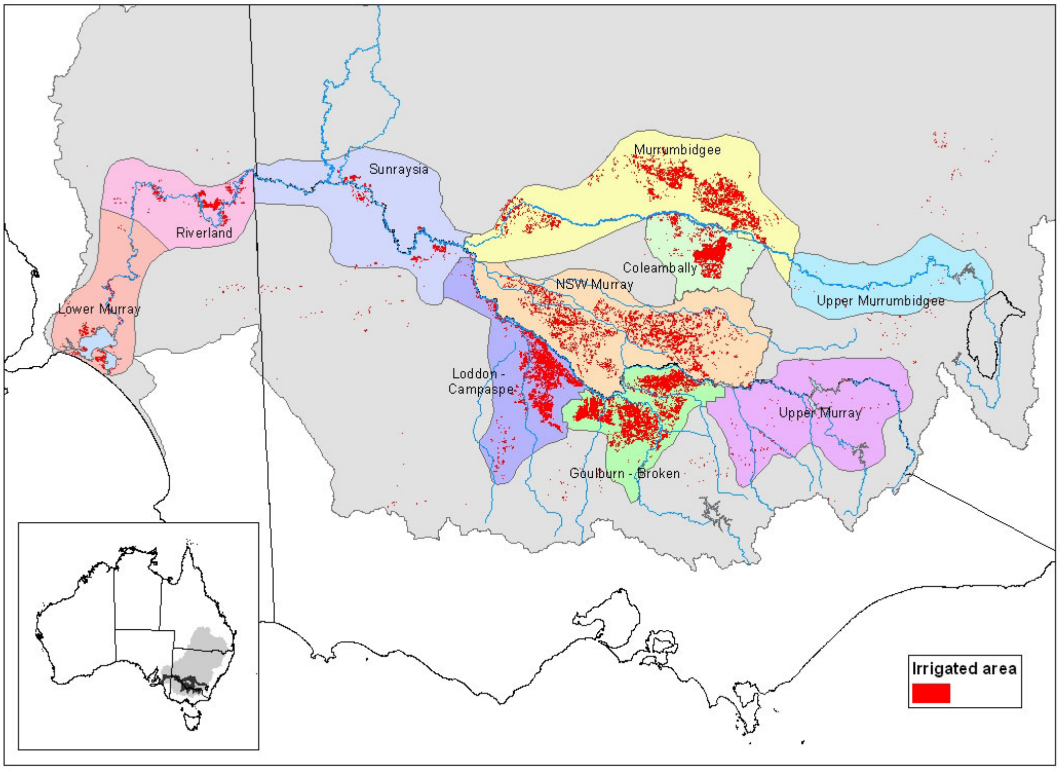

Figure 1 - Location of the nominated regions and distribution of irrigated land area in the Murray and Murrumbidgee Basins.

Water for irrigation is directed through extensive supply and drainage channel infrastructure that has an estimated replacement value of $Aus3.8 billion. This off-farm investment is complemented by an asset value on-farm of $Aus6.3 billion. At the farm level the area irrigated by different application systems is in the ratio of 83:10:7, surface : sprinkler : micro, respectively.

Irrigation – what does it produce and how much is it worth?

With all this infrastructure, water and expertise, what does irrigation in these regions produce? They produce 19% of Australia's vegetables, 50% of all fruit and nuts and 63% of all grapes. The combined estimated revenue for these commodities is $Aus1.7 billion or 40% of all fruit, nut and vegetable production (irrigated and rain-fed) in Australia.

The largest estimated profits for 2000/01, in aggregate, were generated by dairy ($Aus329m), grapes ($Aus289m) and fruit and tree nut crops ($Aus126m). As expected, the largest profits on a per ha and per ML basis were the intensive horticultural activities; vegetables ($Aus941/ML), grapes ($Aus651/ML) and fruit and tree nut crops ($Aus472/ML).

Comparing irrigated and rain-fed districts shows that the total water input from irrigation above rainfall was 2.4 times greater (4.47 ML/ha rain-fed, 10.93 ML/ha rain plus irrigation), with a revenue generation that is 13.1 times greater ($Aus52.45/ML rain-fed, $Aus686.83/ML rain plus irrigation). This increased revenue supports a level of economic activity that is three to five times greater than in the adjacent rain-fed district. The population is greater; there are more businesses, more employment and significantly more services.

The combination of "upstream" and "downstream" dependant activities associated with dairy, fruit, vegetables and wine grapes has an average economic multiplier of 3.5. This means that for every $Aus1000 of farm gate revenue generated, there is an additional $Aus3,500 of dependant economic activity.

There is a substantial difference between those regions in the east (Murrumbidgee, Coleambally, NSW Murray, Goulburn-Broken) on the vast Riverine Plain and those in the west (Sunraysia, Riverland and Lower Murray) within the Murray Basin geological region. The NSW Murray region irrigates 321,000 ha with a diversion volume of more than 2,000 GL to produce irrigated revenue of about $Aus310 million. The Riverland region irrigates 36,000 ha with a diverted volume of 311 GL to produce irrigated revenue of $Aus555 million. The reasons for this difference can be attributed to fundamental differences of geology, soils, and viability of surface irrigation methods. In the "upstream" eastern regions the irrigated areas are flat alluvial plains predominately with deep clay soils while the "downstream" western areas generally adjacent to the incised river have sandy and medium textured soils often overlying calcareous deposits. Eastern regions can divert and distribute water largely without pumping, while in the western regions water needs to be lifted out of the river.

Change in water productivity over time

There are only a few examples of irrigated commodities that have tracked the change in water productivity over time. The rice industry on the Riverine plain in New South Wales (Murrumbidgee, Coleambally and NSW Murray in Figure 1) has documented the improvement in productivity over the last twenty years as illustrated in Figure 2.

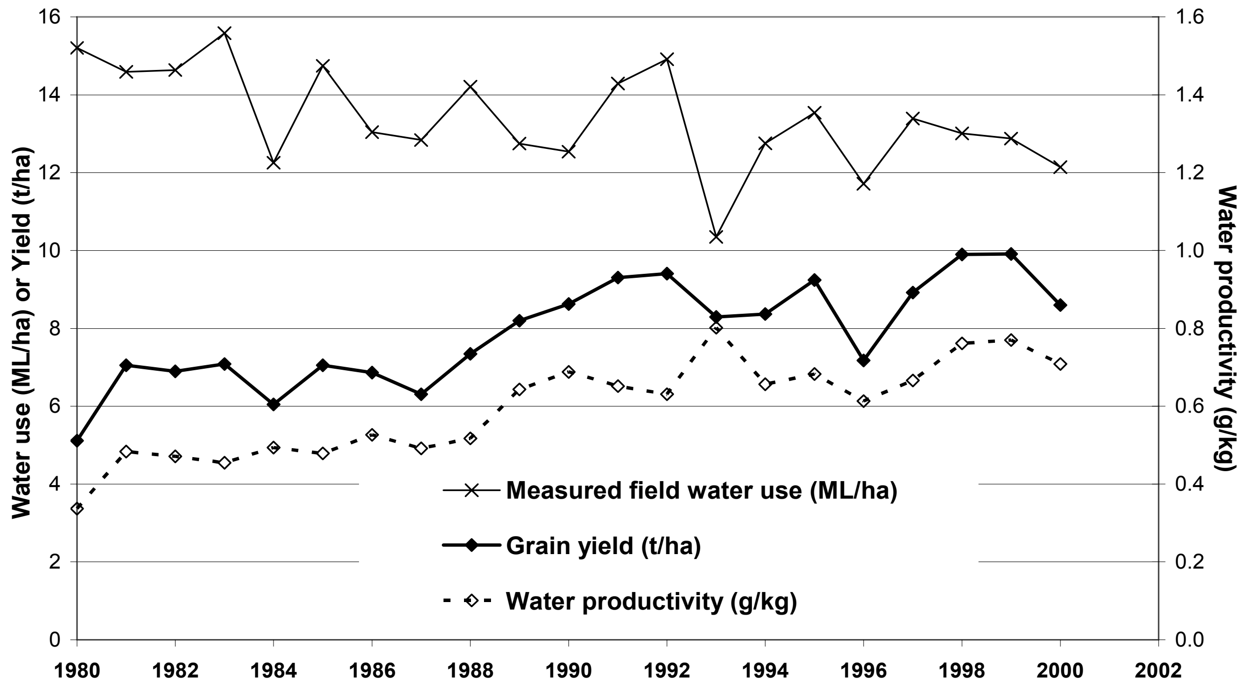

Figure 2 – Change in grain yield and water use in rice over the 20 year period to 2001 with the derived change in water productivity. Data and Figure from Humphreys and Robinson, 2003. Note: units of g/kg x 1000 = kg/ML.

Several recent studies of the irrigated dairy industry in northern Victoria (Armstrong et al 2000, Linehan et al 2004, and Melsen et al 2004) have shown the tremendous variation that exists between dairy farm water productivity – a situation that is consistent with citrus production as shown by Skewes and Meissner (1997). The survey of 170 farms between 1994 and 1996 produced water productivity values with a range from 25 to 115 kg milk fat per ML of irrigation water. A similar, although smaller, survey in 1997 to 1999 indicated that while there had been significantly different water availability conditions between the two survey periods there was no consistent evidence to indicate that limited water had improved water productivity. The Melsen et al (2004) study focused on two case study farms for which long term records had been kept. The indications are that there was a small but gradual improvement in water productivity between 1967 (45 kg milk fat /ML) and 1991 (90 kg milk fat / ML) and that this increased to 150 kg milk fat /ML in 2002. However, as Melsen et al. point out, this later rise is primarily due to the dairy farmer bringing in additional supplementary feed. The amount of irrigation water and productivity from the irrigated pasture is unlikely to have changed significantly. There appears to be some evidence of improved water productivity in dairy but given the complexity of the feed and animal interaction there is need for greater consistency in collecting the data so that we can be sure of the trend.

Other commodities have variable information on change in water productivity but none have collected this in a consistent manner similar to that of rice. A paper by Meyer in 1997 compared water use and energy conversion efficiency from average data 30 years apart(Table 1). This demonstrated that water productivity had improved in all commodities and that the major reason was increased yield rather than a consistent decrease in the water used to produce this yield. Similar anecdotal evidence comes from irrigated almonds in the Riverland and Sunraysia regions (Tony Read, Pers. Comm. 2005). In 1987 yields were about 2.7 tonnes per ha using 13 ML/ha of water. It is expected that in 2005 yields will be closer to 4 t/ha with 15 ML/ha of water use. This means that water productivity has risen from 208 to 267 kg/ML, an improvement of 28% over an eighteen year period.

Crop	Year	Yield	Water use	Water productivity
		(kg/ha)	(ML/ha)	(kg/ML)
Grapes (white)	1960	25172	10.7	2353
	1990	30000	8	3750
Oranges (fresh)	1960	30206	12.2	2476
	1990	40000	15	2667
Rice (white)	1960	5096	15.2	335
	1990	5850	12	488
Wheat (flour)	1960	911	4.6	198
	1990	3750	5	750
Tomatoes (fresh red)	1960	50300	9.1	5527
	1990	80000	8	10000

Table 1 – Example of increased water productivity over time for selected commodities. Adapted from Meyer (1994).

While we have been able to gather some data for commodity water productivity, it is clear that most recording systems are inadequate to enable a confident assessment of progress over time. There is certainly enough evidence to show that improvement is occurring; there is also enough evidence to demonstrate that there is still a very wide range of performance at farm enterprise level. Improvement is occurring and further opportunities for additional improvement are certainly indicated.

Theoretical consideration of water productivity suggests that with current genotypes it may only be possible to realise about a 30% improvement above current best practice, mostly by reducing ground surface evaporation and using higher density plantings. We therefore need to look at other parts of the water supply and irrigation system to identify possible areas for significant improvement.

Improved distribution and application

Data from the Sunraysia region for the period from 1998 to 2003 (Giddings 2004) shows that as improved irrigation delivery and application systems come into effect so the annual application of water decreased. For example, in comparable evapotranspiration and rainfall years of 1998/1999 and 2002/2003, the amount of water applied decreased from 4.56 kL/mm of evaporation minus rain down to 3.7 kL/mm, a decrease of 19%.

This decrease was associated with major shifts towards more controlled irrigation systems when there was synergistic investment in delivery system upgrades and on farm application systems. Three irrigation areas (Pomona, Coomealla and Curlwaa) converted from open channel supply systems to semi pressurised pipelines between 1989 and 2000. This resulted in a 58%, 28% and 34% reduction in the annual delivery volumes for the three areas. Immediately following the installation of these piped delivery systems there was a major shift in on farm irrigation application systems. For example, in 1997 35% of the irrigation was furrow delivered with only 13% through drip systems. By 2003, the distribution ratio was reversed, 13% by furrow, 36% by drip (Giddings, 2004). Similar responses have been recorded in other areas following upgrading of distribution systems. As a bonus, improved distribution and more controlled application systems also lead to decreased drainage to underlying groundwater and increased depths to the underlying, unconfined groundwater.

A major study of the water distribution in the Murrumbidgee River system (Pratt Water, 2004) indicated that significant water savings are possible in both the distribution system and the on farm application system. The study highlighted deficiencies in the measurement systems on the river that may account for up to 10 to 15% of the total annual flow. With the irrigation area distribution system, more than 100 GL per year, or about 10% of total delivery, could potentially be saved through greater control, reduced channel seepage and suppression of channel evaporation. Economic assessment indicated that controlling channel seepage to save up to 20 GL/year would cost from $Aus400/ML to $Aus2000/ML, depending on the methods used. To realise further water savings, the costs rise by an order of magnitude. For on farm application, analysis of possible change in the Murrumbidgee Irrigation Area indicates that water savings of 60 GL (6% of annual water diversion) would require a capital outlay of $Aus150 million. This outlay is associated with conversion of some existing horticultural crop irrigation systems to drip and some surface irrigated crops to moveable sprinkler systems. Realising water savings through improved application systems is not a linear response, however, since an additional $Aus173 to $Aus377 million would be needed to achieve a further saving of 25 GL.

Essential elements for improved irrigation practice

Where significant regional improvement in irrigated practice has occurred there has been a combined effort involving policy change, incentives, system delivery improvement, on farm practice change, community education and increased service provision. Almost always there is a common understanding of the need to act most often in the form of a threat to irrigation water supplies, from increasing drainage and salinity problems or from significant changes in commodity markets. Often, the expression of political will and leadership is needed to trigger a more concerted private sector shift. Indeed, public and private sector interaction is critical but first both parties need to be convinced that there is a better way and a more confident future.

The lesson from the Riverland rehabilitation process in which open channels were replaced with pressurised pipe supply is that capital investment in supply delivery acted as a catalyst for considerable on farm investment. The synergistic effect on improved irrigation performance occurred through improved delivery and water control and also through an improved attitude and confidence in the future of irrigation.

Significant government policy change has seen irrigation water supply entities change from government control to corporate structures. There is a range of structures across the regions and in many, governance responsibilities are still being worked out. Water access entitlements have been more clearly defined and have been uncoupled from land ownership thus enabling trade within, as yet reasonably constrained, trading conditions. Temporary and permanent trade in water access entitlement has set a market value for water that varies with storage and allocation availability. Access and allocation has taken on new importance since a limit, (a "cap") was placed on the amount of water that could be diverted from the rivers.

Our experience is that success in irrigation performance is strongly influenced by the extent of regional community involvement in these change processes. A critical element is the identification of influential community leaders who have enough commitment and persistence to work through the many technical, political, business, and community issues that accompany major change processes. These community leaders have taken a front line position in the consultation and communication needs to bring about successful change.

In many of the irrigated regions in this study there has been the development of regional land and water management plans. These have formed an important focus for government and community input. They have involved documenting the understanding of the current land use, its hydrology, groundwater and vegetation assets which then provides the basis for how these assets can be protected and used. This then triggers an assessment of the consequences of continuing with current practice (the "do-nothing" scenario) and also the assessment of some more desirable intervention scenarios. During this process community consultation is critical and has often found the level of shared understanding is quite low even of the most fundamental processes e.g. water flow patterns and drainage. Several regions have addressed this by developing formal adult education programs which have been delivered to a wide section of the community. Other regions have been well supported through post secondary education providers who have developed regionally specific short courses on irrigation and drainage practice. The deployment of increased technology in delivery and application systems means that information systems and implementation skills need to be upgraded. The education and training provision certainly assists this but there is also need for greater levels of service support in the form of equipment provision and maintenance and advice services. Without these, the uptake and continued use of improved irrigation practice may not continue.

In summary, the elements that are important for sustained regional improvement in irrigation practice and associated water productivity contain the following: shared appreciation of the imperative to act, committed leaders at political and community level, policy and regulatory provision to provide clarity and encouragement to act, combined supply and application improvement, community education and training, and ongoing improvement in equipment and advice services.

This study of the major irrigated areas of inland south eastern Australia showed that there is considerable opportunity for increased production, increased water productivity and a balance between water use for production and that for maintenance of environmental values. Realising the opportunities cannot be achieved through a piecemeal, incremental process, it requires collective action at a regional level so that irrigators, delivery system performance and institutional arrangements work together.

References

Armstrong DP, Knee JE, Doyle PT, Pritchard KE and Gyles OA. (2000). Water-use efficiency on irrigated dairy farms in northern Victoria and southern New South Wales. Australian Journal of Experimental Agriculture. 40: 643 – 653.

Giddings J. (2004). Improving irrigation efficiency in the Lower Murray Darling. Paper at Irrigation 2004. Irrigation Association of Australia Conference, Adelaide.

Humphreys E. and Robinson D. (2003). Improving water productivity in rice cropping systems in Australia: institutions and policy. In: 'Rice science: innovations and impact for livelihood.' Eds T.W. Mew, D.S. Brar, S. Peng, D. Dawe and B. Hardy. Proceedings of the International Rice Research Conference'. 16-19 September 2002, Beijing, China. International Rice Research Institute, Chinese Academy of Engineering and Chinese Academy of Agricultural Sciences.

Linehan CJ, Armstrong DP, Doyle PT and Johnson F (2004). A survey of water use efficiency on irrigated dairy farms in northern Victoria. Australian Journal of Experimental Agriculture, 44: 131 -136.

Melsen M, Armstrong D, Doyle P and Ho C. (2004). A case study of changes in production and resource use over 40 years on an irrigated dairy farm in northern Victoria. Department of Primary Industries. Future Dairy Farming Systems in Irrigation Regions – Phase 2.

Meyer WS. (1997). Smarter Irrigation - An Australian Perspective. Keynote address -Irrigation 97, Smarter Irrigation. Conference Proc. P. 1-1 to 1-7. 20-22 May 1997, Shepparton. Also in Irrigation Australia, IAA Journal **12(1)**, p 20-23.

Meyer Wayne S. (2005). The Irrigation Industry in the Murray and Murrumbidgee Basins. CRC for Irrigation Futures Technical Report No. 03/05. April 2005.

Pratt Water (2004). The Business of Saving Water: The report of the Murrumbidgee Valley Water Efficiency Feasibility Project. Published by Pratt Water, Campbellfield Victoria. 152 p.

Skewes M and Meissner T. (1997). Irrigation benchmarks and best management practices for citrus. Technical Report No. 258, Primary Industries and Resources SA, Adelaide, South Australia.

Surface irrigation management in Alabama cotton

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Abstract: Fluctuations in cotton yield in the Tennessee Valley of North Alabama are common and are usually related to drought or irregular rainfall. A sprinkler irrigation study established in 1999 evaluated a range of irrigation application intervals to identify the minimum design flow rate that will produce optimum yields. Treatments included four sprinkler irrigation intervals ranging from one inch every 12.5 days (1.5 gpm per acre) to one inch every 3.1 days (6.0 gpm per acre) and a non-irrigated treatment. Irrigation was managed using soil moisture sensors and a spreadsheet-based scheduling method. Significant yield differences between irrigated and non-irrigated were noted in most years, with rainfall variability and treatment effects accounting for a wide range of yield responses between irrigated treatments.

Introduction: While the southeastern U.S. has plenty of water available on an average annual basis, large inter-annual variability in rainfall and sporadic convective rainfall during the growing season makes purely rain-fed agriculture a poor competitor to the efficiency of irrigated agriculture. Figure 1 shows the annual distribution of rainfall in Alabama, averaging about 1320mm (52 inches) per year. The research presented in this paper is located in northern Alabama in the Tennessee Valley, an area of widespread cotton production (Figure 2).

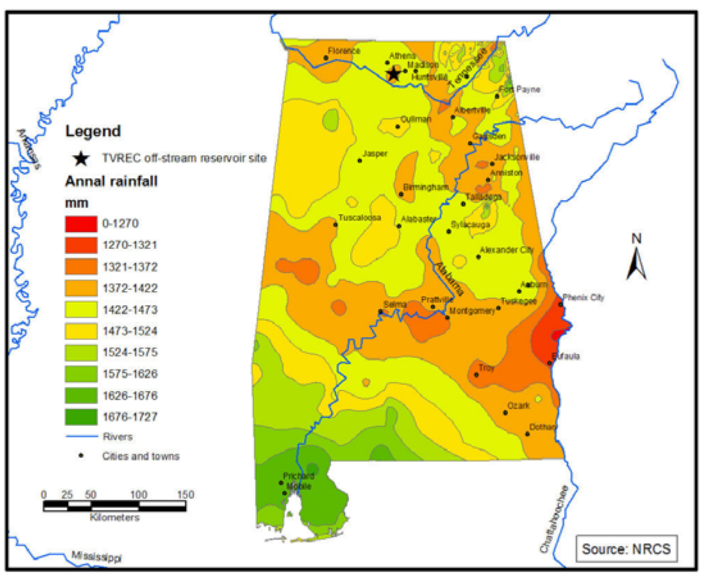

Figure 1. Annual precipitation distribution in Alabama showing location of study area (denoted by a star).

This system design capacity experiment was established in 1999 to evaluate a range of irrigation application capabilities in order to identify the minimum design flow rate that will produce optimum cotton yields. Figure 2 shows the research area and 5.3 ha (13 ac) off-stream water storage reservoir located adjacent to the study site.

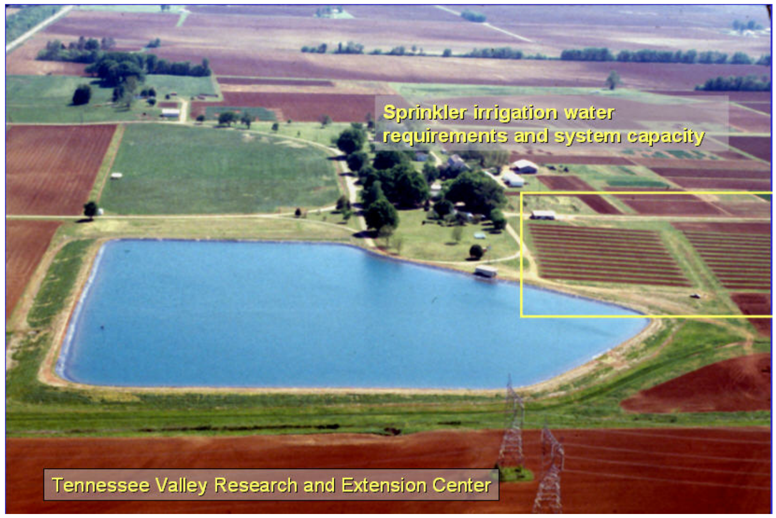

Figure 2. Oblique view south of system capacity test plots and adjacent irrigation storage reservoir, Tennessee Valley Research and Extension Center, Belle Mina, AL.

During the six years of this study, precipitation and evaporation fluctuated across a wide range, providing representative wet and dry years for comparative study (Figure 3).

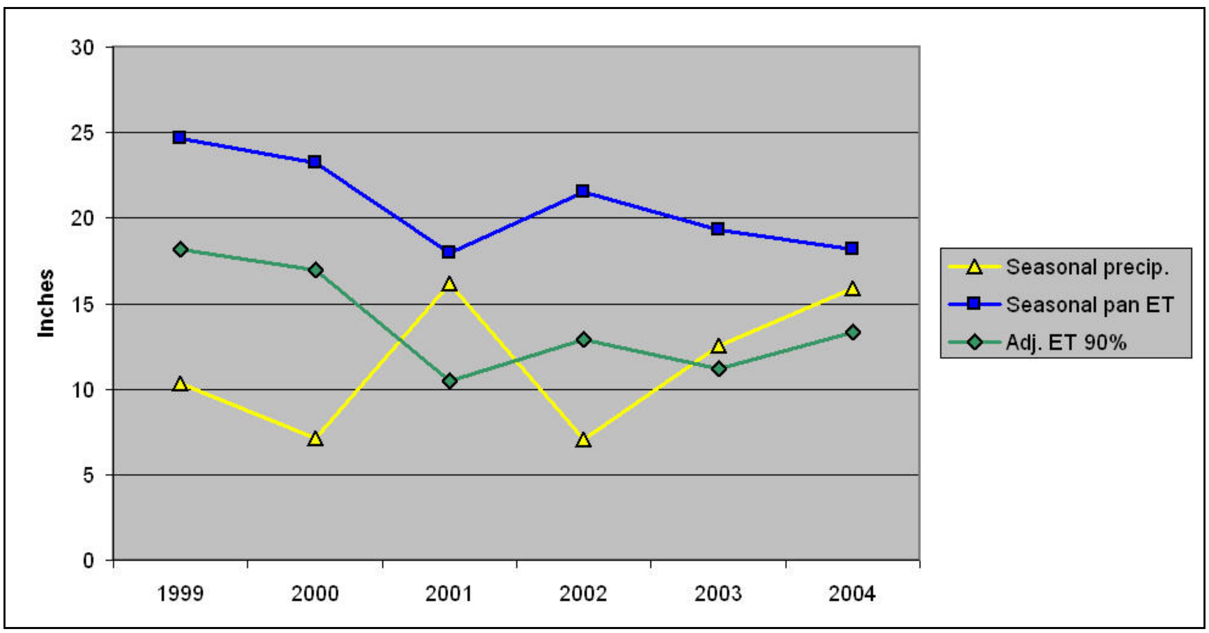

Figure 3. Seasonal precipitation (June, July, and August), pan evaporation, and adjusted evapotranspiration at Belle Mina, AL, during the 6-year study period.

Methods: Treatments included four sprinkler irrigation system capacities and a nonirrigated treatment for cotton. Cotton irrigation was managed using soil moisture sensors and a spreadsheet-based scheduling method. The irrigation system capacities tested were (1) one inch every 12.5 days, (2) one inch every 6.3 days, (3) one inch every

4.2 days, and (4) one inch every 3.1 days. These irrigation capabilities are equivalent to 1.5, 3, 4.5, and 6 gallons per minute per acre. The one-inch amount represents the maximum amount of irrigation applied in the time indicated. Figures 4 and 5 show the location and setup of the replicated treatments used in this study.

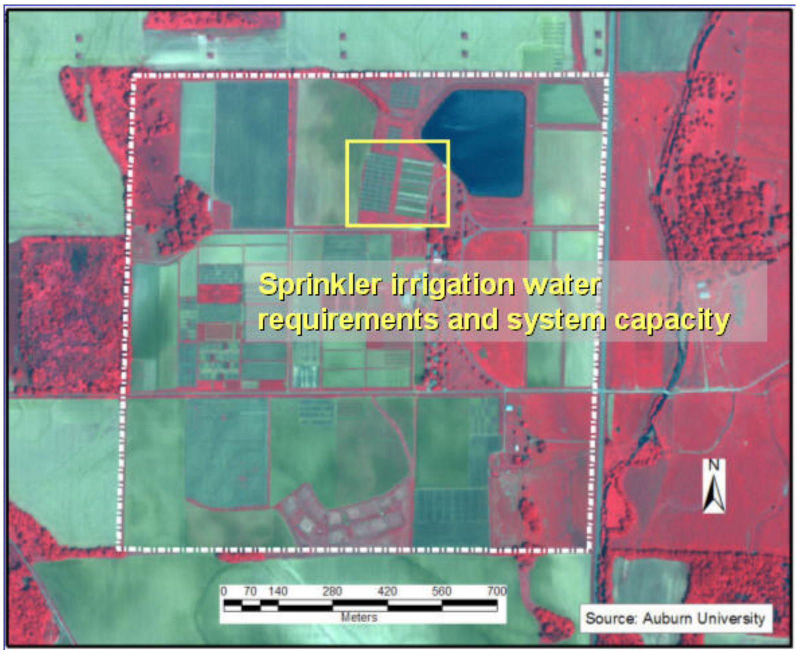

Figure 4. Location of sprinkler system capacity plots, Tennessee Valley Research and Extension Center, Belle Mina, AL.

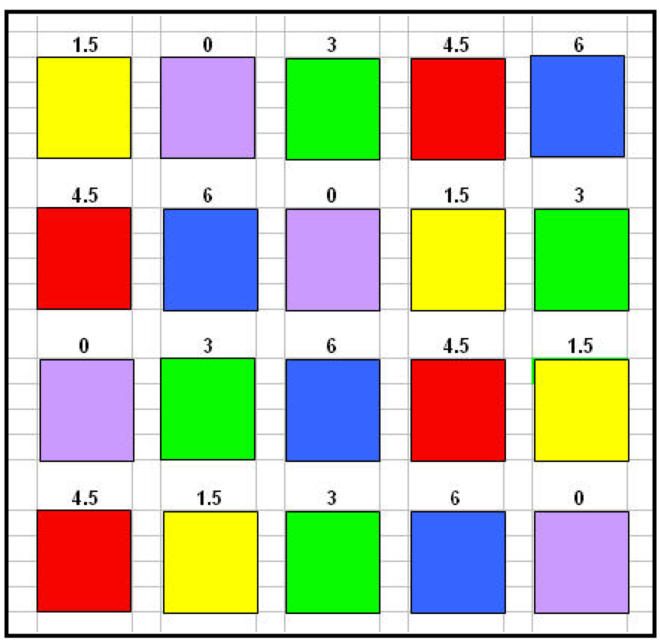

Figure 5. Sprinkler plot layout, beginning of 2002 growing season (0, 1.5, 3, 4.5, and 6 denote dryland treatment, and 1.5, 3.0, 4.5, and 6.0 gpm/ac irrigated treatments).

Individual plots were arranged as a randomize block of five treatments. Each 13.3-foot x 39-foot plot was irrigated with four quarter-throw sprinklers programmed with a "soak-and-cycle" feature to limit runoff. From 1999 to 2000, three replications of each treatment were used. In 2001, a fourth replication was added, as shown in Figure 5. Moisture management and irrigation scheduling was accomplished using Watermark ™ soil moisture sensors, and weekly data entry into a spreadsheet program, Moistcot, developed by Alabama Cooperative Extension (Tyson et al, 1996).

Results: Table 1 presents average yields for the six-year study period in pounds of seed cotton per acre. Average turnout of lint from seed cotton ranged from 35 to 38 percent during the study period.

Table 1. Yearly and average seed cotton yields for system capacity treatments, pounds per acre.

Year	Dryland	1.5gpm/ac	3.0gpm/ac	4.5gpm/ac	6.0gpm/ac
1999	1700	2637	2984	3708	3920
2000	1236	2444	3688	3603	3627
2001	3061	3387	3466	3595	3371
2002	1759	2530	2871	2853	2925
2003	3288	3579	3802	3764	3739
2004	3530	3300	3208	3505	3367
Average	2429 a	2980 a,b	3337 b,c	3505 c	3492 c

Dryland = nonirrigated
1.5gpm/ac is equivalent to 1 inch every 12.5 days.
3.0gpm/ac is equivalent to 1 inch every 6.3 days.
4.5gpm/ac is equivalent to 1 inch every 4.2 days.
6.0gpm/ac is equivalent to 1 inch every 3.1 days.
Similar subscripts (a, b, c) denote 6-year averages not significantly different at alpha value 0.10 (using standard two sample t-test).

In 2004, rainfall was plentiful throughout the growing season, and dryland and irrigated yields were not substantially different. In 2003, rainfall was near optimum through much of the growing season, but a 26-day dry period occurred between August 7 and September 4. A total of only 0.61 inches of rain occurred during this period, and this rainfall was measured in seven minor rainfall events. Three timely one-inch irrigation applications during this period boosted irrigated yields, with 476 additional pounds of seed cotton per acre on the optimum irrigation treatment (one inch every 4.2 days).

In 2002, irrigated yields were significantly higher than nonirrigated yields, but the highest yields were less than in other years for most treatments. The reason for this is unclear but may be related to shutdown of irrigation prior to sufficient boll maturity. Only very small yield differences were noted in 2001, while significant differences were measured in 1999 and 2000. Rainfall variability and treatment effects accounted for the wide range of yield responses for each of these years.

Discussion and summary: Figure 6 shows comparative seed cotton yields from each treatment from1999 to 2004. For the lowest irrigation design flow, 1.5 gpm/ac (1 inch every 12.5 days) yields track those of dryland cotton and in fact are not signicantly different from dryland yields (Table 1). The next highest irrigation design flow, at 3.0 gpm/ac (1 inch every 6.3 days) does not have yields significantly different from 1.5 gpm/ac, but has average 6-year yields significantly higher than dryland cotton. The highest irrigation design flow rates, 4.5 and 6.0 gpm/ac (1 inch every 4.2 and 3.1 days, respectively) result in yields significantly higher than both dryland and 1.5 gpm/ac treatments.

Graphical results (Figure 6) reveal that yields from dryland cotton and the lowest irrigation design flow (1.5 gpm/ac) track seasonal precipitation. The data from this study suggest that the minimum design flow rate that will produce optimum yields in irrigated cotton is 4.5 gpm/ac, which is equivalent to approximately one inch every 4.2 days. This information can be used to optimize the design of pivot irrigation pumping plants by matching pump and storage facility size to the total area irrigated.

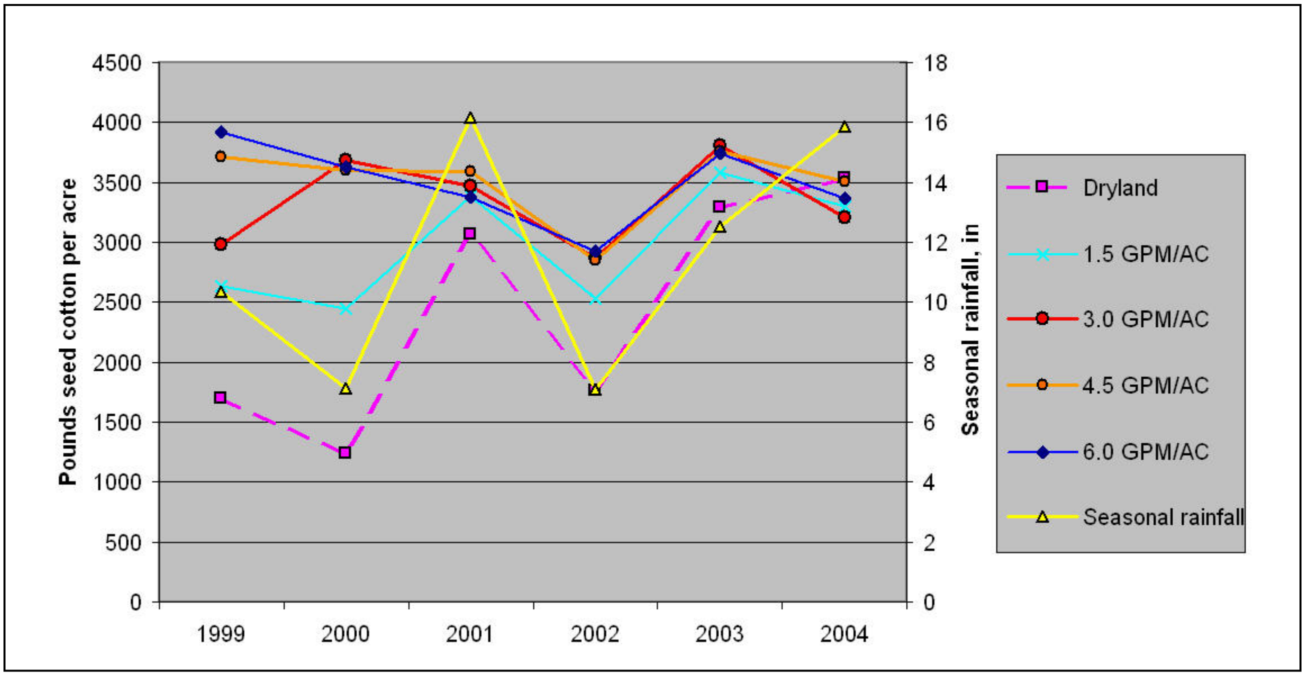

Figure 6. Yield response, pounds of seed cotton, of four irrigated system capacity treatments versus one nonirrigated treatment, 1999-2004, Belle Mina, AL.

References:

Curtis, L.M., Burmester, C.H., Harkins, D.H., and Norris, B.E. 2004. Sprinkler irrigation water requirements and irrigation scheduling, Tennessee Valley Research and Extension Center. In: 2004 Cotton Research Report No. 26, April, Alabama Agricultural Experiment Station.

Dougherty, M., Fulton, J.P., Curtis, L.M., Harkin, H.D., and C.H. Burmester. 2005. Subsurface Drip Irrigation and Fertigation in Northern Alabama. Paper No. 052208. Presented at 2005 ASAE Annual International Meeting, Tampa, Florida, 17 - 20 July 2005.

Fulton, J.P., Dougherty, M. P., Curtis, L.M., Harkin, H.D., and C.H. Burmester. 2005. Subsurface Drip Irrigation (SDI) scheduling and tape placement for cotton production in Alabama. Paper No. 052244. Presented at the 2005 ASAE Annual International Meeting, Tampa, Florida, 17 - 20 July 2005.

Tyson, T.W., Curtis, L.M., and Burmester, C.H. 1996. Using Moiscot: Moisture Management and Irrigation Scheduling for Cotton.Circular ANR-929. The Alabama Cooperative Extension System, Auburn. AL.

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Irrigation Scheduling Using the Oklahoma Mesonet

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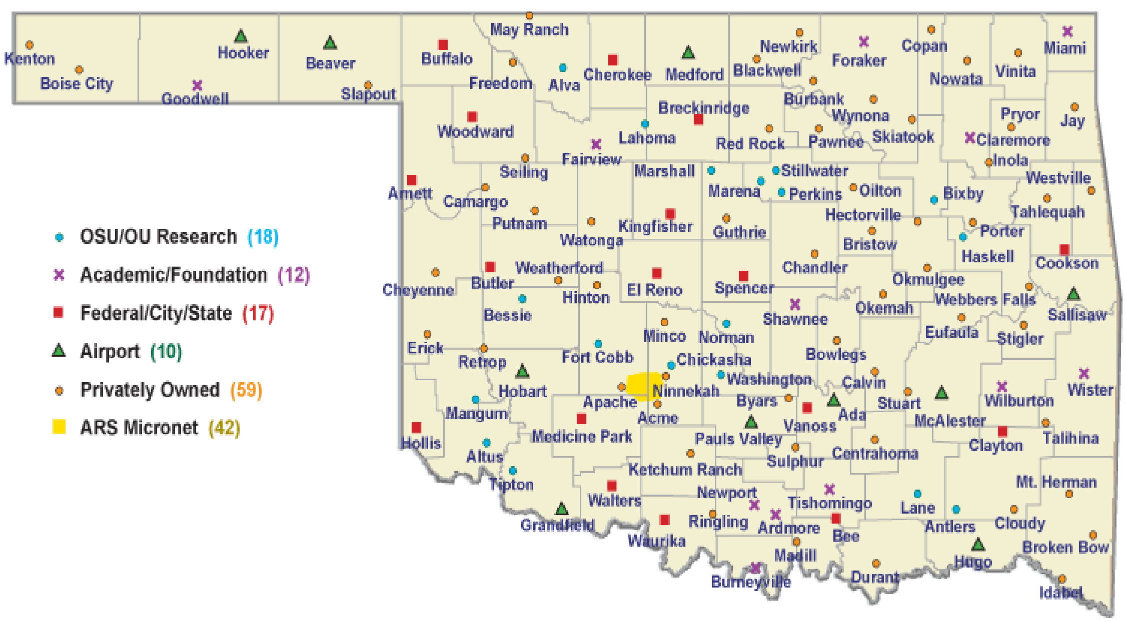
Evapotranspiration estimates are one of the value-added weather products available on the Oklahoma Mesonet agricultural website (http://agweather.mesonet.org/). Daily reference evapotranspiration estimates from the Penman-Monteith equation are posted for irrigation managers who use water balance scheduling methods. Daily evapotranspiration estimates calculated using crop coefficients based on user-supplied planting dates and maturity periods for the major crops of Oklahoma are posted to pages dedicated specifically to that crop. Daily and cumulative water use for major crops are reported in a tabular output which allow agricultural producers and homeowners to estimate water use by crops and turf grass for periods from one day to several days. The Oklahoma Mesonet is a network of 117 automated weather stations that cover all 77 counties in Oklahoma with an average station spacing of 30 km. Data are beamed by radio to a central processing site every 5 minutes, error-checked and posted on the Mesonet website.

Introduction

The Oklahoma Mesonet is a statewide network of 117 automated weather stations that has been operational since 1994 (Brock et. al., 1995). The network is a cooperative effort between the University of Oklahoma and Oklahoma State University. The stations have an average spacing of 30 km and are distributed throughout all 77 counties of Oklahoma. (Figure 1.)

Figure 1. Distribution of Mesonet weather stations in 2003.



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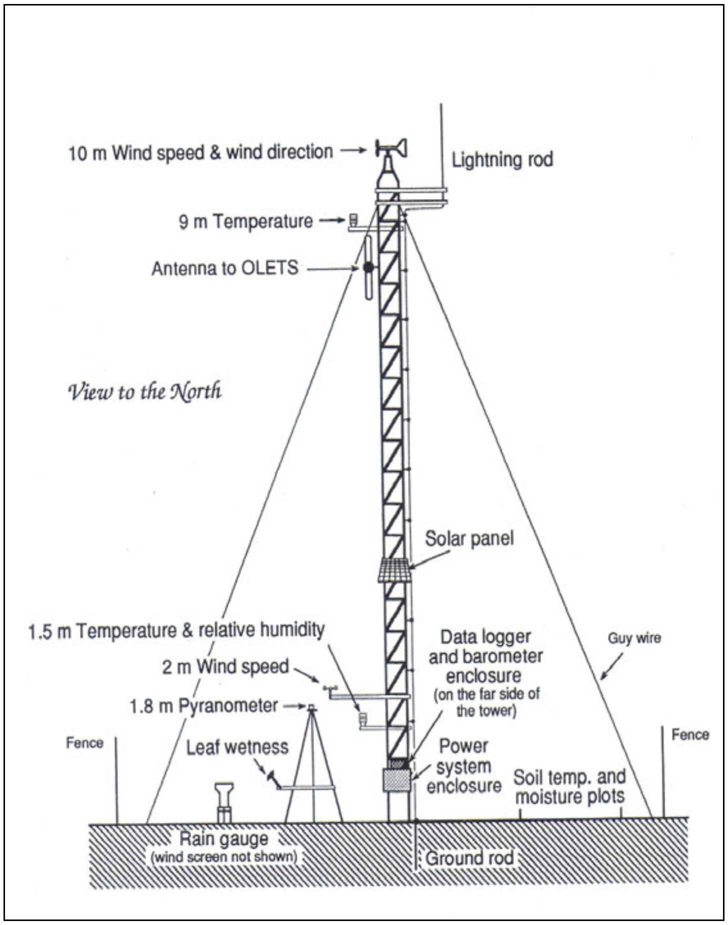
The Mesonet stations collect a wide array of weather data for meteorological, environmental and agricultural research, as well as for public safety purposes (Elliott, et. al., 1994). The data are collected every 15 seconds for a 5-minute period. The 5-minute averages are then sent by radio to the nearest Oklahoma Law Enforcement Telecommunication Service (OLETS) station and then relayed to the Mesonet central computer in Norman, OK. (Figure 2)

Figure 2. Mesonet station configuration and measured parameters.



Weather Parameters Measured

Core Parameters
(measured at all sites)

- Solar Radiation
- Air Temperature (1.5 m)
- Relative Humidity (1.5 m)
- Wind Speed (10 m)
- Wind Direction (10 m)
- Rainfall
- Barometric Pressure
- Soil Temperature (10 cm bare)
- Soil Temperature (10 cm grass)

Supplemental Parameters
(measured at about half of the sites)

- Air Temperature (9 m)
- Wind Speed (2 m)
- Soil Moisture
- Soil Temperature (5 cm bare)
- Soil Temperature (5 cm grass)
- Soil Temperature (30 cm grass)

The raw data are analyzed for quality assurance and processed into a variety of end products. The raw data and end products are posted to a number of Mesonet websites within 10 minutes of collection in most cases. Some of the data are available on websites which require a user's fee, while others are free to the general public.

Agweather Page

The Agweather webpage (http://agweather.mesonet.org) is a public webpage which houses a wide variety of agriculture-related weather information available through Mesonet. The weather data and products on the Agweather webpage are organized in seven general categories: Weather, Soils, Livestock, Rangeland, Crops, Horticulture, Forestry. Users can find an array of weather related information and products related to each category on the appropriate sub-page.

On the Weather page raw data, summaries and end products for the current measurement period can be viewed. One of the end products available is Standardized Reference Evapotranspiration (ET_{sz}).

Reference Evapotranspiration

The Standardized Reference Evapotranspiration (ET_{sz}) calculation used on Mesonet webpages follows the recommendation of the Standardization of Reference Evapotranspiration Task Committee of the Environmental and Water Resources Institute of the American Society of Civil Engineers (ASCE) in their final report of July 9, 2002. A complete explanation of the computation process is viewable on-line by clicking on the information button (? INFO) in the upper right-hand corner of the appropriate webpages. Both short (ET_{os}) and tall (ET_{rs}) crop reference values are available for use in computer-based irrigation scheduling programs. These reference ET values, plus many of the weather-dependent intermediate variables used to compute them, are available on the reference ET webpage (Figure 3).

Figure 3. Reference ET page for a single Mesonet station.

Seasonal Evapotranspiration Data Back to Map

This season's evapotranspiration data for **Goodwell** through **2005-07-11**

```
DATE:     Date
STNM:     Station Number
STID:     Station ID
LAT:      Station Latitude [deg]
LON:      Station Longitude [deg]
ELEV:     Station Elevation [m]
ETOS:     Reference ET, Short [in]
ETRS:     Reference ET, Tall [in]
ETCOOL:   Cool Season Grass ET [in]
ETWARM:   Warm Season Grass ET [in]
PANEVAP:  Pan Evaporation [in]
TMAX:     Maximum Temperature [F]
TMIN:     Minimum Temperature [F]
RHMAX:    Maximum Relative Humidity [pct]
RHMIN:    Minimum Relative Humidity [pct]
RAIN24:   24-Hour Rainfall [in.]
RSOL24:   24-Hour Incident Solar Radiation [MJ/m2]
RSO:      Clear Sky Solar Radiation [MJ/m2]
RA:       Top of Atmosphere Radiation [MJ/m2]
TDEW24:   24-Hour Average Dew Point Temperature [C]
TAVG:     24-Hour Average Temperature [F]
RHAVG:    24-Hour Average Relative Humidity [pct]
WS2AVG:   24-Hour Average Wind Speed at 2m [m/s]
PAVG:     24-Hour Average Station Pressure [kPa]
RNET:     24-Hour Net Radiation [MJ/m2]
G:        Soil Heat Flux [MJ/m2]
VPD:      Avg Vapor Deficit [kPa]
DELTA:    Slope of Vapor Pressure Curve [kPa/C]
GAMMA:    Psychometric Constant [kPa/C]
KP:       Pan Evaporation multiplier
```

DATE	STNM	STID	LAT	LON	ELEV	ETOS	ETRS	ETCOOL	ETWARM	PANEVAP	TMAX	TMIN	RHMAX	RHMIN	RAIN24
2005-07-11	37	GOOD	36.60	-101.60	996	0.27	0.37	0.25	0.17	0.38	90	64	84	36	0.00
2005-07-10	37	GOOD	36.60	-101.60	996	0.35	0.49	0.32	0.21	0.52	94	62	91	29	0.00
2005-07-09	37	GOOD	36.60	-101.60	996	0.32	0.45	0.30	0.20	0.47	92	68	89	31	0.00
2005-07-08	37	GOOD	36.60	-101.60	996	0.29	0.38	0.27	0.18	0.39	94	60	96	29	0.00
2005-07-07	37	GOOD	36.60	-101.60	996	0.33	0.46	0.30	0.20	0.48	92	62	93	27	0.00
2005-07-06	37	GOOD	36.60	-101.60	996	0.27	0.36	0.25	0.17	0.36	90	59	96	32	0.00
2005-07-05	37	GOOD	36.60	-101.60	996	0.22	0.30	0.20	0.14	0.30	84	58	97	34	0.79
2005-07-04	37	GOOD	36.60	-101.60	996	0.24	0.30	0.22	0.15	0.31	86	56	96	39	0.00
2005-07-03	37	GOOD	36.60	-101.60	996	0.39	0.56	0.36	0.24	0.58	100	65	86	18	0.00
2005-07-02	37	GOOD	36.60	-101.60	996	0.33	0.46	0.31	0.21	0.48	94	59	96	29	0.53
2005-07-01	37	GOOD	36.60	-101.60	996	0.27	0.36	0.25	0.17	0.36	91	59	96	26	0.07

DATE	RSOL24	RSO	RA	TDEW24	TAVG	RHAVG	WS2AVG	PAVG	RNET	G	VPD	DELTA	GAMMA	KP
2005-07-11	24.94	30.32	41.10	15.52	77.04	58.58	3.72	90.19	14.65	0.00	1.66	0.19	0.0600	0.7249
2005-07-10	28.42	30.36	41.16	15.04	77.90	54.44	5.60	90.01	16.26	0.00	1.93	0.19	0.0599	0.6617
2005-07-09	26.57	30.40	41.22	16.95	80.23	59.86	5.22	90.14	15.66	0.00	1.82	0.21	0.0599	0.6849
2005-07-08	27.98	30.44	41.27	16.61	76.94	64.13	3.55	90.27	16.43	0.00	1.71	0.19	0.0600	0.7418
2005-07-07	28.84	30.48	41.32	14.32	76.57	56.86	5.04	90.14	16.41	0.00	1.82	0.19	0.0599	0.6836
2005-07-06	26.37	30.51	41.37	15.33	74.52	69.30	3.65	90.27	15.46	0.00	1.51	0.18	0.0600	0.7489
2005-07-05	20.75	30.55	41.42	14.72	70.84	70.13	4.16	90.58	12.64	0.00	1.13	0.16	0.0602	0.7357
2005-07-04	27.28	30.58	41.46	14.96	71.26	65.24	2.88	90.27	16.00	0.00	1.20	0.16	0.0600	0.7630
2005-07-03	28.79	30.61	41.50	14.08	82.31	49.55	4.86	89.54	16.11	0.00	2.68	0.22	0.0595	0.6708
2005-07-02	29.72	30.63	41.53	15.44	76.74	62.41	4.94	89.95	17.11	0.00	1.84	0.19	0.0598	0.6983
2005-07-01	26.09	30.66	41.57	15.15	74.81	64.39	3.51	90.15	15.31	0.00	1.58	0.18	0.0600	0.7433

The authors have developed a PC-based checkbook irrigation scheduling program that interfaces with the Mesonet webpage and automatically downloads daily reference ET. That information is combined with a basal crop coefficient(K_{cb}), a soil water availability coefficient (K_a), and a soil surface wetness coefficient (K_s), which are all stored in a field-specific file that keeps the most recent soil water conditions of the crop root zone, to provide a crop ET estimate corrected for specific soil water conditions.

Many horticultural producers in the state have traditionally used scheduling programs based on pan evaporation. To assist these producers, estimates pan evaporation for the Mesonet site developed from reference ET and pan coefficients are also available on this webpage.

Crop Evapotranspiration
Under the Crops sub-page an array of weather-related information for each of the major agronomic crops produced in Oklahoma is available, including disease and insect development models, degree-day calculators and crop evapotranspiration (ET_c) models. The ET_c calculation uses the short crop reference (ET_{os}) and an appropriate crop coefficient (K_c). In some cases the K_c values are calculated from relationships that have been locally calibrated, while for some crops the K_c's are determined from general relationships recommended by the United Nations Food and Agriculture Organization (Allen, et. al., 1998).

The specific K_c relationship is determined when the user chooses a crop from the *Crops* menu. The actual daily value of the K_c is determined based on the date of the computation, the planting date and maturity/season length information provided by the user. No adjustments are made for reduced soil water availability or wet soil surface conditions. Daily and cumulative ET_c during the season are presented in a table with the most recent day at the top (Figure 4). This crop water use information, combined with the allowable soil water deficit (as determined by the available water holding capacity of the root zone soil, the crop rooting depth and maximum fraction of water that can be depleted) or the expected effective depth of irrigation allows the irrigation manager to determine when to initiate irrigation.

Figure 4. Crop ET example page from the Mesonet website.

Evapotranspiration for corn for Goodwell

Station	Date	Number of Days	Evapotranspiration (inch)	Accumulated Evapotranspiration (inch)	Rainfall (inch)	Accumulated Rainfall (inch)	Water Balance (inch)
GOOD	2005-07-11	1	0.35	0.35	0.00	0.00	-0.35
GOOD	2005-07-10	2	0.45	0.80	0.00	0.00	-0.80
GOOD	2005-07-09	3	0.41	1.21	0.00	0.00	-1.21
GOOD	2005-07-08	4	0.38	1.59	0.00	0.00	-1.59
GOOD	2005-07-07	5	0.43	2.02	0.00	0.00	-2.02
GOOD	2005-07-06	6	0.35	2.37	0.00	0.00	-2.37
GOOD	2005-07-05	7	0.29	2.66	0.79	0.79	-1.87
GOOD	2005-07-04	8	0.31	2.97	0.00	0.79	-2.18
GOOD	2005-07-03	9	0.51	3.48	0.00	0.79	-2.69
GOOD	2005-07-02	10	0.43	3.92	0.53	1.32	-2.60
GOOD	2005-07-01	11	0.35	4.27	0.07	1.39	-2.88
GOOD	2005-06-30	12	0.46	4.73	0.00	1.39	-3.34
GOOD	2005-06-29	13	0.60	5.33	0.00	1.39	-3.94
GOOD	2005-06-28	14	0.60	5.93	0.00	1.39	-4.54
GOOD	2005-06-27	15	0.53	6.47	0.00	1.39	-5.08
GOOD	2005-06-26	16	0.46	6.92	0.00	1.39	-5.53
GOOD	2005-06-25	17	0.44	7.36	0.00	1.39	-5.97
GOOD	2005-06-24	18	0.50	7.87	0.00	1.39	-6.48
GOOD	2005-06-23	19	0.51	8.38	0.00	1.39	-6.99
GOOD	2005-06-22	20	0.46	8.84	0.00	1.39	-7.45
GOOD	2005-06-21	21	0.38	9.22	0.00	1.39	-7.83
GOOD	2005-06-20	22	0.38	9.61	0.00	1.39	-8.22
GOOD	2005-06-19	23	0.44	10.05	0.00	1.39	-8.66
GOOD	2005-06-18	24	0.38	10.42	0.00	1.39	-9.03
GOOD	2005-06-17	25	0.36	10.78	0.00	1.39	-9.39
GOOD	2005-06-16	26	0.38	11.17	0.00	1.39	-9.78

For the example shown in Figure 4, if the corn crop had a fully developed root depth of 48 inches in a sandy loam soil with an available water capacity of 0.125 inches of available water per inch of soil and a maximum of 40% of the soil water in the root zone can be depleted before water stress affects crop performance, the allowable water deficit is 2.4 inches. Looking down the water use table, the manager can see that cumulative water use of the crop is 2.37 inches since July 6. If the crop was last irrigated on July 6, it is time to irrigate again. If the last irrigation occurred on July 7, the manager can see that based on the most recent ET_c values he has one more day until irrigation must be initiated. Similarly, if the irrigation manager likes to apply no more than 1.25 inches of net water depth with his center pivot system, he can see that after 3 days it is time to irrigate and apply 1.21 inches of water.

The crop ET table also includes daily and cumulative rainfall amounts measured at the Mesonet weather station site, allowing the calculation of a water balance for the site. Users are advised that no adjustment has been made for effective rainfall is made in this calculation. They are also advised that the high spatial variability in rainfall, especially the rainfall from single-cell thunderstorms in the Southern Plains region, makes this information of limited value. They are instead advised to maintain a rain gauge at the site of each field they are irrigating.

The authors acknowledge that there are certain limitations inherent in this approach to predicting actual crop ET_c because adjustments for soil water availability and soil surface wetness are ignored. However, no bookkeeping is required by the user and no files need to be stored on the user's computer to use this method. It is our belief that a simple irrigation scheduling system of reasonable accuracy that requires minimal feedback from the user is more likely to be used consistently by irrigators who have not previously used a weather-based scheduling method than a more accurate, but more complicated system.

Future Improvements

The evapotranspiration products currently available on the Mesonet website include reference ET for short and tall reference crops, and the primary crops of economic importance in Oklahoma. At this time there are ET estimates for eight agronomic crops (alfalfa, corn, cotton, grass hay, peanuts, sorghum, soybeans and wheat), three fruit and nut crops (grapes, peaches, and pecans), three vegetable crops (general small vegetables, tomatoes and watermelons), and two turf crops (cool season grasses and warm season grasses). As time and resources permit ET products for additional crops will be added.

Discussions have been initiated with Mesonet managers about making system resources available for field specific scheduling data. This would set aside storage space that would allow irrigation managers to keep water budget files for individual irrigation systems on-line.

Summary

The Oklahoma Mesonet has implemented a simplified, on-line evapotranspiration modeling system that allows irrigators to use near-real-time weather data to estimate crop water use. The system provides daily reference ET estimates, as well as estimates of actual crop ET for potential conditions for all of the major crops of economic importance in Oklahoma. The listing of cumulative crop ET that the user can adjust for planting date and crop maturity group permits reasonably accurate timing of irrigation events with minimal effort required of the irrigation manager.

References

Allen, R. G., L. S. Pereria, D. Raes and M. Smith. 1998. *Crop evapotranspiration – Guidelines for computing crop water requirements*. FAO – Irrigation and Drainage Paper 56. Food and Agriculture Organization of the United Nations. Rome, Italy. 328 pp.

Allen, R.G., I.A. Walter, R.L. Elliott and T.A. Howell. 2005. *The ASCE Standardized Reference Evapotranspiration Equation*. American Society of Civil Engineers. New York, NY. 216 pp.

Brock, F.V., K.C. Crawford, R.L. Elliott, G.W. Cuperus, S.J. Stadler, H.L. Johnson, and M.D. Eilts. 1995. The Oklahoma Mesonet: a technical overview. *J. Atmospheric and Oceanic Technology*, 12: 5-19.

Elliott, R.L., F.V. Brock, M.L. Stone, and S.L. Harp. 1994. Configuration decisions for an automated weather station network. *Appl. Engineering in Agriculture*, 10:45-51.

AZSCHED V2.0: CLIMATE-BASED IRRIGATION SCHEDULING IN ARIZONA

Edward C. Martin[1] Donald C. Slack

ABSTRACT

Timely information on crop water needs is essential for any effective irrigation scheduling strategy. Use of historical or average weather data may suffice in the short term, but often causes significant errors in crop water use estimates when used over long periods of time. AZSCHED (AriZona Irrigation SCHEDuling) program utilizes real-time weather data from the AZMET (AriZona METeorological) database to estimate reference crop evapotranspiration (ET_o). These data are then combined with crop coefficient data (K_c) to estimate daily crop water use for 28 different crops grown in Arizona and the Southwest. AZSCHED V1.0 is already available on the Internet and has been downloaded to over 300 users. This new version allows for the use of tree crops and incorporates many new features that can be used with drip and micro sprinkler systems. This paper discusses some of the new features and how the new V2.0 system operates.

INTRODUCTION

Recent droughts in the Southwest have many agricultural producers thinking about their water use and ways to conserve water. In-field tools such as soil sampling, tensiometers and gypsum blocks serve a purpose, but quite often growers are too busy to make frequent visits to all of their fields. Other monitoring devices, such as Time Domain Reflectometry, capacitance probes and crop imaging often carry a hefty price tag. One alternative is computerized irrigation scheduling programs.

To help growers increase their water use efficiency, the University of Arizona's Department of Agricultural and Biosystems Engineering developed a computerized irrigation scheduling program called AZSCHED (Fox et al., 1992; Martin, et al., 2003). AZSCHED calculates the crop evapotranspiration (ET_c) as the product of a crop coefficient (K_c) and a reference evapotranspiration (ET_o). ET_o is estimated from real time weather data using the modified Penman equation (Doorenbos and Pruitt, 1977). Crop coefficients are taken from 28 crop curves developed from existing water use data and normalized by heat units to account for climatic variability (Slack et al., 1996; Martin et al., 1996). AZSCHED V1.18 system, originally developed in 1992 by Fox et al., is now a Windows-based program available for downloading on the Internet (Martin, et al., 2003). AZSCHED V1.18 can only be run under Windows-based operating systems. These systems include Windows NT, Windows 98, or Windows XP. If real time weather is to be used, then an internet connection may be useful. It is recommended that the computer used to run the software have at least 20MB of free hard disk space for the program files and associated Visual Basic .DLL files.

With the success of the AZSCHED V1.18, the developers began the design of AZSCHED V2.0. Version 2.0 has new programming to accommodate tree crops and drip irrigation systems.

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PROGRAM STRUCTURE

AZSCHED V2.0 is not available to the general public. However, AZSCHED V1.18 can be downloaded directly from the Internet at **http://ag.arizona.edu/crops/irrigation/irrigation.html**. In addition to the program itself, a Users Guide is downloaded. This handbook is available by clicking "Help" on the first screen of AZSCHED V1.18. From the main page of AZSCHED V2.0 (Fig. 1), Users can enter data, retrieve data and get a schedule of all the fields managed with AZSCHED. Below are detailed descriptions of AZSCHED V2.0

Field Options

This is the portion of the programming where the majority of the user/program interface takes place. Choosing this option, the User is given five additional options plus a "Go Back" button to return to the main menu. A diagram of the screen is shown in Fig. 2.

Field Display

This option will display all of the fields currently being scheduled. The User can choose on how the fields are displays (i.e., according to planting date, crop type, next irrigation or field name). The total number of fields displayed on the screen at one time is determined by the User entered value from the "Configuration" option in the main menu. The fields are displayed in color according to their irrigation needs. Green fields are within the specified soil moisture, yellow fields are closing approaching irrigation or harvesting and red fields are in need of immediately attention.

Field Selection

In this option, the User can either select a field to be updated, create a new field, or select a field to be harvested/deleted. Harvested/deleted fields are removed for the field list but the data is saved. Thus, if the User wanted to review data from a field harvested several years ago, it would still be possible to go back and printout a summary/history of that field.

Creating a new field

The creation of a new field requires several inputs from the Users and it would be best to gather the information prior to initiating a field. The first screen asks for crop type and soil data format. Crop type is selected from a list. For the soil format, there are two choices: Fixed soil layers – Soil are defined by "fixed" layers of a certain thickness. For example, the soil can be defined every 6 inches… or every 12 inches. Or, the soil format can be defined as Variable soil layers – where each individual layer is defined. Thus, if the soil has about 3 inches of top soil, then 6 inches of clay, then 7 inches of sandy clay, etc., this option will allow the User to define the thickness of each individual layer.

Next, the User needs to input a field ID, planting date, a weather station nearest the field being scheduled, an irrigation efficiency and the maximum allowable deficiency (MAD). The MAD should be in percent and is the threshold of the percent of Plant Available Water (PAW) in the plant rootzone at which the User wants an irrigation to occur. The weather station selection is a list of AZMET (Arizona Meteorological Station) weather station locations. These stations collect hourly data on a variety of atmospheric conditions (Brown, 1998). However, if the User created a Custom Weather file, using weather data from a station not on the AZMET network, this station can be chosen here. Then, the program will also look first to this file for updated weather information. There is also a selection for soil, asking whether the User wants to enter new soil data, use soil data from an existing field or use soil data from a harvested/deleted field. Then the User is given the option to alter the crop's maximum rooting depth.

If the crop to be scheduled is alfalfa, then there are two more entries. One is the Critical MAD and the other is the Field Drying Time. The Critical MAD is a depletion percentage that you never want the field to fall below. Quite often, the cutting date and the scheduled irrigation date conflict. Thus, the program may be calling for irrigation the day before a scheduled cut. In order to avoid this, the program will use the Critical Mad and the Field Drying Time. The default for the Field Drying Time is 7 days. This means that the field can be safely entered with machinery 7 days after an irrigation event. The program will calculate this and may ask for an irrigation earlier than the entered MAD to assure that the hay will be cut and removed before the soil water falls below the Critical MAD. Normally, the Critical MAD is set 5-10% higher than the MAD.

Finally, if the crop chosen is a tree crop, additional information on orchard geometry and the size of the tree is requested. First, the User is asked to enter ft/m between rows and between trees. Then the User is asked to enter the Effective Crop Canopy (ECC). The ECC is a method for helping to determine the age, size and thus water use of an orchard tree. When trees are young, their canopy size is limited and the amount of canopy coverage on the orchard floor is low. As the trees grow, they begin to cover more and more of the orchard floor. Once the ECC equals 70%, it is assumed that the trees are transpiring at their maximum (Sammis et al., 2005). The User can enter any number from 10-100%, although there is no adjustment once the ECC gets beyond 70%. However, lower numbers reduce the K_c and the root coverage of the crop by the ECC factor given in Equation 1:

$$\text{ECC Factor} = (-0.0001*\text{ECC}^2+0.0221*\text{ECC})*100 \qquad (1)$$

Here, the ECC Factor will be used to reduce crop water use (via a reduction in K_c) and reduce the actual soil volume available for water uptake. A diagram of the Input Screen for a tree crop for AZSCHED V2.0 is shown in Fig. 3.

Once this information is entered, the program will automatically check to see if there is weather data available for the field created. If not, a window will now pop up saying that weather data is required. The User can then either download data automatically from the Internet or use default data. The internet data will be automatically downloaded from the AZMET (the University of Arizona's weather station system; Brown, 1998) website and will download data from the weather station the User entered. The second option is to allow the program to use default weather data. The program automatically computes weather data for your station based on the average over many years. This data is not the best to use for scheduling since it uses averages.

Soils Data

When initially setting up the field, the User had the option to either enter soil water data one of three methods: 1) Enter new data; 2) Use data from an existing field; or 3) Use data from a harvested/deleted field. If the User chose to enter new data, a soil screen will appear requesting information of the soil's available water holding capacity and the initial soil water content at planting. If options 2 or 3 were chosen, the User is given a list of existing or harvested/deleted fields to choose from. Once the soils data is entered, the program then predicts the next irrigation.

Field Options

The *Field Options* pull-down menu allows the User to enter data throughout the season on water added to the field. It also allows the User to change certain parameters such as the MAD, irrigation efficiency or field depletion. The User can also get a quick view of the Field Summary and Field Details.

Field Reports

This pull down menu has three options: 1) Print/Save/View irrigation schedule for all fields; 2) Print/Save/View the field report for the field selected; 3) Print the field report for a harvested/deleted field. The irrigation schedule gives a list of all fields presently being scheduled, their present soil water status and the predicted next irrigation date, along with irrigation amount. For alfalfa, the next predicted cutting data is also give.

The field report (Fig. 4) contains daily data on the selected field including the following (Text in **bold** is how the data is reported in the field report):

Date
Day (DAP) - days after planting
Avail (in) - available water in inches
Depl (%) – percent available water depletion
GDD (F) – growing degree days in Fahrenheit, for that day
GDD (Cumm) – cumulative growing degree days in Fahrenheit
ETR (in) – reference evapotranspiration (ET_o) for that day, in inches
ETR (Cumm) – cumulative ETR
Kc – crop coefficient
Kd – soil dryness coefficient
ETC (in/acre – gals/tree) – crop ET_c*. It is the ET_o times the K_c times the soil dryness factor, in inches
ETC (Cumm) – cumulative ET_C
Irr (in) – irrigation amounts
Rain (in) – rainfall amounts
Cut No. – the number of the cut that was taken off a field (for hay only)

* **Gallons** or liters per tree only for tree crops and only if selected by the User.

The final option is to print a field report of a harvested/delete field. This report is the same as previously described in the last paragraph. However, since these are harvested/deleted fields, only printed copies can be obtained.

Weather Data information section

The "Weather Data" is chosen from the main menu and gives the User several options of adding or viewing weather data. If not previously done, the program will first prompt the User to choose a weather station. Then the User can choose from three pull down menu: 1) Add Weather Data; 2) View Weather Data 3) Custom Disk Weather Files (Fig. 5).

Add Weather Data

In this section the User can: 1) download data from AZMET; 2) enter/edit weather data; or 3) load default weather data. Downloading AZMET data allows the User to download weather data without having to have a field to schedule. This way, the User can view weather data from any available AZMET station. Option 2, enter or edit weather data, allows the User to enter weather data for any AZMET station. Caution must be used here because the entered data will be saved by the program and used to schedule irrigations. This option should only be used when it is known that the weather data already saved by AZSCHED is incorrect. Loading default weather data can be helpful if there is no Internet connection and the User wants to view historical averages.

View Weather Data

This selection allows the User to view the weather data from the selected station for years that have been downloaded, either directly in the menu or automatically through scheduling. The User also has the option of printing the weather data shown on the screen or printing the entire weather file.

Custom Disk Weather Files

This selection allows the User to create, update or delete a custom weather file. This is for User's outside of the AZMET weather network who may want to use AZSCHED V2.0. Also, a page describing the format of weather files required by AZSCHED is given.

Configuration section

This section allows the User to change the date the program has set as today's date, set units to English or metric, and set field display – which allow the User to change the number of fields that are displayed on your computer screen when the Field Options > Field Displays menu choice is selected.

ESTIMATING CROP WATER USE

AZSCHED uses the "water-balance method" to estimate daily crop water use. In this approach, the soil is viewed as a water storage reservoir from which plants extract water. This water is then replaced by either irrigation or precipitation. In using this method, reliable information on the soil available water holding capacity (AWC) is essential. The AWC is generally defined as the amount of water retained in the soil between "field capacity" (FC) and the "permanent wilting point" (PWP).

Crop water use is estimated using a calculated reference crop evapotranspiration (ET_o) data and a crop coefficient. The method used in AZSCHED for estimating ET_o is the FAO Modified Penman equation (Doorenboos and Pruitt, 1977). This equation estimates the ET of a healthy, cool season grass, 8-15 cm in height maintained in a well watered environment. The Modified Penman equation requires daily information on max/min temperatures, max/min relative humidity, net radiation, wind speed and the day/night wind ratio. The equation, often refereed to as the combination equation, has the form:

$$ET_o = c * [W * R_n + (1 - w) * f(u) * (e_a - e_d)] \tag{2}$$

Where c is an adjustment factor to compensate for the effect of day and night weather conditions; W is a temperature related weighing factor, f(u) is a wind function, R_n is the net radiation equivalent in mm/day and (e_a-e_d) is the vapor pressure deficit.

To estimate actual crop water use, AZSCHED uses the ET_o data with crop coefficient values (K_c), derived from several sources (Erie, et al., 1982; Sammis et al., 1985; Martin, et al., 1996). The crop coefficient is defined as:

$$K_c = \frac{ET_c}{ET_o} \tag{3}$$

Where ET_c is the actual crop evapotranspiration and ET_o is calculated as previously described.

A unique feature of AZSCHED program is the use of growing degree days (gdd) as the unit of time measurement. Growing degree days are often referred to as heat units or thermal time. In its simplest form, gdd are defined as:

$$gdd = T_{mean} - T_{base} \qquad (4)$$

Where T_{mean} is the daily mean air temperature and T_{base} is the minimum daily mean air temperature required for crop growth. The value of T_{base} is unique to the crop. Equation 4 is only valid when $T_{base}<T_{mean}<T_{max}$. In areas such as Arizona, where summer temperatures often rise well above 100 °F, an upper threshold temperature similar to T_{base}, and referred to as T_{max} is required. If $T_{mean}>T_{max}$, then formula for computing gdd is:

$$gdd = T_{\max} - T_{base} \qquad (5)$$

Where T_{mean} is the daily mean air temperature and T_{max} is the maximum daily mean air temperature that once reached, no additional significant crop growth occurs. Snyder (1985) developed a method for calculating gdd for a variety of temperature scenarios. This method was used in the AZSCHED program to determine daily gdd accumulation.

CONCLUSION

Over 300 copies of AZSCHED V1.18 have been downloaded from the University of Arizona website. It is hoped that this new version of AZSCHED will also be used so widely. With initial testing continuing this year, it is hoped that a Beta version will be available by the end 2005, with a public release by June of 2006.

Acknowledgements: This work was made possible through a grant and MOU with the Bureau of Reclamation, US Department of Interior. Special thanks to Mark Niblack and Henry Detwiler, BOR-USDI, Yuma, AZ, for there continued support of AZSCHED.

REFERENCES

Brown, P.W. (1998) "AZMET computation of reference crop evapotranspiration." <http://www.ag.arizona.edu/AZMET> (1998).

Doorenbos, J., and W.O. Pruitt. 1977. Crop water requirements. FAO Irrigation and Drainage Paper #24. Food and Agricultural Organization of the UN. Rome. 144pp.

Fox, F.A., Jr., T.F. Scherer, D.C. Slack, and L.J. Clark. 1992. Arizona irrigation scheduling (AZSCHED version 1.01): Users Manual. The University of Arizona, Coop. Ext. Ser. Agr. and Biosystems Engr. 35pp.

Erie, L.J, O.F. French, D.A. Bucks and K. Harris. 1982. Consumptive Use of Water by Major Crops in the Southwestern United States. USDA-ARS Conservation Res.Rep.No. 29.

Martin, E.C., D.C. Slack, and E.J. Pegelow. 1996. Basal crop coefficients for vegetables in central Arizona. Proc. International Evap. and Irrig. Sched. Conf. Amer. Soc. Agric. Engrs. Dallas, TX. November 1996.

Martin, E.C., H. Detwiler and D.C. Slack. 2003. AZSCHED V1.13 (Arizona Irrigation Scheduling) System. Users handbook. University of Arizona, Cooperative Extension. Pub. # 1321. 17pp.

Sammis, T. W., C. L. Mapel, D. G. Lugg, R. R. Lansford and J. T McGuckin. 1985. Evaporation crop coefficients predicted using growing degree days. Trans. ASAE. 28:773-780.

Sammis, T.W., A. Andales, L. Simmons and V. Gutschick. 2005. Adjustment of Closed Canopy Crop Coefficients of Pecans for Open Canopy Orchards. Trans. of ASAE. (In Review).

Snyder, R. L. 1985. Hand calculation degree days. Ag. and For. Meteor. 35:353-358.

Slack, D.C., E.C. Martin, A.E. Sheta, F.A. Fox, Jr., L.J. Clark, and R.O. Ashley. 1996. Crop coefficients normalized for climatic variability with growing-degree-days. Proc. International Evap. and Irrig. Sched. Conf. Amer. Soc. Agric. Engrs. Dallas, TX. November 1996.

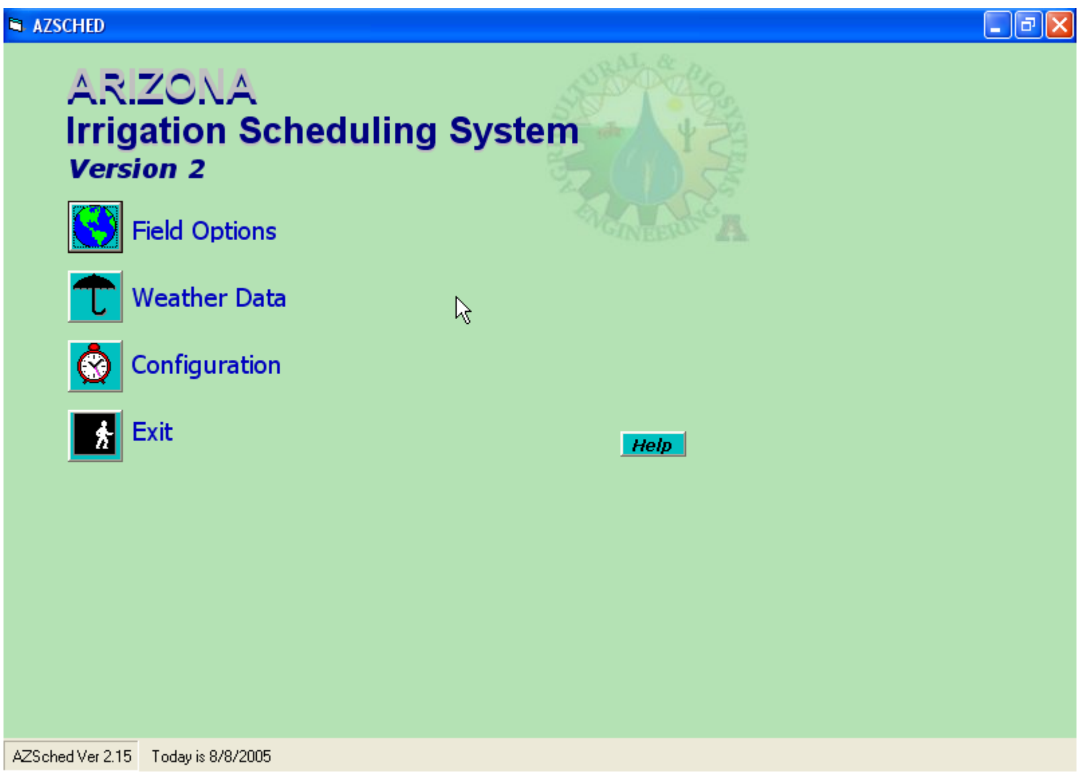


Figure 1. The main menu screen for the AZSCHED Version 2 program.

Figure 2. The Field Options screen from AZSCHED. This screen shows data from an orange test plot with a budding date of 3-23-04.

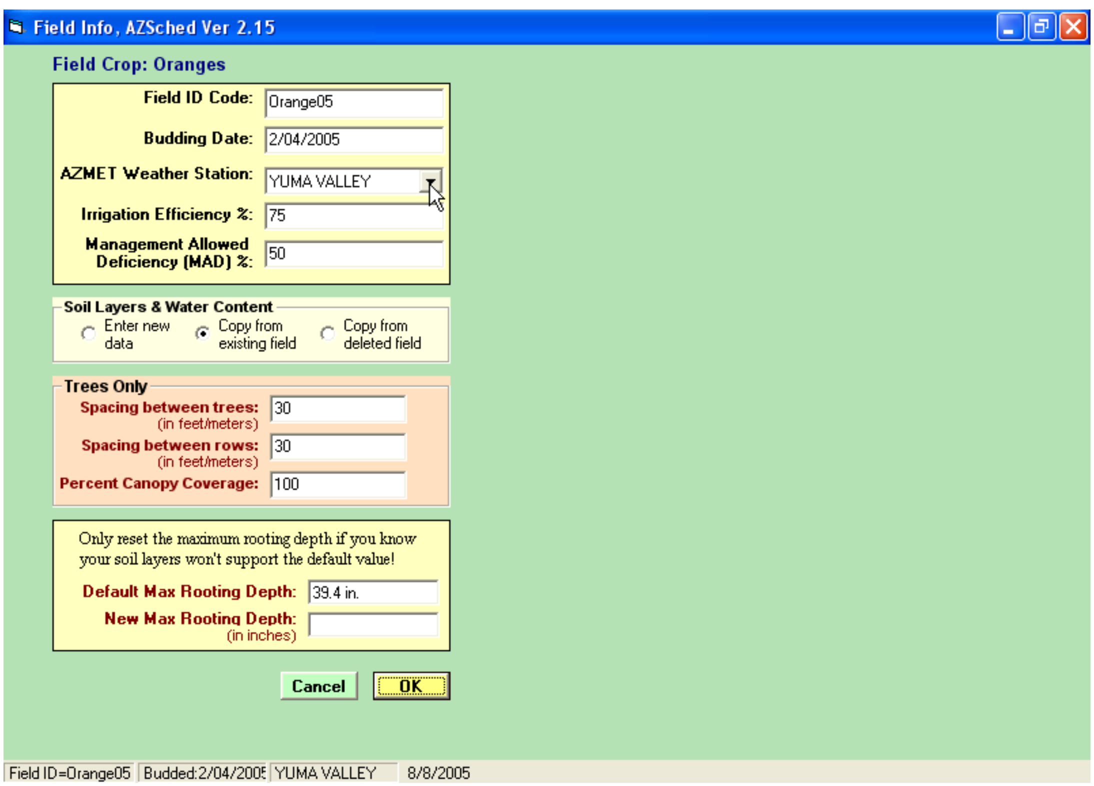
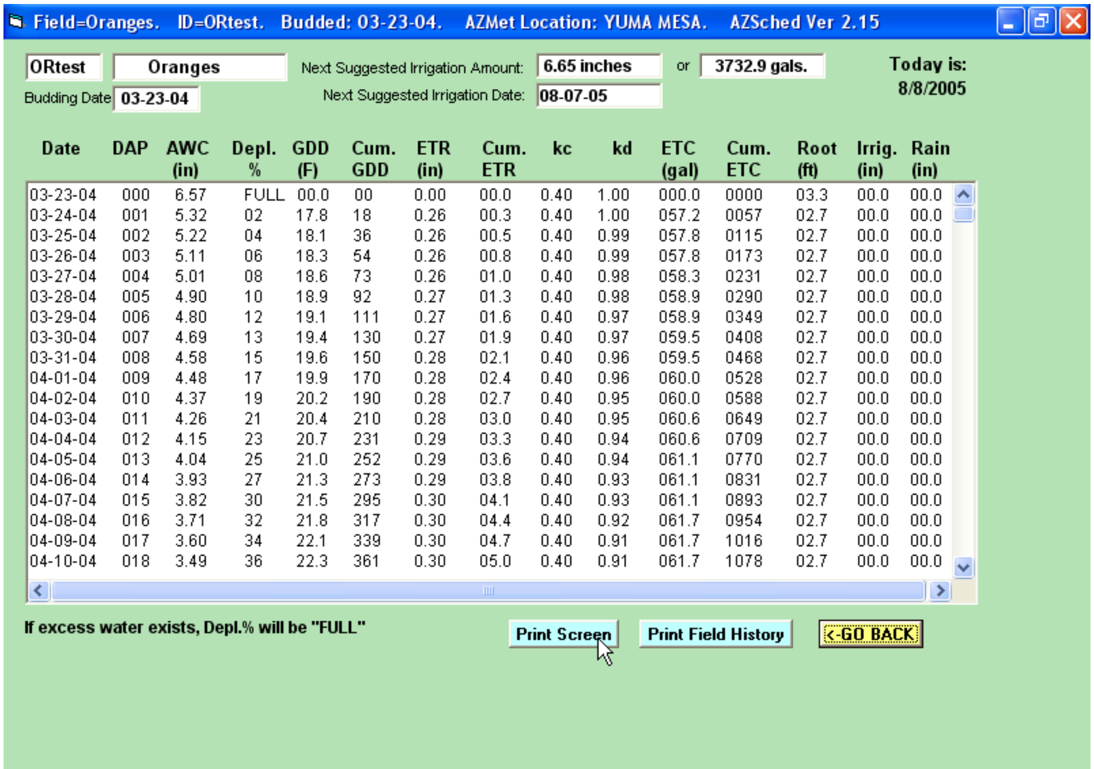


Figure 3. Field input screen for AZSCHED V2. This is for an orange crop.



Date	DAP	AWC (in)	Depl. %	GDD (F)	Cum. GDD	ETR (in)	Cum. ETR	kc	kd	ETC (gal)	Cum. ETC	Root (ft)	Irrig. (in)	Rain (in)
03-23-04	000	6.57	FULL	00.0	00	0.00	00.0	0.40	1.00	000.0	0000	03.3	00.0	00.0
03-24-04	001	5.32	02	17.8	18	0.26	00.3	0.40	1.00	057.2	0057	02.7	00.0	00.0
03-25-04	002	5.22	04	18.1	36	0.26	00.5	0.40	0.99	057.8	0115	02.7	00.0	00.0
03-26-04	003	5.11	06	18.3	54	0.26	00.8	0.40	0.99	057.8	0173	02.7	00.0	00.0
03-27-04	004	5.01	08	18.6	73	0.26	01.0	0.40	0.98	058.3	0231	02.7	00.0	00.0
03-28-04	005	4.90	10	18.9	92	0.27	01.3	0.40	0.98	058.9	0290	02.7	00.0	00.0
03-29-04	006	4.80	12	19.1	111	0.27	01.6	0.40	0.97	058.9	0349	02.7	00.0	00.0
03-30-04	007	4.69	13	19.4	130	0.27	01.9	0.40	0.97	059.5	0408	02.7	00.0	00.0
03-31-04	008	4.58	15	19.6	150	0.28	02.1	0.40	0.96	059.5	0468	02.7	00.0	00.0
04-01-04	009	4.48	17	19.9	170	0.28	02.4	0.40	0.96	060.0	0528	02.7	00.0	00.0
04-02-04	010	4.37	19	20.2	190	0.28	02.7	0.40	0.95	060.0	0588	02.7	00.0	00.0
04-03-04	011	4.26	21	20.4	210	0.28	03.0	0.40	0.95	060.6	0649	02.7	00.0	00.0
04-04-04	012	4.15	23	20.7	231	0.29	03.3	0.40	0.94	060.6	0709	02.7	00.0	00.0
04-05-04	013	4.04	25	21.0	252	0.29	03.6	0.40	0.94	061.1	0770	02.7	00.0	00.0
04-06-04	014	3.93	27	21.3	273	0.29	03.8	0.40	0.93	061.1	0831	02.7	00.0	00.0
04-07-04	015	3.82	30	21.5	295	0.30	04.1	0.40	0.93	061.1	0893	02.7	00.0	00.0
04-08-04	016	3.71	32	21.8	317	0.30	04.4	0.40	0.92	061.7	0954	02.7	00.0	00.0
04-09-04	017	3.60	34	22.1	339	0.30	04.7	0.40	0.91	061.7	1016	02.7	00.0	00.0
04-10-04	018	3.49	36	22.3	361	0.30	05.0	0.40	0.91	061.7	1078	02.7	00.0	00.0

Figure 4. A sample of the Field Report from AZSCHED Version 2.

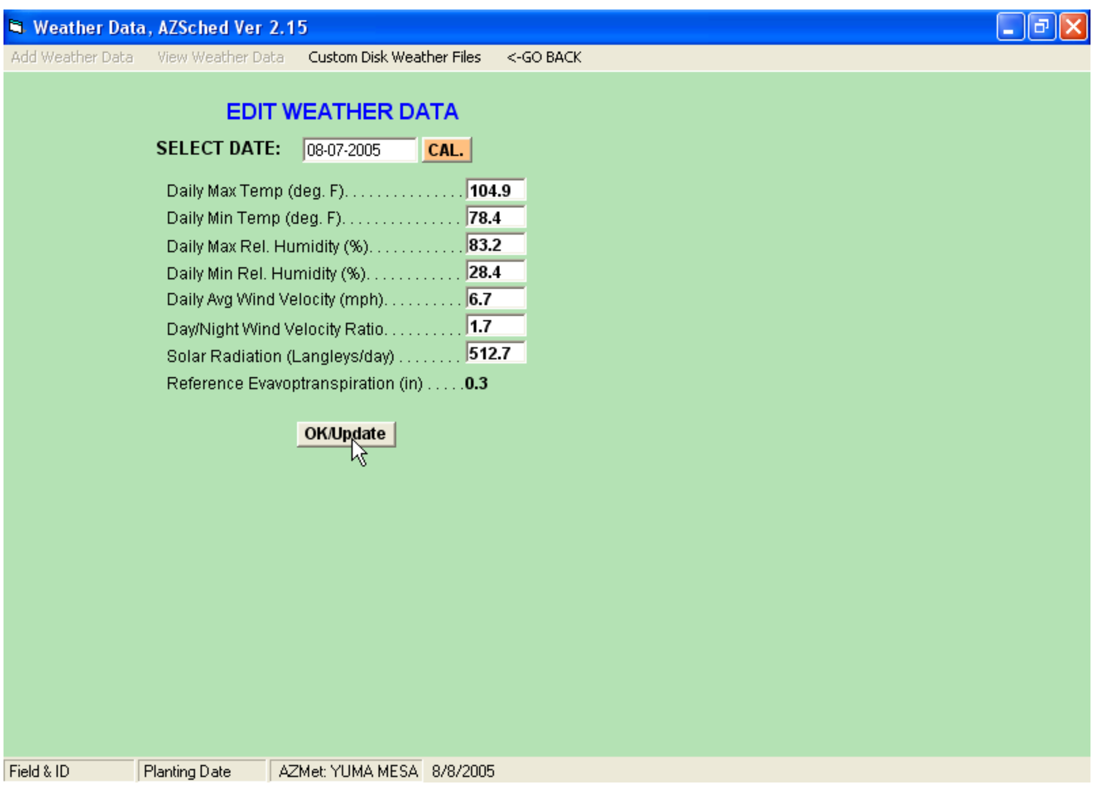


Figure 5. The Weather Menu from the AZSCHED V2 program.

Automated Water Management for Center Pivot Irrigation Systems

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Abstract

Simulations were conducted to determine the effectiveness of a software package that fully automates center pivot irrigation systems on fields planted to corn for years 1985-2004. A total of seven sites from the Central and Northern Plains were chosen for analysis (Akron, CO, Ames, IA, Brookings, SD, Sandyland, KS, Oakes, ND, Ord, NE, and Rock Port, MO). System pumping capacities of 37.9, 50.5, and 63.1 liters/second were simulated at each site along with the soil available water holding capacities of 83, 125, and 167 mm/meter. A comprehensive analysis is presented in this paper for all sites for a pumping rate of 50.5 liters/second and an available water holding capacity of 125 mm/meter of soil. The average days under minimum allowable soil moisture capacity in a single growing season ranged from 37 at Akron, CO to one at Oakes, ND. Akron, CO also had the greatest average number of irrigation cycles in a growing season (24) with both Ames, IA and Oakes, ND having the least average number of irrigation cycles per season of sites analyzed with 12. The average ratio of actual evapotranspiration to water inputs for all sites was greatest at Sandyland, KS (0.95) and least at Oakes, ND (0.90).

Introduction

Center pivots irrigate more than 8 million hectares in the United States (Werner, 2000). The popularity of these systems can be attributed to their ease of use and relative high application efficiencies. To achieve the greatest yield return from a center pivot irrigation system while efficiently using water resources and energy, scientific irrigation scheduling must be used (Field et al., 1994, Shae et al., 1999, Heinemann et al., 2000, Steele et al., 2000). In the Steele et al. study in 2000, they were able to save 30% in irrigation inputs (water and energy) along with increasing yield 5% using scientific scheduling compared with grower practices. The practice of scientific irrigation scheduling is, however, seldom used by farmers. Lieb et al. (2002) found that as of 1998, as few as 18% of irrigators used scientific scheduling, even with consultants available for technical support.

The challenge to scheduling center pivot irrigations is being able to apply an adequate amount of water at the correct time in order to eliminate a future deficit. It is also imperative not to water excessively which can cause transport of nutrients out of the crop root zone, wasted pumping energy, and of course, wasted water.

The objective of this project was to create a software package to implement a water balance that relieves the producer of the daily tedium of scheduling irrigation.

Methods and Materials

The irrigation software calculated soil moisture balances and determined irrigation timing and depth of application for each six degree section on a full circle (360 degree) center pivot. The following parameters were held constant for all simulations:

Distance from center to furthest point reached by end gun = 418 m
Initial soil water content = 80% of field capacity
System application efficiency = 90%
Crop planted = Corn
Angles analyzed = 175-180

Scientific irrigation scheduling relies on the ability to accurately estimate evapotranspiration (ET). The FAO Penman Monteith (Allen et al., 1998) equation was chosen as the most reliable and accepted means of determining ET.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} \mu_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\mu_2)} \quad (1)$$

ET_o - reference evapotranspiration [mm day^{-1}],
R_n - net radiation at the crop surface [MJ m^{-2} day^{-1}],
G - soil heat flux density [MJ m^{-2} day^{-1}],
T - mean daily air temperature at 2 m height [°C],
u_2 - wind speed at 2 m height [m s^{-1}],
e_s - saturation vapour pressure [kPa],
e_a - actual vapour pressure [kPa],
$(e_s - e_a)$ - saturation vapour pressure deficit [kPa],
Δ - slope vapour pressure curve [kPa °C^{-1}],
γ- psychrometric constant [kPa °C^{-1}].

Required weather data were collected and recorded at automatic weather stations for each of the simulated sites and downloaded from the High Plains Regional Climate Center online databases. The reference evapotranspiration (ET_0) value was calculated for each day past a given planting date (Table 1).

Table 1. Planting dates and season lengths for the seven locations.

Site	Planting Date	Season Length (Days)
Akron, CO	April 1	180
Ames, IA	April 1	180
Brookings, SD	April 15	165
Sandyland, KS	April 1	180
Oakes, ND	May 1	150
Ord, NE	April 1	180
Rockport, MO	April 1	180

ET_0 was multiplied by a crop coefficient and a plant available water coefficient (Equation 2). The crop coefficient was adapted from FAO coefficients (Allen et al., 1998) to fit the growing season length for each chosen site.

$$ET_c = ET_o * K_c * K_a \tag{2}$$

Et_c – actual evapotranspiration (mm)
ET_o – reference evapotranspiration (mm)
K_c – crop coefficient
K_a – plant available water coefficient

The plant available water coefficient decreases as the amount of available water in the soil decreases (Jensen et al., 1990).

$$K_a = \frac{\ln(AW + 1)}{\ln(101)} \tag{3}$$

K_a – plant available water coefficient
AW – available water (%)

Initial rooting depth of the corn crop was set to 0.3 m to provide a buffer at the beginning of the season and was gradually increased to a maximum depth of 0.9 m when the crop reached maximum height above the soil surface. Minimum soil moisture levels were set to 30% of field capacity in the initial growing stage, increased from 30% to 60% during the developmental stage, maintained at 60% of field capacity during midseason, and decreased from 60% to 35% in late season.

A maximum irrigation application depth was set to provide a buffer which would allow for a rainfall event after an irrigation that would not exceed field capacity. The maximum application depth value was set to 60% of field capacity in the initial growing stage, increased from 60% to 80% during the developmental stage, maintained at 80% of field capacity during midseason, and decreased from 80% to 50% in late season. The maximum depth of water that could be applied at one time was set at 32 mm with a minimum depth set to 13 mm.

ET forecasting was used to determine the timing and depth of irrigation applications. The predicted four day future ET total was found by taking the average of the previous two days ET and projecting it for the next four days. This predicted four day ET total was then subtracted from the current soil moisture balance for each six degree section of the pivot. If this predicted balance fell below the minimum allowable soil moisture, that individual section of the field was determined to be in need of irrigation at that future time. The application depth was then determined for each section by subtracting the predicted balance from the maximum application depth. Provided that this depth was between the allowable limits, the center pivot was operated to apply the specified amount to each section.

Daily rainfall was added to the soil moisture balance. If the soil moisture balance for any one day exceeded the field capacity due to rainfall, irrigation, or a combination of the two, the balance was held at field capacity for an additional day. The only exception to this rule was when the ET for the additional day was greater than the excess amount above field capacity. In this case, the soil moisture balance was found by subtracting the ET from the sum of field capacity and excess. All excesses were considered to be lost to runoff or deep percolation.

To analyze the effectiveness of the simulation software, an ET ratio (water balance ratio) was calculated for each simulation.

$$ETratio = \frac{ET_c}{(R + I - Ex + Ex_I)} \qquad (4)$$

ETratio - ratio of evapotranspiration to soil moisture inputs
ET_c – actual evapotranspiration (mm)
R – rainfall (mm)
I – irrigation (mm)
Ex – amount above field capacity (mm)
Ex_I - amount above field capacity caused by an irrigation event (mm)

All variables in the ratio are seasonal totals. The amount above field capacity (*Ex*) is calculated on a daily basis by subtracting the field capacity value from the actual balance. The amount above field capacity caused by an irrigation event (Ex_I) is any amount above field capacity that takes place up to four days after an irrigation event in any given section of the field. This ratio was developed to determine if the software was able to schedule irrigation events to meet the soil moisture losses incurred by evapotranspiration. A ratio of one indicates that all ET losses were replenished by rainfall and irrigation. The overall effectiveness of the software package was determined by finding the ET ratio and number of days that the section of the field being analyzed was under the minimum allowable water content.

Simulation software to fully automate the center pivot irrigator was written in ***National Instruments Labview Version 7.1***.

Results

A comprehensive analysis was completed on all sites with the variables of pumping rate and soil available water holding capacity held constant at 50.5 L/s and 125 mm/m of soil, respectively (Table 2). The goal of the project was to analyze sites for the years 1985-2004. However, downloadable weather data were not available for all years at all locations.

Table 2. Summary of results for the seven locations with a pumping capacity of 50.5 L/s and water holding capacity of 125 mm/m.

	Total ET (mm)	Rainfall (mm)	Irrigation (mm)	Excess Water (mm)	Excess Caused By Irrigation (mm)	ET Ratio	Days Under Minimum Allowable	Irrigation Cycles
Akron, CO	961	340	729	87	37	0.94	37	24
Ames, IA*	694	647	346	305	80	0.92	3	12
Brookings, SD	641	406	397	133	32	0.92	4	13
Oakes, ND**	576	354	355	102	31	0.90	1	12
Ord, NE	765	442	474	131	39	0.93	9	16
Rock Port, MO***	716	574	399	253	53	0.93	4	14
Sandyland, KS	913	436	630	145	42	0.95	26	21

* average values for 1986-2004
**average values for 1990-2004
***average values for 1991-2004

The ratio of average rainfall to average ET for the season was least at the Akron, CO site (0.35). This low ratio indicates a greater need for irrigation to replenish the losses from ET resulting in an average seasonal irrigation of 729 mm. The highest ratio for the sites analyzed was at Ames, IA (0.93) which triggered the lowest average seasonal irrigation depth of 355 mm.

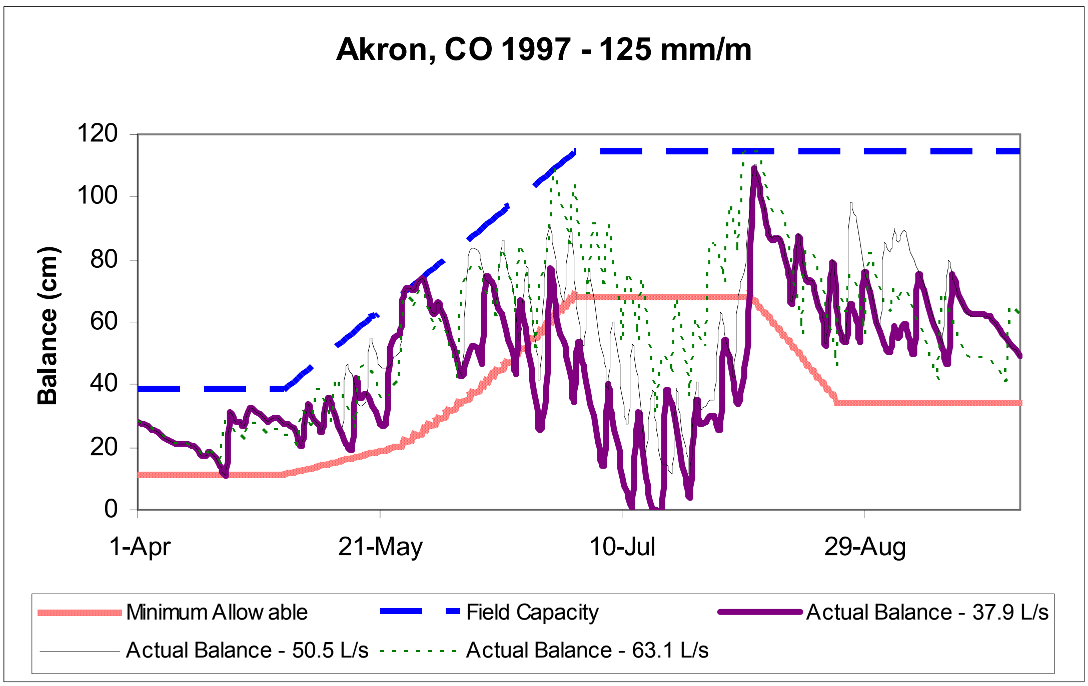

Figure 1. Soil water content for three pumping capacities at Akron, CO in 1997.

Akron, CO averaged the greatest number of days under the minimum allowable soil moisture (37) despite the system completing an average of 24 irrigation cycles per season. This is an indicator that the system pumping capacity is not adequate enough to meet the ET needs of a corn crop with this soil moisture capacity located in this particular climate. Even the higher pumping rate of 63.1 L/s was unable to maintain soil water content greater than minimum allowable at Akron (Figure 1). The total calculated ET for this growing season was 930 mm with a seasonal rainfall of 292 mm. The days under minimum allowable water content dropped from an estimated total of 45 days at a pumping capacity of 37.9 L/s to 18 days at 63.1 L/s.

At the simulated pumping capacity of 50.5 L/s and available soil moisture of 125 mm/m of soil, the Oakes, ND site only had only four years (1991 ,1992, 2001, 2002) that had any days during the growing season in which the actual soil balance dropped below the minimum allowable balance. In 1997 at Oakes, all system pumping capacities simulated were able to keep up with the ET demand (Figure 2).

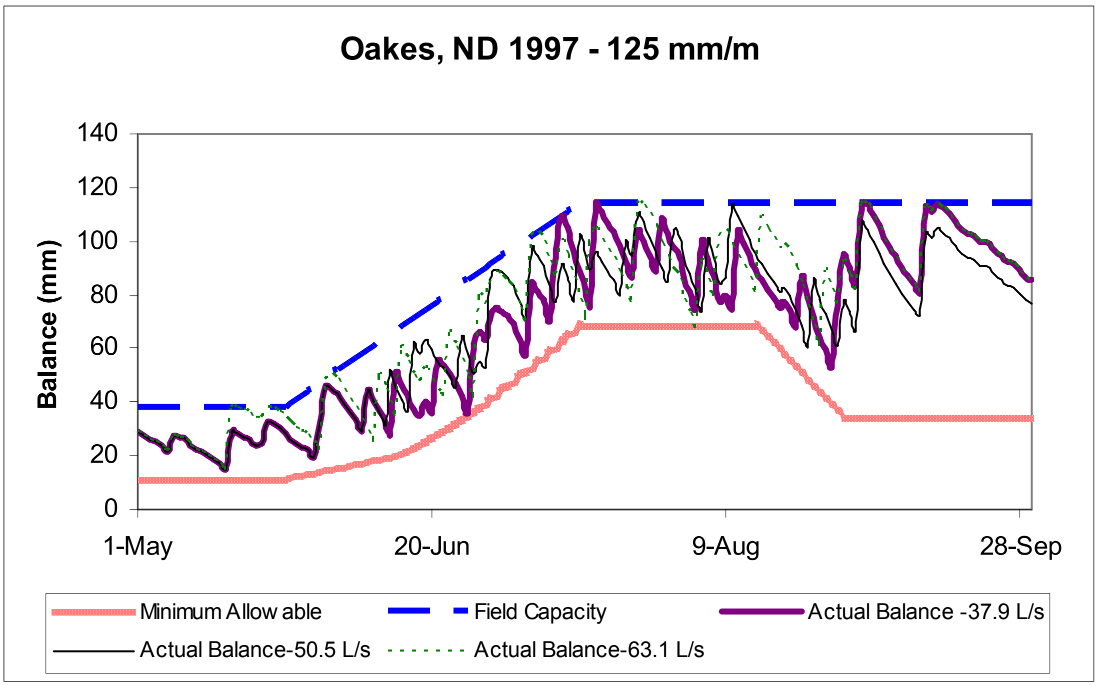

Figure 2. Soil water content for three pumping capacities at Oakes, ND in 1997.

At some of the sites, excessive water inputs lowered the ET ratio values. Though they may appear as a result of irrigation, most are caused by ill-timed or excessive rainfall. Quite frequently, the reason for the apparent excess water is caused by rainfall occurring during non-critical stages of crop development both early and late in the growing season.

In 1989 at Ames, IA, the wettest growing season in this study, there was a total of 1166 mm of rain (Figure 3). This total is over 500 mm greater than the average seasonal rainfall of 648 mm for the years analyzed. These rainfall events, which were often large early in the growing season, contributed 638 mm of the 826 total mm of excess water. The total rainfall for the season was much greater than the ET losses (648 mm). Since much of the rainfall occurred before the critical growing stage for corn, the simulation software instructed the pivot to apply 272 mm of water to overcome deficits during critical growth stages in July and August when rainfall was deficient.

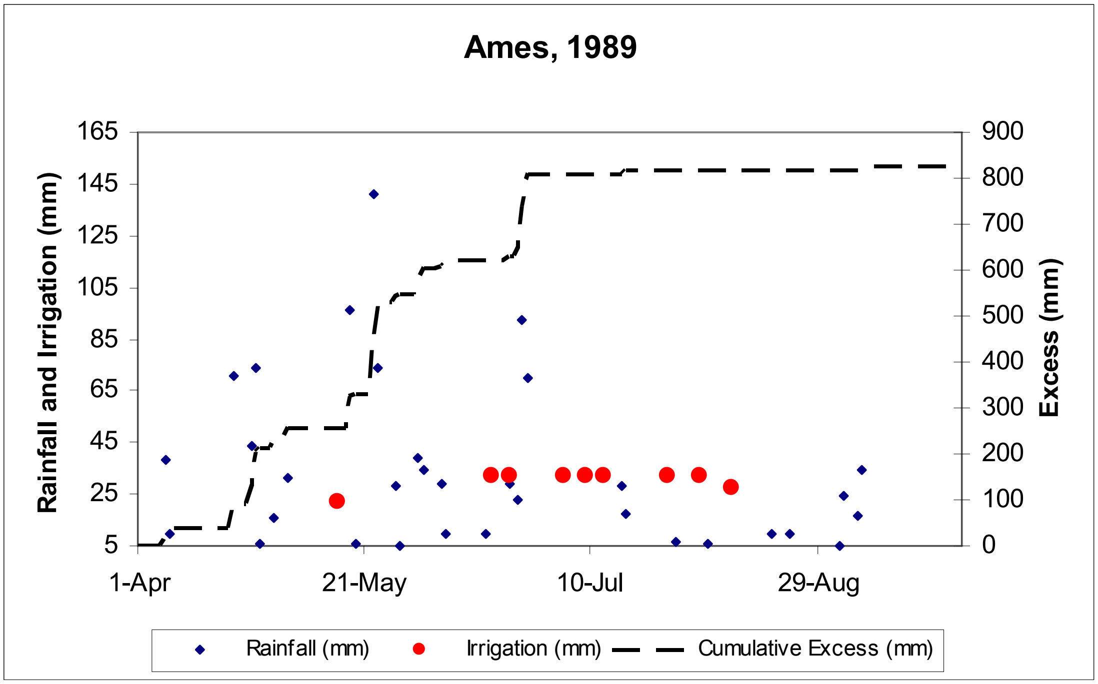

Figure 3. Timing of rainfall and irrigation events in relation to the overall excess moisture above field capacity at Ames, IA in 1989.

Discussion

Simulation software was developed to perform irrigation scheduling using 20 years of weather data for seven locations in the Upper Great Plains where center pivots are the dominant method of irrigation. Simulations were conducted for three system capacities and three soil moisture holding capacities. ET was estimated for corn using the FAO Penman-Monteith method. Minimum soil depletion allowances were set for various growth stages to minimize crop water stress.

The simulation model addressed the system operating limitations for the center pivot. Water could only be applied if the irrigation system was available at that location in the field. An ET forecasting scheme projected water use and operated the pivot to minimize crop water stress throughout the field.

The simulation model was able to effectively manage a center pivot irrigation system over the growing season. Where system capacity was adequate to meet crop water needs for a given soil, the simulator maintained the soil water balance between field capacity and the minimum balance specified. Even though a buffer was included in the model to allow for rainfall storage, unplanned rainfall events often exceeded field capacity of the soil. During crop development periods when evaporative demand is high and rainfall is low, even high capacity systems may not be able to prevent stress events.

Actual field tests will need to be performed to determine any corrections or adjustments that may need to be made to the simulation software. Future research is needed to document the impact of stress events upon predicted crop production.

References

Allen, R. A., L.S. Pereira, D. Raes, and M. Smith, Crop evapotranspiration. 1998. FAO Irrigation and Drainage Paper 56, Rome.

Field, J. G., L. G. James, D. L. Bassett, and K. E. Saxton. 1988. An Analysis of Irrigation Scheduling Methods for Corn. Transaction of the ASAE 31:508-512.

Heinemann, A. B., Googenboom, G. A. Georgiev, R. T.de Faria, and J. A. Frizzone. 2000. Center Pivot Irrigation Management Optimization of Dry Beans in Humid Areas. Transaction of the ASAE 43:1507-1516.

Jensen, M. E., R. D. Burman, and R. G. Allen. 1990. Evaportranspiration and irrigation water requirements. ASCE Manuals and Reports on Engineering Practice No. 70. ASCE.

Lieb, B. G., M. Hattendorf, T. Elliot, and G. Matthews. 2002. Adoption and adaptation of scientific irrigation scheduling: trends from Washington, USA as of 1998. Agricultural Water Management 55:105-120.

Shae, J. B., D. D. Steele, and B. L. Gregor. 1999. Irrigation Scheduling Methods for Potatoes in the Northern Great Plains. Transaction of the ASAE 42:351-359.

Steele, D. D., E. C. Stegman, and Raymond E. Knighton. 2000. Irrigation management for corn in the northern great plains. Irrigation Science 19:107-114.

Werner, Hal. 2000. Center pivots – transforming irrigation in the Great Plains. In proceedings of the Fourth National Irrigation Symposium. ASAE, St. Joseph, MO.

Development of a peanut irrigation management decision aid using climate-based information

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Abstract

Water demand for irrigation in the Southeast is expected to increase in the future. There is a need to combine climate information and risk analysis for peanut irrigation in the southeastern US. This paper describes a peanut irrigation decision support system which was developed to assist growers and to provide information on the levels of profitability of peanut production with and without irrigation under different climate forecasts. The system provides probability distributions of the seasonal cost to irrigate peanuts and amount of water required. Yields were simulated for both irrigated and non-irrigated peanuts using the CSM-CROPGRO-Peanut model. Results of a case study were presented for the Georgia Green variety grown in Miller County, Georgia. The probability of obtaining a high net return under irrigated conditions increased when planting dates were delayed for El Niño years. Dryland peanut production was profitable in a La Niña year if peanuts were planted between mid-April and early May. The prototype irrigation decision support system will be deployed as a web-based tool on the AgClimate web site (www.AgClimate.org) after additional testing and evaluation.

Introduction

El Niño refers to the oceanic component of the El Niño-Southern Oscillation (ENSO) system and is characterized by a large-scale weakening of the trade winds and warming of the surface layers in the eastern and central equatorial Pacific Ocean (NOAA, 2001). El

Niño events occur irregularly at intervals of 2 to 7 years, although the average is about once every 3 to 4 years. The southeastern United States is one of the regions affected by ENSO events (Peters et al., 2003). During an El Niño event the winter in the Southeast is marked by above normal precipitation while summers are typically dry (Green et al., 1997). Crop yields in the southeastern United States are impacted by ENSO and are different, depending on the ENSO phase (Adams et al., 1996; Hansen et al., 1998, 2001).

Peanut is a major crop grown under rainfed and irrigated conditions in the Southeast. From 1997 to 2002, the total peanut farm acreage under irrigation in the region has increased (NASS, 2004). Irrigation systems provide farmers with an option to provide supplemental water to crops during dry conditions and to mitigate some of the effects of temporal rainfall variability in the region. Despite the prospect of higher yields due to irrigation, a grower always faces the question of whether or not to invest in an irrigation system and to install it in his/her field. It is possible that the expense of owning and operating an irrigation system outweighs income benefits when calculated over several years (Martin et al., 1996).

Studies have shown the potential benefits and needs of climate forecasts for the main agricultural commodities in the southeastern US (Hildebrand et al., 1999; Breuer et al. 2003). Available climate information can be used by growers to assess different scenarios and alternatives for different agricultural activities; and there is a need to combine climate information and risk analysis for peanut irrigation especially for growers in the southeastern US.

This paper presents a prototype peanut irrigation decision support system based on long-term climate information. We also present a case study for Miller County, Georgia, and the effect of irrigation, planting dates, and climate forecasts on the level of profitability on peanut production.

Climate-based Decision Support Systems

AgClimate (www.agclimate.org) is an online climate information delivery system developed by the Southeast Climate Consortium (SECC). It encompasses an interactive web site with climate, agriculture, and forestry information that allows users to assess resource management options with respect to their probable outcomes based on forecasted climate conditions. The SECC comprises six member institutions namely: Auburn University, Florida State University, University of Alabama-Huntsville, University of Florida, University of Georgia and University of Miami. Its mission is to use advances in climate sciences, including improved capabilities to forecast seasonal climate, to provide scientifically sound information and decision support tools for agriculture, forestry, and water resources management in the southeastern USA.

Agclimate consists of a web-based decision support system (DSS) in which information and dynamic applications or tools are embedded (Fraisse et al., 2005). Some of the web-based applications that have been implemented so far include a climate risk tool and a yield risk tool for peanut, tomato, and potato. One of the activities of the SECC is to develop prototypes of decision support tools relevant to agricultural and natural resource management. Development of prototypes allow SECC researchers and extension specialists to evaluate and refine the products based on stakeholder input and suggestions prior to final implementation as a web-based tool on the Agclimate web site. One of the tools that was recently developed is the Peanut Irrigation Decision Support System (PIDSS).

Peanut Irrigation Decision Support System

The PIDSS was developed to assist peanut producers in evaluating their long-term economic risks associated with strategic decisions related to irrigation. The program was developed using Microsoft™ VisualBasic, and it links to an Access database. The program requires output from a crop simulation model that is used to calculate the probabilities of several seasonal economic and crop management variables, namely: net return, irrigation cost, irrigation water, and rainfed/irrigated yield ratio (Fig. 1).

The system has two forms or windows. The first window shows the main interface (Fig. 2) and the second window is for the detailed cost structure (Fig. 3). Using the main window, users can select the peanut variety, location, and soil type using the dropdown menus located on the left side. The right side of the main interface shows the probability table and chart. The table has three tabs, namely: probability, probability of exceedance, and average, from which users can select. The system provides users with a quick and interactive way of analyzing the effect of different ENSO phases on the probability distribution and probability of exceedance for different locations and soil types. Users can also highlight selected columns, i.e. planting dates, and the system will automatically generate a probability histogram for the selected planting date(s).

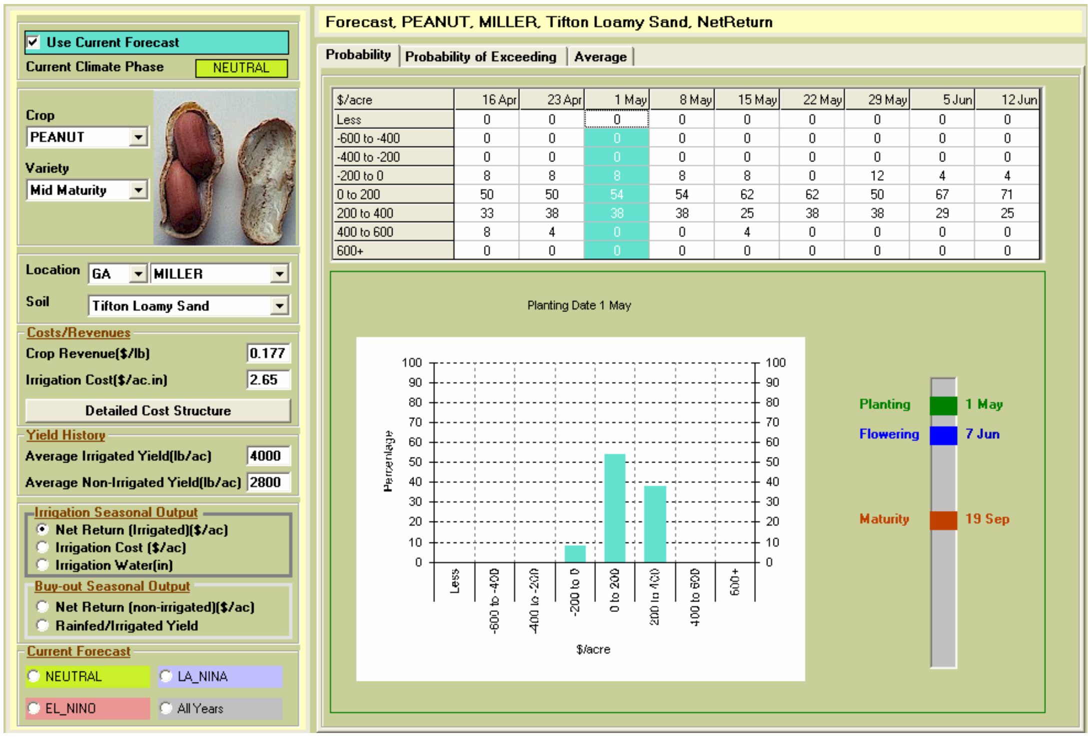


Figure 1. The Peanut Irrigation Decision Support System interface showing the probability table and chart of net return (US$/ac) of irrigated peanut production in Miller County, GA.

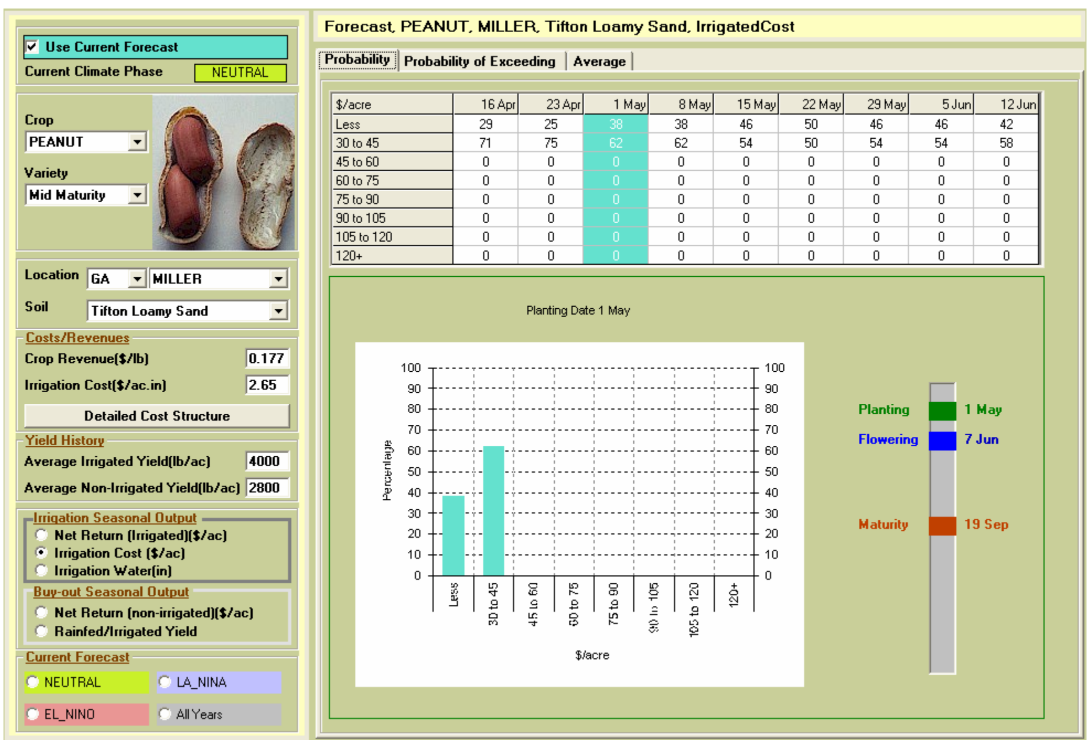
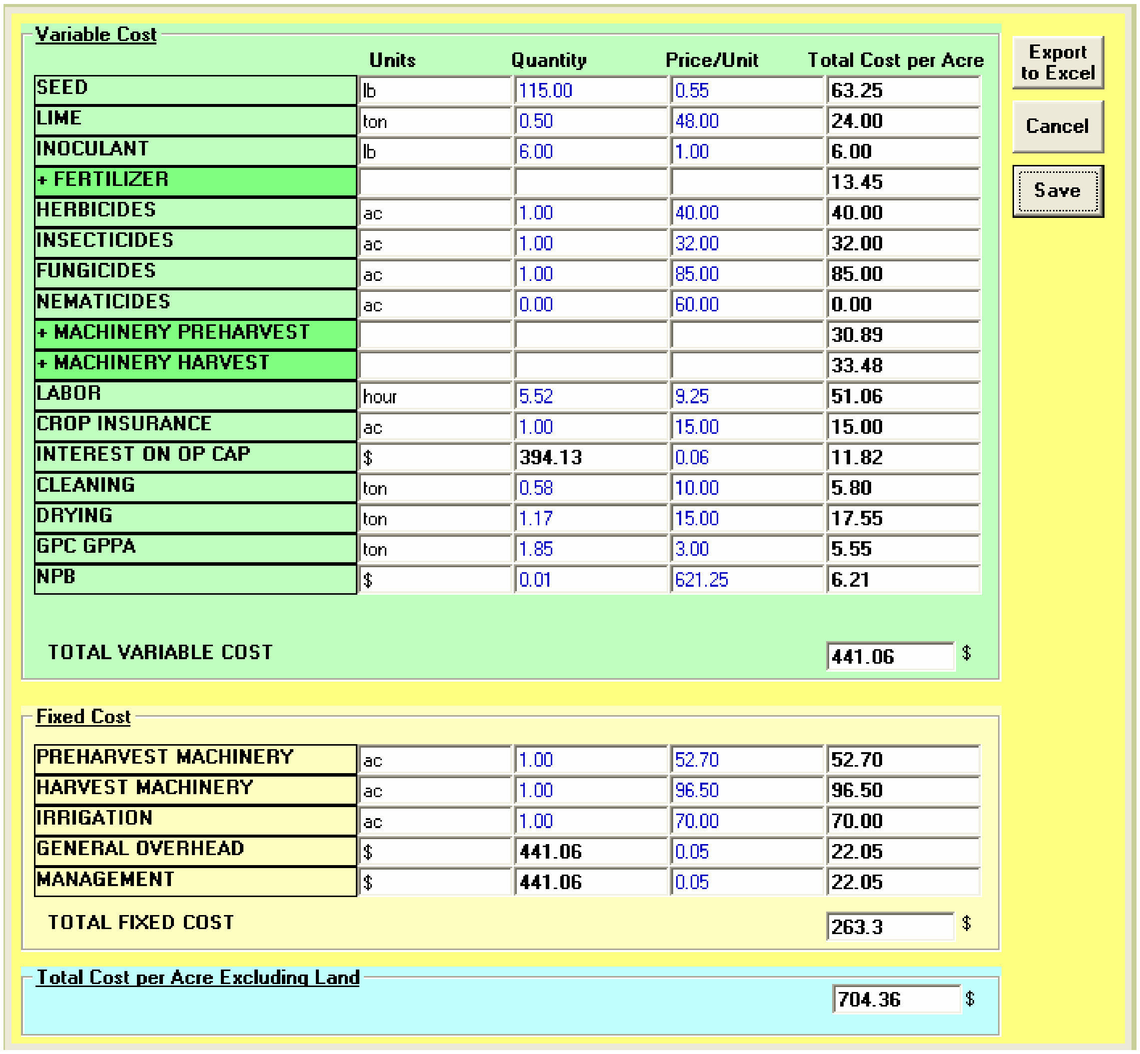


Figure 2. Probability table and chart of estimated irrigation cost (US$/ac) of peanut production in Miller County, GA.



Variable Cost

	Units	Quantity	Price/Unit	Total Cost per Acre
SEED	lb	115.00	0.55	63.25
LIME	ton	0.50	48.00	24.00
INOCULANT	lb	6.00	1.00	6.00
+ FERTILIZER				13.45
HERBICIDES	ac	1.00	40.00	40.00
INSECTICIDES	ac	1.00	32.00	32.00
FUNGICIDES	ac	1.00	85.00	85.00
NEMATICIDES	ac	0.00	60.00	0.00
+ MACHINERY PREHARVEST				30.89
+ MACHINERY HARVEST				33.48
LABOR	hour	5.52	9.25	51.06
CROP INSURANCE	ac	1.00	15.00	15.00
INTEREST ON OP CAP	$	394.13	0.06	11.82
CLEANING	ton	0.58	10.00	5.80
DRYING	ton	1.17	15.00	17.55
GPC GPPA	ton	1.85	3.00	5.55
NPB	$	0.01	621.25	6.21
TOTAL VARIABLE COST				441.06 $

Fixed Cost

	Units	Quantity	Price/Unit	Total Cost per Acre
PREHARVEST MACHINERY	ac	1.00	52.70	52.70
HARVEST MACHINERY	ac	1.00	96.50	96.50
IRRIGATION	ac	1.00	70.00	70.00
GENERAL OVERHEAD	$	441.06	0.05	22.05
MANAGEMENT	$	441.06	0.05	22.05
TOTAL FIXED COST				263.3 $

Total Cost per Acre Excluding Land: 704.36 $

Figure 3. PIDSS cost structure section which allows the user to customize prices and quantities according to local conditions.

The other window shows the detailed cost structure which provides the different components of the variable and fixed costs used in the enterprise cost analysis for irrigated peanuts (Smith et al., 2004). This section allows the user to customize prices and quantities according to his/her local conditions. The program also allows users to export the values to a spreadsheet. Changes made in the cost structure are automatically reflected in the probability tables and charts of net returns and irrigation cost.

In addition to net returns and irrigation cost, users can examine the distribution of total irrigation water requirements for a particular planting date under different ENSO phases (Figure 4).

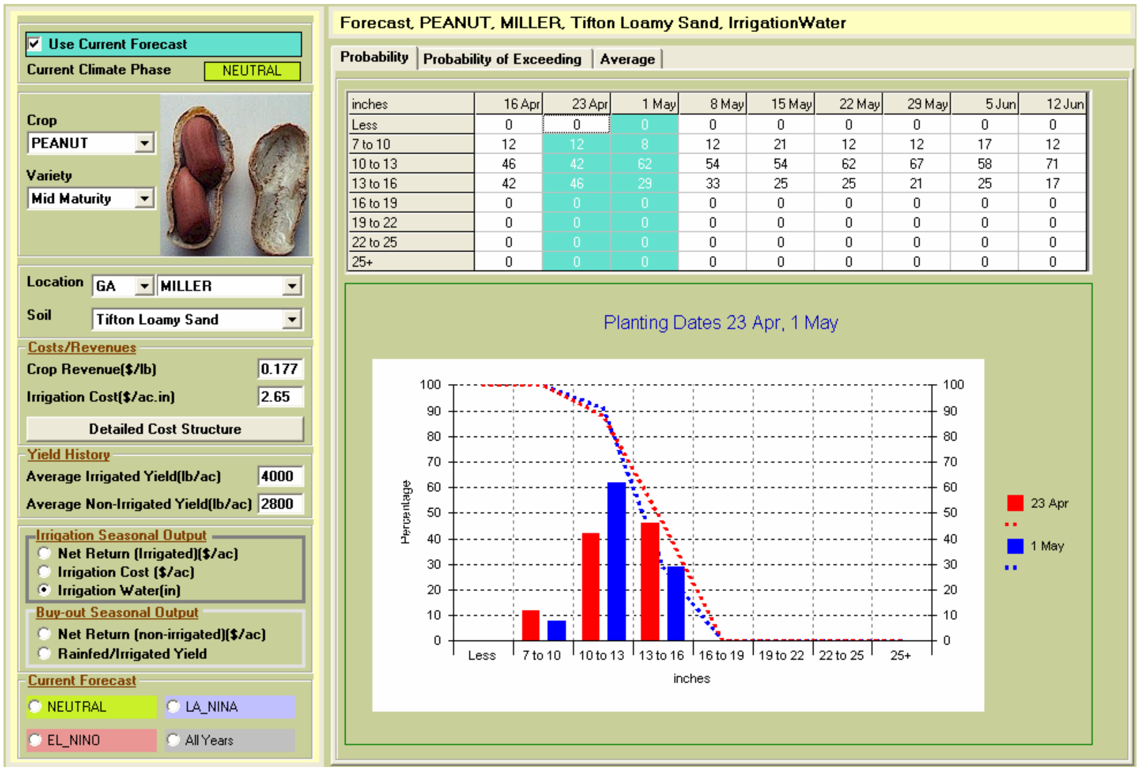


Figure 4. Probability table and histogram of total irrigation consumption for selected planting dates during Neutral years.

Case Study

A comparison of rainfed and irrigated peanut production for Miller County in Georgia is presented to showcase the features of the system and to examine the effect of irrigation, planting dates, and climate on the level of profitability on peanut production. Miller County was chosen because it had the largest area devoted to irrigated peanuts based on the 2002 census of agriculture (NASS, 2004).

The CSM-CROPGRO-Peanut model (Boote et al., 1998; Jones et al., 2003) was used to simulate peanut yield responses to different climate, irrigation, and planting date scenarios. The CSM-CROPGRO-Peanut model, which is part of DSSAT Version 4.0 (Hoogenboom et al., 2004), is a process based model that simulates crop growth and development and the plant and soil water, and nitrogen balances. Long-term historical weather data (1900-2004) were obtained from the National Weather Service (NWS) Cooperative Observer Program (COOP) network and compiled by the Center for Oceanic-Atmospheric Prediction Studies (COAPS), through the SECC. Weather variables include daily maximum and minimum temperatures and precipitation. A solar radiation generator, WGENR, with adjustment factors obtained for the southeastern USA (Garcia y Garcia and Hoogenboom, 2005) was used to generate daily solar radiation data.

Georgia Green peanut cultivar, a medium maturing runner-type peanut variety, was selected as the representative variety for all counties included in the simulation. The soil profile data of three representative soils for each county were obtained from the soil characterization database of the USDA National Resource Conservation Service. Eight planting dates (April 16, 23; May 1,8, 15, 22, 29; June 5 and 12) were considered in the simulation. These represent all possible planting dates at weekly intervals. The typical planting window for peanuts is between mid-April and mid-June. Finally, peanut responses were simulated with and without irrigation and yield and associated variables, including irrigated water requirements and number of irrigation events, were predicted.

In simulating the crop response to irrigation, an irrigation event is triggered when soil moisture at the top 20 inches of the soil profile reaches 60% of the available soil moisture. The soil profile is automatically refilled with water until soil moisture reaches field capacity. Peanut yield was simulated for several counties in Alabama, Florida, and Georgia (Table

1). In addition to peanut yield, the number of irrigation events and total irrigation applied were extracted from the model output files and imported into the PIDSS database.

Table 2 was generated by selecting a particular net return category and the corresponding probabilities under different climate phases. For this particular example, the net return was calculated based on the yield response of peanut grown in Tifton loamy sand. Since three representative soil types in each county were used in the simulation, differences in responses of peanuts grown in each of the soil types are to be expected hence, net returns will be different as well. Under irrigated conditions, the likelihood of obtaining higher net return increased when the planting date was delayed for El Niño years. However, the probability decreased when peanuts were planted after May 29. During La Niña years, growers have a greater chance of achieving net returns of $200-400/acre if peanuts are planted in mid- to late-April. In Neutral years, the calculated probabilities of net return appear to be fairly even across different planting dates. These observations also magnify the importance of proper planting date. While proper planting date is only one phase of peanut production management, it is important to note the impact of this decision on the profitability of irrigated peanuts. The information provided by the system will allow growers to examine all possible planting dates at weekly intervals between mid-April to mid-June, and weigh the risks and benefits of selecting a particular planting date for irrigated peanuts. For growers with large irrigated systems, planting peanuts using a staggered schedule may be a feasible solution to allow him or her to spread the risk.

Table 1. Counties in Alabama, Florida and Georgia that were included in the climate-based cost analysis for peanut production.

Alabama		Florida		Georgia	
Autauga	Dallas	Calhoun	Levi	Baker	Lee
Baldwin	Escambia	Escambia	Marion	Burke	Miller
Barbour	Hale	Gadsden	Okaloosa	Calhoun	Mitchell
Bullock	Henry	Gilchrist	Santa Rosa	Coffee	Seminole
Butler	Houston	Holmes	Walton	Colquitt	Sumter
Clarke	Mobile	Jackson	Washington	Decatur	Tattnall
Coffee	Monroe			Dooly	Terrell
Conecuh	Montgomery			Early	Tift
Covington	Pike			Irwin	Worth
Crenshaw	Russell				
Dale	Washington				
Total = 22		Total = 12		Total = 18	

Table 2. Probabilties (%) of achieving net returns of $200-400 per acre for irrigated peanuts in Miller County, Georgia. Irrigation cost is set at $2.65 per acre-inch

Planting date	Neutral	El Niño	La Niña
Apr 16	33	8	58
Apr 23	38	8	50
May 1	38	8	50
May 8	38	17	33
May 15	25	25	33
May 22	38	25	25
May 29	38	42	42
June 5	29	42	33
June 12	25	25	42

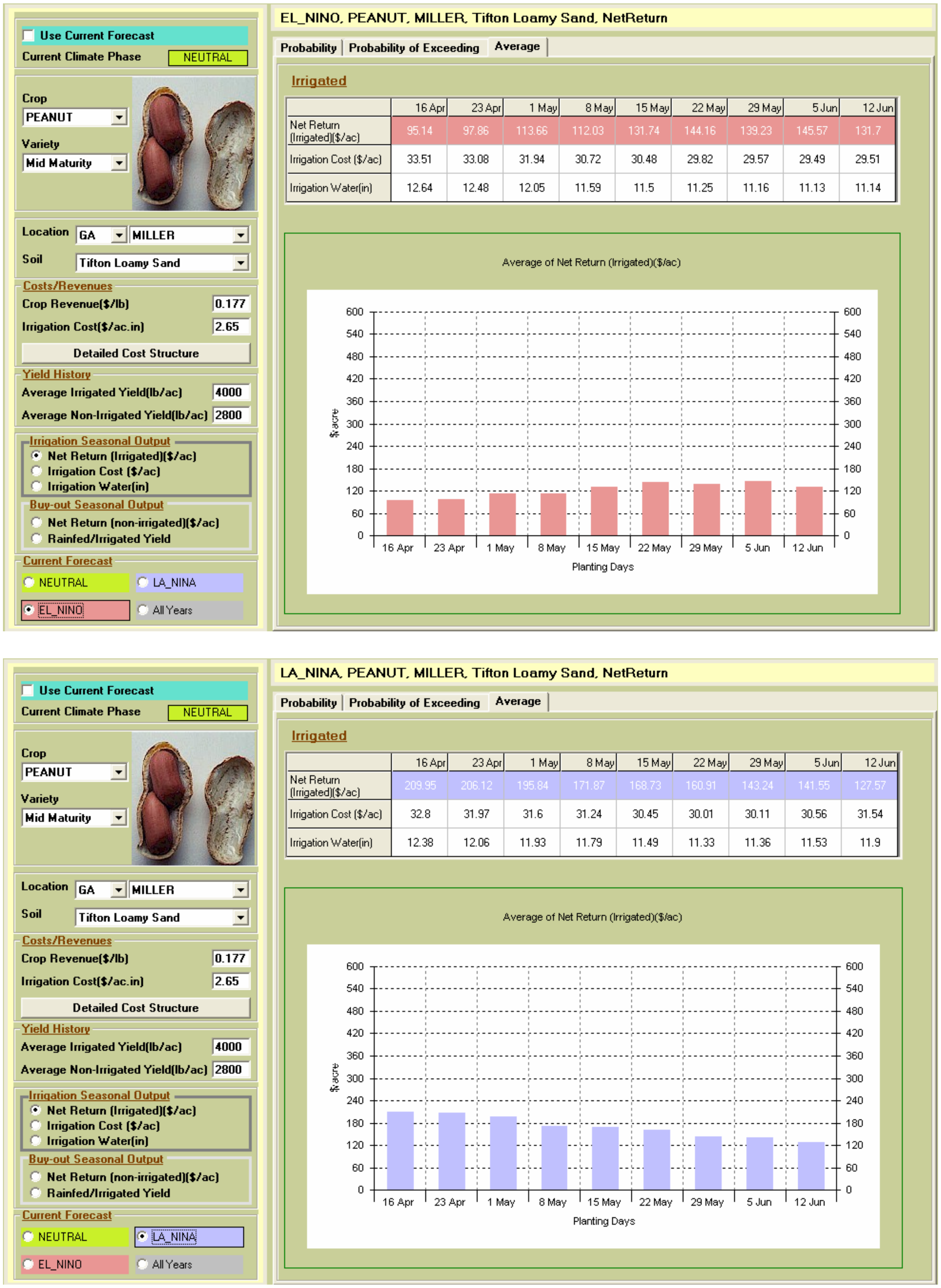
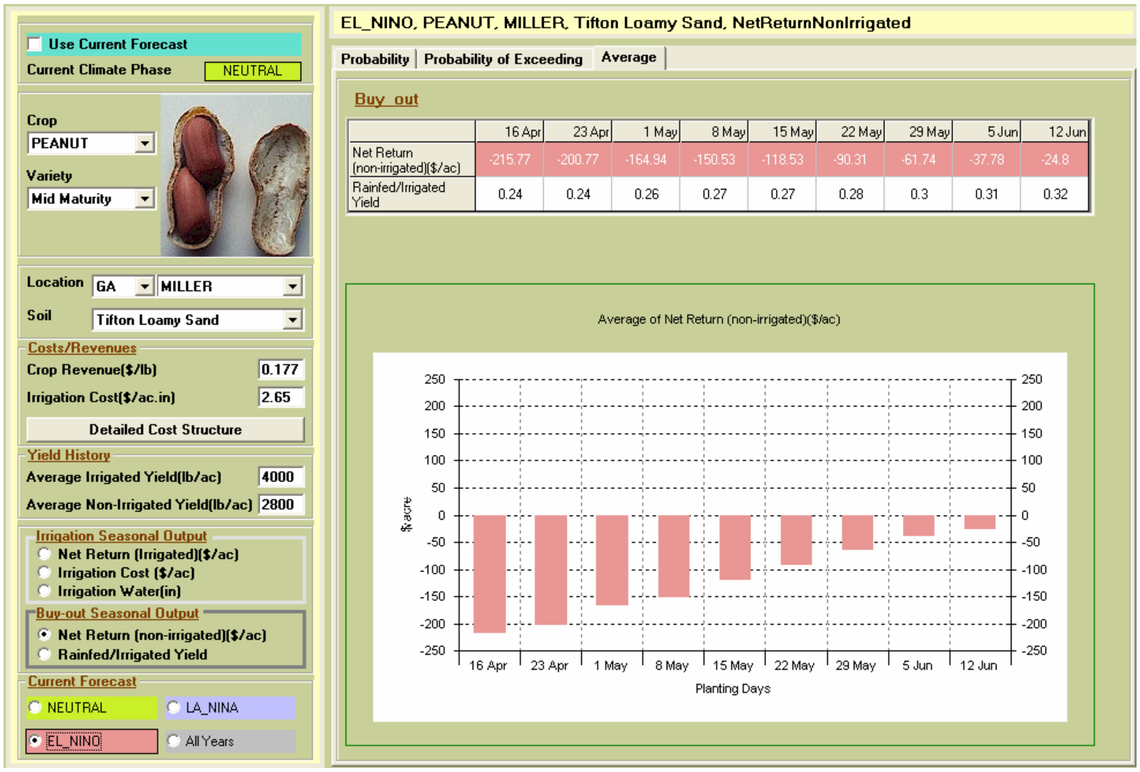


Figure 5. Average net return of irrigated peanuts for different planting dates under El Niño (top) and La Niña (bottom).



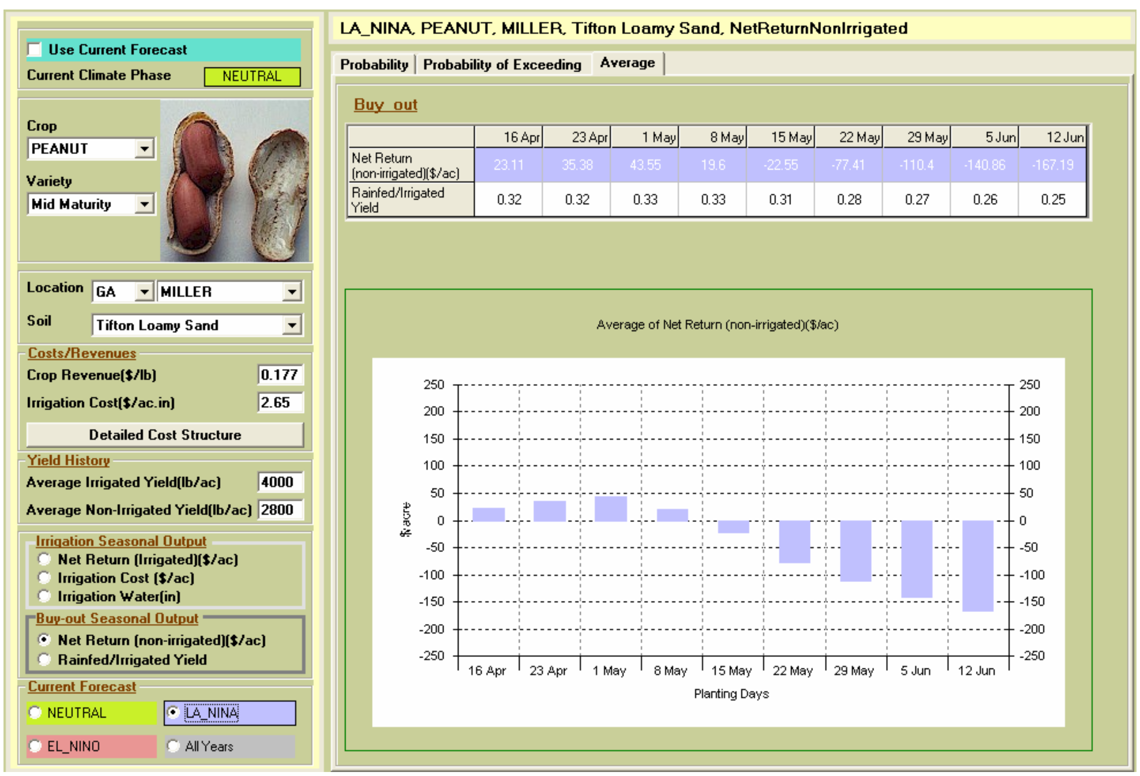


Figure 6. Average net return of non-irrigated peanuts for different planting dates under El Niño (top) and La Niña (bottom).

Under El Niño, average net returns increased from $95.14 per acre for an April 16 planting date to $145.57 per acre for peanuts planted on June 5 (Fig. 5). In La Niña, the net returns ranged from $127.57 to $209.95 per acre for irrigated peanuts, and followed a decreasing trend as planting date was delayed. The trends observed for this case study may not be the same for all soils and counties included in the PIDSS database. Nonetheless, average net returns are expected to be positive under irrigated conditions.

This decision support system also allows the user to examine the economic impact under rainfed conditions. For example, dryland peanut production in Miller County, Georgia is profitable in La Niña years if peanuts are planted between April 16 and May 8 (Fig. 6). Delayed planting will result in significant economic losses ranging from $22.55 per acre to $167.19 per acre for peanuts planted on May 15 and June 12, respectively. Under El Niño, non-irrigated peanut is not a profitable endeavor for most planting dates because of low yields. Regardless of planting date and ENSO phase, average net returns of non-irrigated peanuts are considerably lower compared to irrigated peanuts.

Summary

The peanut irrigation decision support system was developed to assist growers and to provide information on the levels of profitability of planting peanuts with and without irrigation. The CSM-CROPGRO-Peanut model was used to simulate peanut yields under irrigated and non-irrigated conditions from 1900-2004 for several counties in Alabama, Florida and Georgia. Results of the crop model simulations were imported into the PIDSS database. The decision support system provides the probabilities of achieving net returns for different planting dates and soil types for main peanut-producing counties in the southeastern US under different climate scenarios. The tool also provides probability distributions of the seasonal cost to irrigate peanuts and the amount of water that would be required.

A case study and an example analysis was conducted for irrigated and rainfed peanuts for Miller County, Georgia. Under irrigated conditions, average net returns increased when peanuts were planted between April 16 and June 5 in El Niño years. In La Niña years, the net returns followed a decreasing trend as planting date was delayed. Non-irrigated peanut was found not to be profitable in El Niño years for most planting dates because of low yields. In La Niña years, dryland peanut production was only profitable when peanuts were planted between April 16 and May 8.

The prototype will be demonstrated to groups of stakeholders consisting mainly of county extension agents and growers. After additional testing and evaluation, the prototype irrigation decision aid will be deployed as a web-based tool on the AgClimate web site (www.AgClimate.org). In addition, the program will serve as a platform for other row crops (e.g. cotton, corn, soybean) that will be included in the irrigation return analysis tool in the near future.

References

Adams, R.M., K.J. Kelly, B.A. McCarl, D.M. Legler, J. Obrian, A. Solow, and R. Weiher. 1995. Value of improved long-range weather information. *Contemporary Economic Policy* 13:10-10.

Breuer, N. V. Cabrera, P. E. Hildebrand, and J. W. Jones. 2003. Potential response of north central Florida livestock producers to long-term climate forecasting. Southeast Climate Consortium Staff Paper Series 01-03. 22 pp.

Boote, K.J., Jones, J.W., Hoogenboom, G., and Pickering, N. B. 1998. The CROPGRO Model for Grain Legumes. pp. 99-128. *In* G. Y Tsuji, G. Hoogenboom, and P. K. Thornton (eds.) Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Fraisse, C., J.W. Jones, N. Breuer, and D. Zierden. 2005. AgClimate: Information and Tools for Decision Making in Agriculture. ASAE Paper No. 053021. St. Joseph, MI: ASAE.

Garcia y Garcia, A. and G. Hoogenboom. 2005. Evaluation of an improved daily solar radiation generator for the southeastern USA. *Climate Research* 29:91-102.

Green, P. M., D. M. Legler, C. J. M. Miranda V, and J. J. O'Brien, 1997: The North American Climate Patterns Associated with El Niño-Southern Oscillation. Report 97-1, Center for Ocean-Atmospheric Prediction Studies, Tallahassee, FL 32306-2840, 17 pp.

Hansen, J. W., A. W. Hodges and J. W. Jones. 1998. ENSO influences on agriculture in the Southeastern US. *J. of Climate* 11(3), 404-411.

Hansen, J.W., Jones, J.W., Irmak, A., and Royce, F.S. 2001. ENSO impacts on crop production in the Southeast US. pp. 55-76 *In*: Rosenzweig, C., Boote, K.J., Hollinger, S., Iglesias, A., and Phillips, J. (Eds.), Impacts of El Niño and Climate Variability on Agriculture. ASA Special Publication No. 63. Madison, WI: ASA.

Hildebrand, P. E., A. Caudle, V. Cabrera, M. Downs, M. Langholtz, A. Mugisha, R. Sandals, A. Shriar, and D. Veach. 1999. Potential use of long range climate forecasts by agricultural extension in Florida. Florida Consortium Technical Report Series, FC-UF-2000-01. 24 pp.

Hoogenboom, G., J.W. Jones, P.W. Wilkens, C.H. Porter, W.D. Batchelor, L.A. Hunt, K.J. Boote, U. Singh, O. Uryasev, W.T. Bowen, A.J. Gijsman, A.S. Du Toit, J.W. White, and G.Y. Tsuji. 2004. Decision Support System for Agrotechnology Transfer Version 4.0. [CD-ROM]. University of Hawaii, Honolulu, HI.

Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens, U. Singh, A.J. Gijsman, and J.T. Ritchie. 2003. DSSAT Cropping System Model. *European Journal of Agronomy* 18:235-265.

Martin,E.C., J.T.Ritchie, and B.D.Baer. 1996. Assessing investment risk of irrigation in humid climates. *J of Production Agriculture* 9:228-233.

NOAA. 2001. Definitions of El Niño, La Niña, and ENSO. National Oceanic and Atmospheric Administration, Tropical Atmosphere Ocean Project. Available at: http://www.pmel.noaa.gov/tao/proj_over/ensodefs.html. Accessed August 14, 2005.

Peters, A.J., L. Ji, and E. Walter-Shea. 2003. Southeastern U.S. vegetation response to ENSO Events (1989–1999). *Climatic Change* 60 (1-2):175 – 188.

Smith, N., C. Lacy, D. Shurley, K. Kightlinger, C. Escalante, and G. Shumaker. 2004. South Georgia crop enterprise cost analysis. The University of Georgia College of Agricultural and Environmental Sciences. Cooperative Extension Service. 37 p.

USDA. 2004. 2002 Census of Agriculture Volume 1: County Level Data. Washington, DC: USDA National Agricultural Statistics Service. Available at: http://www.nass.usda.gov/census/census02/volume1/index2.htm. Accessed August 2, 2005.

Abstract

The complexity of scheduling irrigation can be greatly reduced by the use of publicly available computer programs. However, irrigation scheduling is more complicated in humid regions than arid locations, due to factors such as cloudy weather, rainfall, and temperature swings caused by the movement of weather fronts. Weather conditions vary greatly in humid regions from year to year, and even within a year, and the variability must be accounted for in the scheduling program. The Arkansas Irrigation Scheduler has been in use for over twenty years and is currently used in Arkansas and surrounding states. The current version was released in 2000 and a new release is planned for 2006. The new version will maintain the objectives of the earlier releases, except that it will be field-, rather than system-based. The change allows the users to view information on more of their fields at one time and group the fields however they feel most suitable. Drip irrigation scheduling will be added for both surface and subsurface systems. While new crop coefficient functions will not be included initially, they can be added as appropriate. Using the program to properly schedule irrigation can save energy and therefore money by reducing unnecessary pumping, and help to alleviate water shortages being experienced in many agricultural areas.

Introduction

The complexity of scheduling irrigation can be greatly reduced by the use of publicly available computer programs. Henggeler (2002) summarized eight programs developed in locations ranging from Arizona to North Dakota and varying greatly in complexity and input requirements. However, not all programs work equally well in both arid and more humid climates. Irrigation scheduling is more complicated in humid regions than arid locations, due to factors such as cloudy weather, rainfall, and temperature swings caused by the movement of weather fronts. Weather conditions in humid regions vary greatly from year to year, and even within a year, and the variability must be accounted for in the scheduling program.

One of the programs discussed by Henggeler (2002) was the Arkansas Irrigation Scheduler (Scheduler). The Scheduler has been in use by farmers in Arkansas and surrounding states for over twenty years and a new version will be released in 2006. The updated version will include improvements to incorporate knowledge gained since the 2000 release of version 1.1w, to feature more intuitive operation similar to other Windows-based programs, and to be more universally applicable, rather than just aimed at users in Arkansas and surrounding states.

Arkansas Irrigation Scheduler

The Scheduler was developed in the 1970s and early 1980s under the leadership of Dr. James Ferguson to aid Arkansas farmers in managing irrigation. Arkansas producers were just beginning to irrigate their crops, rather than depending solely on rainfall to meet the crop's water needs. In fact, during the years 1972 through 1981, the first ten years with separate records collected for irrigated and nonirrigated crops in Arkansas, an average of only 8% of the soybean and 14% of the cotton crop was irrigated (NASS, 2005).

Like many scheduling programs, the Scheduler uses a water-balance approach to scheduling irrigation, similar to managing a checkbook. The system balance represents the soil water deficit (SWD), the difference between the soil's existing moisture content, summed over the rooting depth, and the moisture content of the soil at its well drained upper limit (~24 hours after surface water was removed). Deposits to the system include rainfall and irrigation. Withdrawals from the system include evapotranspiration (ET), runoff, and deep percolation below the root zone. The program doesn't attempt to estimate runoff; instead the user is asked to input the effective rainfall, or the amount in excess of runoff. Deep percolation is considered negligible when the SWD > 0. Rooting depth is not used explicitly in the program, but is implicit in the choice of a maximum allowable SWD. More detailed descriptions of the program were presented by Cahoon et al. (1990) and that information will not be repeated here. Rather, this report will deal with how the version of the program planned for release in 2006 will be different from previous versions.

The program has gone through many changes as both knowledge and personal computing power have advanced. The earliest versions were mainframe-computer based (Yar, 1984), since personal computers (PCs) were somewhat rare and not very powerful at that time. The initial program was only for center pivot systems. Later versions included support for towable center pivot systems (Edwards, 1986) and eventually furrow and flood irrigation (Cahoon et al., 1990). The current (2000) version also includes support for graded border irrigation.

The original PC version of the program was written in BASIC for the Radio Shack TRS-80 computers (mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture or University of Arkansas) in many University of Arkansas Cooperative Extension Service (CES) and some farm offices. Several updated versions were released by CES for the MSDOS™ operating system, and the most recent version was written for Microsoft Windows™.

Cahoon et al. (1990) reported the five objectives for their program were: 1) to be user friendly and easily operated; 2) to require minimal input data; 3) to be applicable to mid-South climatological conditions and crops; 4) to be system-based as opposed to field-based; and 5) to be useful as a prediction tool, as opposed to a monitoring tool. While increases in computing power have reduced the need to be system based, four of those objectives still apply.

Changes for the 2006 Release

Early in 2005 a group of program users met to discuss ways to improve the program for the next release. One commonly heard comment was that the program should operate similarly to other Windows-based programs, making it easier for new users to learn to operate the program. Therefore, many of the changes were intended to make the program more user friendly (obj. 1).

The program was developed for Arkansas producers, and much of the funding for developing and supporting the program was provided by Arkansas soybean producers through their checkoff funds. However, producers in the states surrounding Arkansas also use the program and many researchers use the program as well. In the past, producers or researchers with extensive weather data were only able to use the maximum daily temperature and rainfall data and required to select one of six locations (Stuttgart, Keiser, and Hope, Arkansas; Jackson, Tennessee; Stoneville, Mississippi; and Calhoun, Louisiana) most similar to their own location for estimating ET. Most researchers and some nearby states, including Louisiana and Missouri, had electronic weather networks that provided more extensive weather data than was available to most Arkansas producers. The new release will allow users to input a reference ET directly, rather than having the program estimate one. Those with limited data can still allow the program to estimate ET in the same way as before. Therefore, while only minimal input data is still required to use the program (obj. 2), the changes will allow the user to take advantage of the data available when it exceeds the minimum required.

While the program will be applicable to more areas than before, it is still intended primarily for use in humid climates (obj. 3). Wet soil conditions typical of winter and early spring simplify the choice of a starting SWD. In addition, small errors that accumulate over time from the use of limited weather data will usually be erased by rainfall.

Recent versions of the program have changed from system-based to field based (obj. 4). In the early versions, computer memory and storage restricted the program to only consider a small number of fields. A representative situation was selected as a four-field system, representing quadrants of a stationary center pivot field, halves of two towable center pivot fields, or four fields sharing one well for surface irrigation. Recommendations were made for when to irrigate each of the fields in the system. More powerful PCs allow many more fields to be considered simultaneously. Being able to view the soil moisture status of most or all of the fields on a farm at the same time was believed to be more advantageous than retaining the system base. The user could then choose to group the fields in whatever way best fit the situation.

The program has kept its utility as a prediction tool, rather than just a monitoring tool (obj. 5). The predictive capability of the program is one of its most important assets under mid-South conditions, where multiple crops are often irrigated from the same water supply. In addition, irrigation decisions are often coordinated with pesticide applications or other field operations.

Support for two new types of irrigation systems will be included in the new release: surface and subsurface drip. The surface drip routine will be similar to the center pivot routine, except that the assumed application efficiency will be 95%, whereas 90% was assumed for center pivot systems (Cahoon et al., 1990). The subsurface drip routine will also assume 95% efficiency, and assume no soil surface wetness associated with irrigation.

There are currently no plans to change the crop coefficient functions in the program., However, considerable research is being conducted on crop coefficients and new functions can be added as improvements are developed for the currently included crops (cotton, soybean, corn, milo), or if schedules are needed for additional crops.

Even with all of the changes to the Scheduler, users must remember that many things can affect the accuracy of the program output. Considerable runoff can result from thunderstorms or from too high of application rates with a center pivot. Care must be taken when estimating effective rainfall or the actual irrigation amount. With furrow irrigation, soil crusting, irrigating every other middle, or irrigating a field with appreciable slope may result in less than saturated conditions following irrigation, even though the assumption in the program is SWD = 0 (Cahoon, 1990). Another assumption in the program is no standing water (i.e., all rainfall or irrigation applied in excess of the SWD will run off the field). Standing water can cause the soil to remain saturated for several days, stressing the crop and continuing to affect water use after the standing water is removed. Estimates for water use in the program are based on a healthy, well watered crop. A crop that has been drought stressed or experienced oxygen stress from standing water may never recover to the expected water use rate.

Beginning with the 2006 release, an internet version of the program will be available, where the user is always assured of having the latest version and doesn't have to bother with installation of the software. The internet will continue to be the means for program distribution for those who want a stand-alone program. A voluntary registration will continue to be used to maintain a user list in case programming bugs are discovered or later releases become available.

Finally, the new release of the program will be applicable to more areas than before, and will offer improvements for users already familiar with the program. Using the program will aid producers in determining the optimum irrigation schedule for their situation. Properly scheduling irrigation can save energy and therefore money by reducing unnecessary pumping. In addition to saving money, however, reducing unnecessary pumping can help to alleviate water shortages being experienced in many agricultural areas.

Summary

The Arkansas Irrigation Scheduler has been in use for over twenty years and is used in Arkansas and surrounding states. The current version was released in 2000 and a new release is planned for 2006. The new version will be field-, rather than system-based; otherwise it maintains the objectives of the previous releases. The change allows the users to view more of their fields at one time and group the fields however they feel most suitable. Other changes will make the program easier to learn, allow the user to take advantage of more extensive weather data if it is available, make the program applicable to more areas than before and include support for drip irrigation. While new crop coefficient functions will not be included initially, they can be added as appropriate. . Using the program to properly schedule irrigation can save energy and therefore money by reducing unnecessary pumping, and help to alleviate water shortages being experienced in many agricultural areas.

References

Cahoon, J., J. Ferguson, D. Edwards, and P. Tacker. 1990. A microcomputer-based irrigation scheduler for the humid mid-South region. Applied Engineering in Agriculture 6(3):289-295.

Edwards, D. R. 1986. Development and evaluation of a microcomputer program to schedule center pivot irrigation in sub-humid climates. Unpublished M.S. thesis. University of Arkansas, Fayetteville.

Henggeler, J. 2002. Software programs currently available for irrigation scheduling. In Proc. 23rd Annual International Irrigation Show & Conference (Oct. 24-26, New Orleans). Irrigation Association. Arlington, VA

NASS. 2005. Quick Stats: Agricultural Statistics Data Base. Available online at: http://www.nass.usda.gov/QuickStats/.

Yar, A. 1984. On-farm irrigation scheduling by computer simulation in Arkansas. Unpublished Ph.D. diss. University of Arkansas, Fayetteville.

Fertigation with Drip Irrigation for Maximum Availability and Minimum Leaching of Nitrate

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Introduction

Fertigation is the process of applying fertilizers through the irrigation water. For microirrigation systems, a recommendation frequently used for fertigation is to inject during the middle one-third or the middle one-half of the irrigation set time to insure a field-wide uniformity of applied fertilizer equal to that of the irrigation water and a relatively uniform chemical distribution in the root zone. However, a common practice is to fertigate for a short period of time, i.e. one or two hours. The primary motivation for this practice is convenience.

Short-term fertigation events could result in relatively nonuniform distributions of fertilizer in the root zone and an increased potential for fertilizer leaching depending on the fertigation strategy. The objective of this study was to determine the effect of different fertigation strategies for microirrigation systems on water and nutrient use efficiencies and on nitrate leaching.

Materials and Methods

The HYDRUS-2D computer simulation model was used to assess the effect of different fertigation strategies on water and nutrient use efficiencies and on nitrate leaching. Outputs of the model include distributions of nitrate and soil water and a mass balance of nitrate in different parts of the root zone.

Phase I of the project evaluated the effect of different fertigation scenarios on the nitrate distribution in the soil and on nitrate leaching using a nitrate only fertilizer. A 28 d simulation period was used for the fertigation scenarios which were:

- microirrigation systems: microsprinkler (citrus) using a sprinkler discharge rate of 5 gal/h (SPR); surface drip irrigation (grapes) using 1 gal/h emitters (DRIP); surface drip irrigation (strawberries) using drip tape with a tape discharge rate of 0.45 gpm/100 ft (SURTAPE); subsurface drip irrigation (tomatoes) using drip tape buried at 8 inches with a tape discharge rate of 0.22 gpm/100 ft (SUBTAPE)

• soil types: sandy loam (SL); loam (L); silt clay (SC); anisotropic silt clay (AC) with a ratio of horizontal hydraulic conductivity to vertical conductivity equal to 5.

• fertigation strategies: inject for 2 hours starting one hour after start of irrigation (B); inject for 2 hours in the middle of the irrigation set (M); inject for 2 hours starting 3 hours before cutoff of irrigation water (E); inject during the middle 50% of the irrigation set time (M50); inject continuously during the irrigation set (C).

Phase II evaluated the effect of fertigation strategies on the distribution and leaching of ammonium, urea, and nitrate for subsurface drip irrigation (SUBTAPE) and surface drip irrigation (DRIP) in loam. Fertilizer concentrations simulated the different forms of nitrogen found in UAN 32, an urea-ammonium nitrate (32-0-0) fertilizer solution commonly used for microirrigation. Reaction parameters used in the model were: hydrolysis – 0.38/d, nitrification rate – 0.2/d, and partition coefficient (K_d) for ammonium – 3.5 L/kg.

RESULTS AND CONCLUSIONS

Phase I - Nitrate

Nitrate is a highly mobile ion that moves readily with water. Thus, nitrate distributions around drip lines will be strongly affected by a particular fertigation strategy. The nitrate distributions shown in Figures 1 thru 5 occurred at the end of the first irrigation event after the start of fertigation.

Subsurface Drip Irrigation (SUBTAPE)

● Injecting for 2 h starting 1 h after the start of irrigation cycle resulted in a band of nitrate near the periphery of the wetted pattern at the end of the irrigation for in sandy loam with little or no nitrate near the drip line (shown by the white color) (Fig. 1A). The irrigation time was 27 h. Higher nitrate concentrations occurred above the drip line compared to below the drip line, the result of water flowing upward into dry soil above the drip line. Similar distributions occurred for loam and silty loam soil.

● Injecting for 2 h near the end of the irrigation accumulated nitrate in the immediate vicinity of the subsurface drip line as indicated by the red color near the drip line (Fig. 1B). Higher nitrate concentrations occurred in the soil compared to injecting near the beginning of the irrigation cycle strategy. Similar distributions occurred for loam and silty loam soil.

● Injecting during the middle 50% of the irrigation cycle spread the nitrate throughout most of the wetted area (Fig. 1C). Higher nitrate concentrations occurred below the drip line compared to above the line. This behavior is the result of a wetter soil above the drip line at the start of injection than occurred at the beginning of the irrigation, which reduced the upward flow of water for this strategy. Similar distributions occurred for loam and silty loam soil.

Surface Drip Irrigation (DRIP)

● Injecting for 2 h near the beginning of the irrigation resulted in band of nitrate starting about 15 to 18 inches from the drip line and extending to the periphery of the wetted pattern for a 2 h injection in loam (Fig. 2A). Leaching of nitrate occurred near the drip line (white color). The irrigation time was 1.5 days. Similar behavior occurred in sandy loam.

● Injecting for 2 h near the end of the irrigation resulted in a zone of relatively high nitrate concentrations next to the drip line (Fig. 2B). Similar behavior occurred in sandy loam.

● Injection during the middle 50% of the irrigation cycle caused a more uniform nitrate distribution throughout the soil profile compared to the other injection times (Fig. 2C). Similar behavior occurred in sandy loam.

● In silt loam, a horizontal band of nitrate extending nearly 20 inches from the drip line occurred with depth for a 2 h injection time near the beginning of the irrigation (data not shown). Ponded water on the soil surface flowing downward caused this behavior. Ponded water occurred because of the small infiltration rate of the soil compared to sandy loam and loam soil. Injecting near the end of the irrigation caused nitrate to accumulate near the surface in a horizontal band extending about 2 ft from the drip line. Injecting during the middle 50% of the irrigation distributed nitrate more evenly with depth.

Microsprinkler Irrigation (SPR)

● Nitrate patterns for a microsprinkler irrigation system reflected the water application pattern of the microsprinkler (data not shown). Most of the water applied by this sprinkler occurred within four feet of the sprinkler. Injecting for 2 h near the beginning of the irrigation for a short time period moved the nitrate down to depths between 18 and 40 inches near the sprinkler. Beyond 40 inches, nitrate remained near the soil surface.

● Injecting for 2 h near the end of the irrigation left most of the nitrate near the soil surface.

● Injecting during the middle 50% of the irrigation distributed the nitrate more evenly throughout the soil for distances smaller than 40 inches from the drip line compared to the other injection strategies.

Surface Drip Irrigation (SURTAPE)

The previous contour plots showed nitrate distributions for long irrigation times. However, for a short irrigation time of 3.2 h, little differences were found in the nitrate distributions for the various fertigation scenarios (data not shown).

Phase II

Urea is a highly mobile molecule that moves readily with water flowing through the soil. Urea is transformed to ammonium by hydroloysis. Ammonium is adsorbed to soil particles and does not move readily with water flowing through the soil. Ammonium is transformed to nitrate through a process called nitrification.

Results of the HYDRUS-2D modeling of urea, ammonium, and nitrate movement are illustrated by the data of SUBTAPE (loam) with 2 h fertigations occurring near the beginning of irrigation. Urea was distributed around the periphery of the wetted area with little urea immediately adjacent to the drip line prior to the start of the second fertigation event (3.54 d) (Fig. 3). After the end of the second fertigation (3.625 d), urea was highly concentrated in the immediate vicinity of the drip line, but at the end of the second irrigation (4.65 d), most of the urea was distributed near the periphery of the wetted area due to continuing the irrigation for a relatively long time period after injection ceased. Little urea remained in the immediate vicinity of the drip line. At the start of the third irrigation (7.00 d), the urea concentration had decreased substantially compared to that of 4.65 d due to hydrolysis. The urea distribution at the end of the 28 d simulation period (data not shown) was similar to that of 7.00 d.

Little movement of ammonium occurred between irrigations due to its adsorption characteristics (Fig. 3). At the end of the second fertigation event, relatively high concentrations occurred immediately adjacent to the drip line, but those concentrations decreased by the end of the second irrigation. Little change in the ammonium distribution occurred during the 28 d simulation period.

At the beginning of the second fertigation event, nitrate was distributed relatively uniformity around the drip line until near the edge of the wetted area (Fig. 3). At the end of the second fertigation event (3.625 d), nitrate was highly concentrated immediately adjacent to the drip line. However, at the end of the second irrigation (4.65 d), the nitrate concentration near the drip line decreased substantially due to leaching during the remainder of the irrigation, while nitrate concentrations further away from the drip line increased with higher nitrate concentrations above the drip line than below. At the beginning of the third irrigation (7.00 d), nitrate concentrations had increased throughout much of the wetted area compared to that at the end of the second irrigation (including near the drip line) due to hydrolysis of urea and nitrification of ammonium. Nitrate continued to accumulate in the soil profile during the 28 day simulation period.

Conclusions

For surface drip irrigation systems, short fertigation events at the beginning of irrigation followed by a long irrigation time resulted in nitrate accumulating in the periphery of the wetted pattern, beyond the area of maximum root density and in more leaching of nitrate compared to short fertigation events near the end of the irrigation cycle. The nitrate distribution in the soil was more uniform for fertigations during the middle 50% of the irrigation cycle compared to short fertigation events. Nitrate leaching was highest for short fertigations near the beginning of irrigation, while leaching was smallest for fertigations near the end of the irrigation.

For subsurface drip irrigation, no conclusions could be made about the effect of a fertigation strategy on nitrate leaching because of upward flow of water above the drip line. This flow resulted in more nitrate accumulation above the drip line for short fertigation events at the beginning of irrigation compared to the other strategies. Nitrate accumulation above the drip line was the smallest for short fertigation events at the end of the irrigation cycle because little upward flow occurred due to the wet soil at the time of fertigation.

Similar nitrate distributions occurred for short irrigation events, regardless of the fertigation strategy.

Urea readily moved with water during irrigation, but because of hydrolysis, urea did not accumulate in the soil with time. Little ammonium movement occurred throughout the wetted area, and little ammonium accumulation occurred with time due to nitrification. Nitrate continued to accumulate below the drip line during the simulation period. Nitrate leaching was slightly smaller for the UAN 32 fertilizer compared to the nitrate only fertilizer used in Phase I.

References

Hanson, B.R., J.W. Hopmans, A. Gardenas, and J. Simunek. 2004. Crop Nitrate Availability and Nitrate Leaching under Microirrigation for Different Fertigation Strategies. Progress Report, May 20, 2004, submitted to the California Department of Food and Agriculture Fertilizer Research and Education Program.

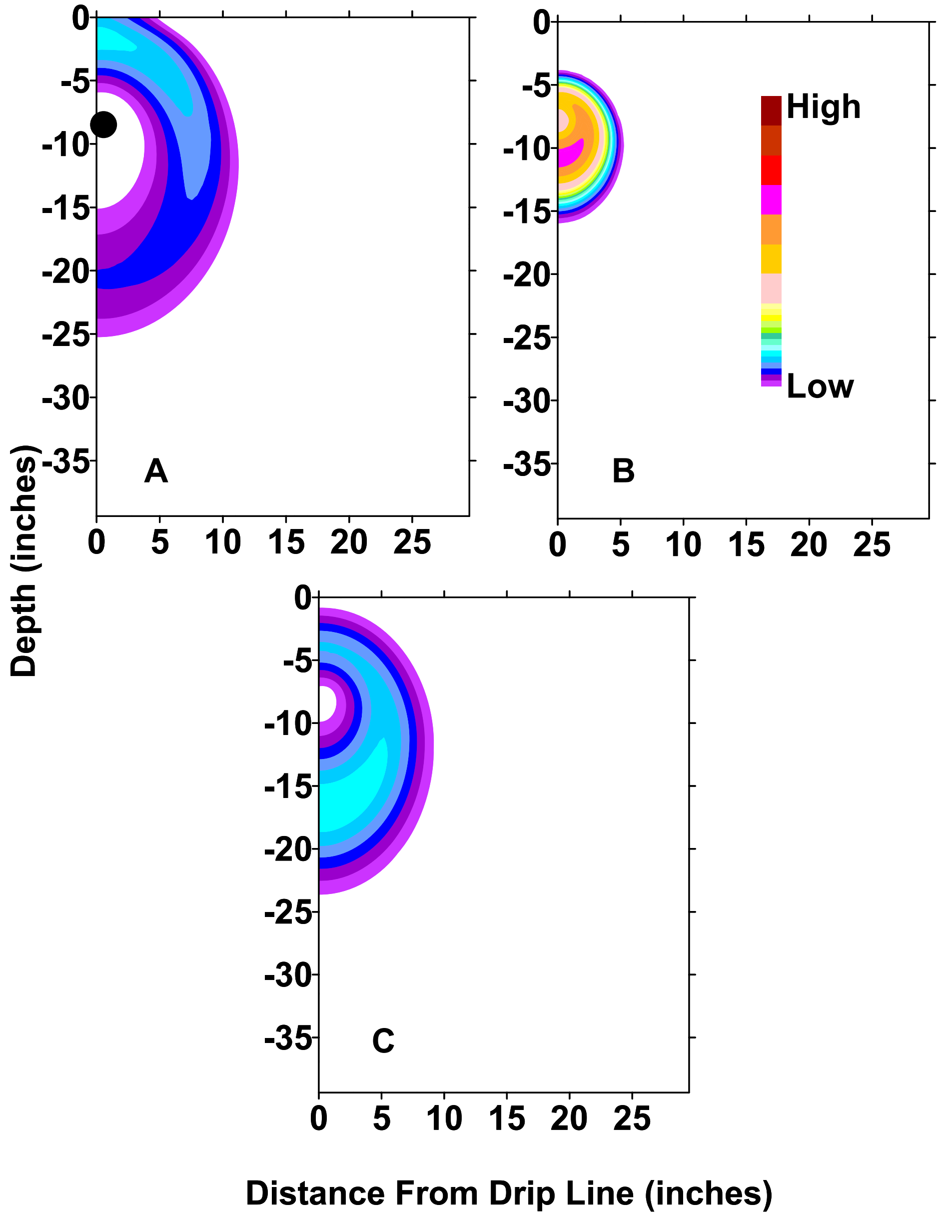

Figure 1. Nitrate distributions around the drip line at the end of the first fertigation event of a subsurface drip system in sandy loam for A) nitrate injection for 2 hr at the beginning of the irrigation starting 1 h after start of irrigation, B) injection for 2 h ending 1h before the end of the irrigation, and C) injection during the middle 50 percent of the irrigation set. Duration of irrigation was 27 h. The black dot is the location of the drip line. The color bar shows relative concentrations.

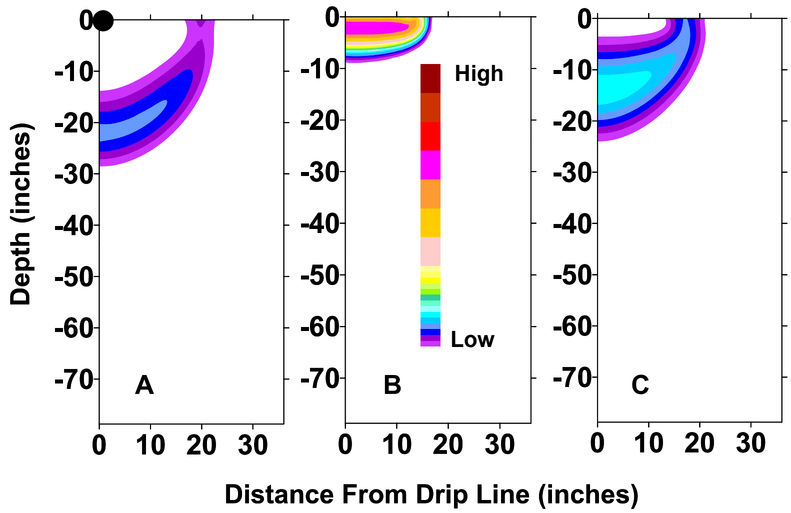

Figure 2. Nitrate distributions around the drip line of a surface drip system in loam soil at the end of the first fertigation event for A) nitrate injection for 2 hr at the beginning of the irrigation starting 1 h after start of irrigation, B) injection for 2 h ending 1h before the end of the irrigation, and C) injection during the middle 50 percent of the irrigation set. Duration of irrigation was 36 h. The black dot is the location of the drip line. The color bar shows relative concentrations.

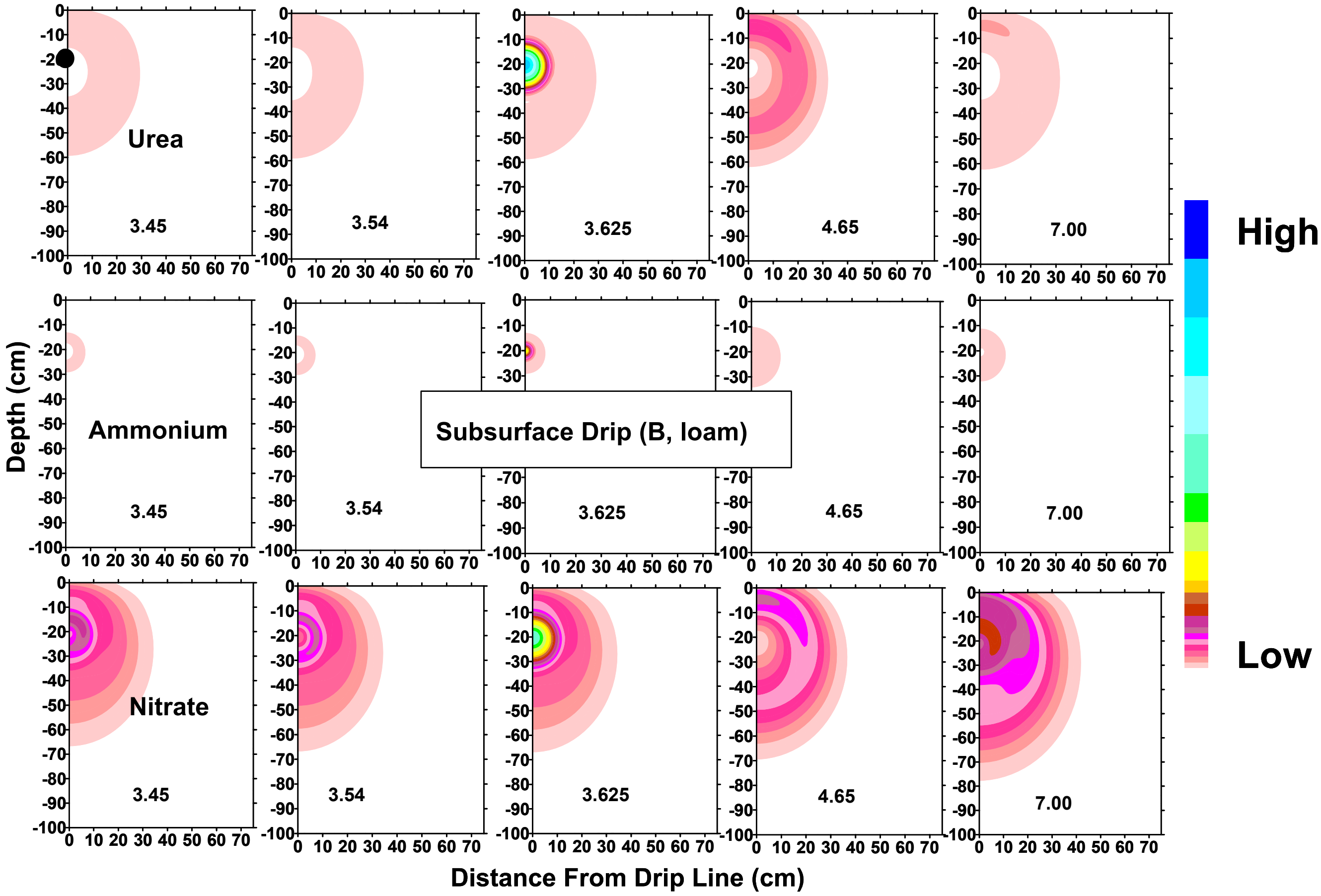

Figure 3. Distributions of urea, ammonium, and nitrate during the second fertigation event for the subsurface drip irrigation. Fertigation occurred for 2 h starting 1 h after the start of irrigation. Numbers are the days after start of the fertigation simulations: 3.45 - start of second irrigation; 3.54 - start of second fertigation; 3.625 - end of second fertigation; 4.65 - end of second irrigation; 7.00 - start of third irrigation.

Adapting On-Farm Water Supplies for High Value Irrigation Uses

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Throughout much of the humid east, irrigated row-crop fields are being converted to higher valued production including vegetables, orchards, ornamental plant nurseries, and sod production. In part, this is in response to greater competition resulting in lower prices for bulk traded commodities. Increasing land values and competition for water is forcing land and water to higher valued uses. Conversion from row-crop irrigation requires a reevaluation of water supply systems. Throughout the humid region, most irrigation water is obtained from on-farm surface and underground supplies. This paper briefly explores government limitations in place and proposed. Then, using data gathered from 800 farms in Georgia, it explores water needs for higher valued crops. Finally it lays out a systematic process that evaluates feasible options with current water supplies, steps to increase efficiency of the supply, and design and management changes that will assure flexibility and dependability for these high value crops.

WATER MANAGEMENT IMPROVEMENTS
IN CACHE VALLEY IRRIGATION CANALS

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Abstract

Detailed surveys of several Cache Valley, Utah, irrigation canals were conducted and key management and operations personal were interviewed about operations and maintenance practices. After completing a comprehensive survey of existing flow measurement structures in several Cache Valley canals, recommendations were made with regard to calibration shifts and need for maintenance. Management and operations personnel were interviewed about water delivery plans and locations for new flow measurement structures were selected. Seepage losses were measured in several reaches of the selected canals. And, a new, expanded map of the canals was developed for distribution to canal companies and publishing on a web site. Currently, new operation and maintenance plans are being developed in a collaborative and participative manner with the canal management personnel to enhance water delivery service and help improve the management of water resources which are becoming increasingly scarce in the valley.

Keywords: Irrigation, water management, flow measurement, operations and maintenance.

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Introduction

Cache Valley, Utah, has several irrigation canals which take water from streams and rivers flowing into the valley from surrounding mountains. Many of these canals were constructed early in the 20th century and remain mostly unlined. As the population of Cache Valley grows, greater demand for good-quality water has occurred, and the need for improved water management has become more important. Irrigation water users are especially targeted for water management improvements because they still use the largest quantities of water in the valley. The situation is exacerbated by the fact that water measurement capability in the canals is very limited, and the O&M budgets of the canal companies are very low, leading to significant deferred maintenance of the infrastructure.

For these reasons, steps have been taken to assess the current state of water management in several Cache Valley canals, including surveys to develop improved (and expanded) maps of the canals, the state of the infrastructure, and the current management practices. New operation and maintenance plans are being developed for each of the canals, and an overall water allocation plan is to be proposed for the canals included in the study. In addition to these measures, each of the existing flow measurement structures in the main canals have undergone calibration checks, and those structures which cannot function as flow measurement devices have been identified. New flow measurement structures will be built in the coming months to replace severely damaged structures, and to help improve water management at new key locations within the canals.

Methodology

All of the main canals receiving water from the Logan River which flow west and north through the valley were selected for inclusion in this study. The flow in these canals makes up more than half of the irrigation water used in the valley. The process followed by the authors has comprised several related steps, including the following:

1. Detailed physical surveys of selected canals and related infrastructure;
2. Interviews with canal company personnel;

3. Measurement of seepage losses;
4. Preparation of operations and maintenance plans to assist agency managers in achieving improved management of water resources.
5. Calibration of existing flow measurement structures in the main canals;
6. Design and construct several flow measurement structures in appropriate locations in order to improve the flow measurement capability;

Detailed Surveys

Surveys were conducted on the selected Cache Valley canals to determine the present condition and functioning of these canals, including culverts, gates, flumes, and other structures along the main canals. Attention was paid to all the minute physical details by walking in and along the canals, also giving opportunities to meet and talk with some of the water users and canal operations personnel. This type of survey is termed a *Diagnostic Walk-Thru* (Skogerboe and Merkley 1996). The *Diagnostic Walk-Thru* surveys were conducted on nine irrigation canals that carry water from the Logan River to the northern side of Logan River. During the surveys, several hundred digital photographs of flow measurement and water delivery structures, among other noteworthy locations, were taken, along with comments about operations and maintenance issues which were recorded in the field notes at the time each photo was taken. The coordinates of each location (including each of the photos, and others where photos were not taken) were taken with a GPS unit and were also registered in the field notes. A version of the new canal map is given in Fig. 1, and a few of the photographs with GPS coordinates and comment about them are shown in Figs. 2 - 5.

Some inconveniences were encountered during the *Diagnostic Walk-Thru* surveys. These problems included obstacles due to the construction of residential buildings and fences on and in the canals where there was no access, unleashed and aggressive dogs which sometimes blocked the way along the canal, snakes in the canals, lengthy pipe and culvert sections (where the outlet was unknown), and others.

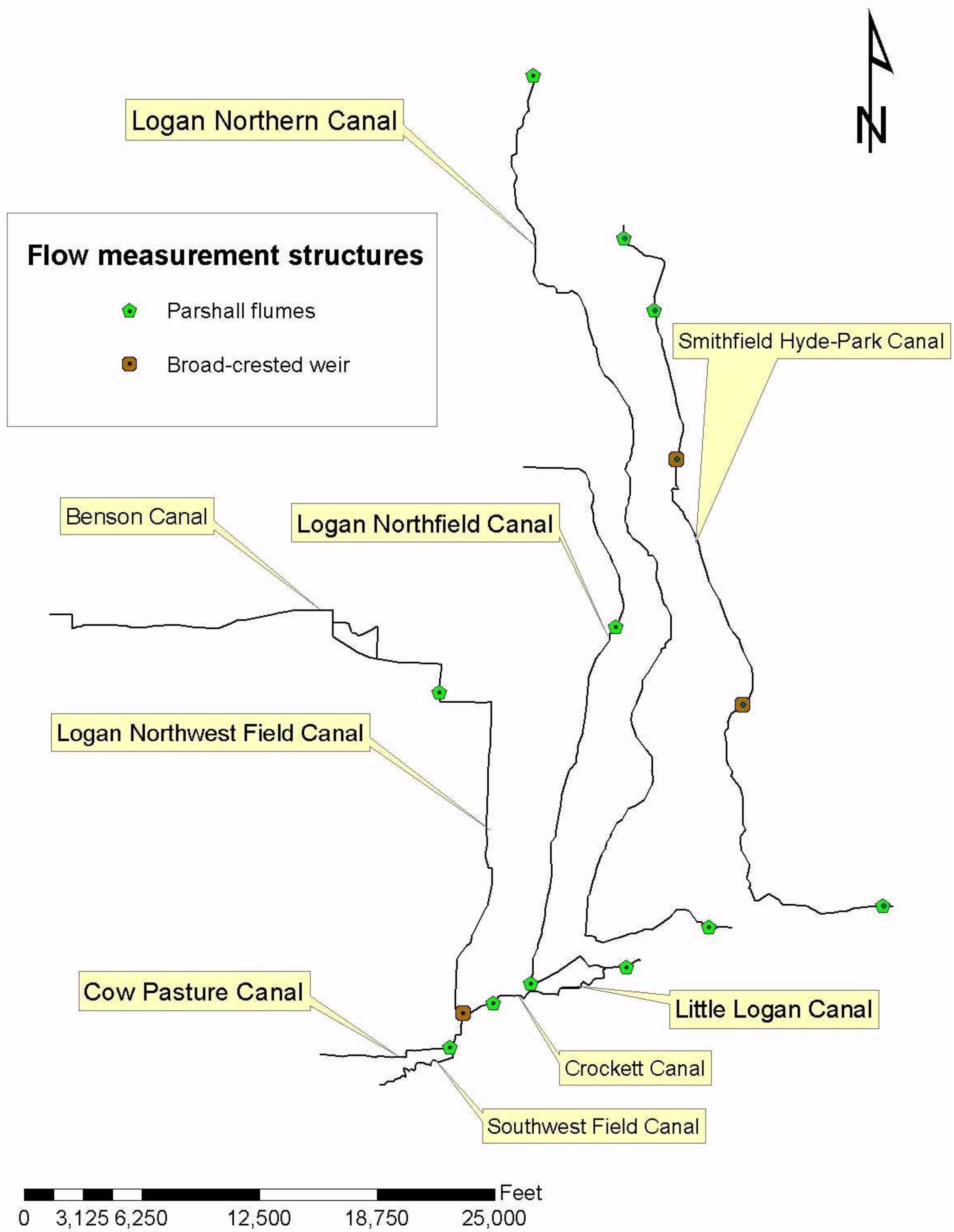

Fig. 1. Selected Cache Valley, Utah, irrigation canals

Fig. 2. Culvert inlet and a deteriorated outlet gate (Northwest Field canal)

Fig. 3. Interviewing a water user (Northwest Field canal)

Fig. 4. Much weed growth and algae and narrow canal width (Logan Northwest Field canal)

Fig. 5. Upstream side of a bridge where debris has collected (Logan Northwest Field canal)

Interviews

The process of developing operations and maintenance plans for irrigation canals should be highly participatory because active participation of these people in making the plans will help their adoption and sustainability. Many of those involved in the canal system played an important role in the entire process of development of these plans for irrigation canals. In this process, efforts were made to communicate with canal management officials, learn their present methods, strategies, concerns, and problems in achieving the goal of meeting irrigation water requirements economically with minimum water losses.

Interviews were conducted with Benson Canal Company President, Mr. Rick Reese, Northwest Field Canal Company President, Mr. Peter Kung, and the Logan

Northern Canal Company ex-President, Mr. Don Hansen, who served as president for 20 years on that canal. At the time of this writing, the other canal company interviews were being arranged.

Fig. 6. Interview with Don Hansen, ex-president of the Logan Northern canal

The observations of the *Diagnostic Walk-Thru* surveys were discussed in the interviews with the canal company presidents and water masters, and photographs taken at the time of survey were shown to them on a notebook computer to get a clear idea of key locations in the canals and their importance. Since it was a participatory program, canal company presidents' issues, their problems with the very small longitudinal bed slopes in some reaches, storm water inflows (often causing the canals to overtop), and so on, other canals were also discussed during the interviews. The Benson Canal Company president, Rick Reese, was very happy to meet with the authors and know about the present study. The authors arranged a meeting in Rick's office and introduced themselves, the study objectives, source of funding, and other details. He discussed various problems of the Benson canal with the authors, such as flooding problems which tend to occur after rainfall events in the valley, especially since the recent developments in which farmland is converted to municipal and industrial areas. There are several canals on the Eastern side of the valley, and whenever there is surplus of water, it is ultimately diverted into the Benson canal. The Benson canal, with a small cross section cannot accept all of the diverted water after many of the annual rainfall events, so the canal tends to overflow, causing damage to adjacent lands and even flooding onto the roads. The major concern of the Logan Northern canal, as told by Don Hansen in an interview, is the low longitudinal bed slope of the 15-mile-long canal. The Logan Northern canal water users think that due to the small longitudinal bed slope of the canal, the water is ponding upstream of the flow measurement structure (a Parshall flume) constructed in the canal, and this water is seeping through the banks and causing drainage problems in the field along the canal.

For this reason, Logan Northern canal water users removed the flow measurement structure built in the canal. The result of the above-mentioned problem in the Logan Northern canal is a 15-mile-long canal left with a single flow measurement structure near the upstream end, resulting in little quantitative knowledge about water management along the canal. Also, in the interview with Peter Kung of the Logan Northwest Field canal, it has been said that they have lot of storm water drainage into the canal that interrupts operations and sometimes causes flooding problems to the residents near the canal. This is perhaps the greatest operational problem for the canal companies at the present time. Storm water drainage sometimes erodes the channel bed where it enters the canal changing the section of the canal, causing additional maintenance problems.

Secondly, many water users who are beneficiaries of this study were contacted to know their requirements, learn their practices, share their experiences and problems, and welcome their suggestions. During the *Diagnostic Walk-thru* survey, the authors explained the objective of the study to the water users and discussed the issues of the canal from their point of view. Water user involvement has been encouraged in developing and maintaining the water delivery system. Their suggestions and ideas to improve the performance of water delivery subsystem will be included in the operations and maintenance plan that could be served as a set of guidelines for all of them later. Field staff of management agency was also interviewed to know the practical problems involving satisfaction of both water-users and agency management while meeting design standards. Ryan Weber, water master for the Northwest Field Canal, was interviewed, resulting in a great deal of information regarding the canal water management. These interviews have been helpful to know the practical problems that are not only technical but also practical. The entire discussion of the interviews was then documented in a report and to serve as a good support to propose the solutions for the problems mentioned above.

A meeting was arranged with the Logan River Commissioner, Ms. Colleen Gnehm, by the authors to discuss canal operational issues and observe her work while recording water depth information from flow measurement structures in the main canals. She explained to the authors how she allocates the water to different canal companies, following the *Kimball Decree* chart. After checking the water level recorders on the Logan River and determining the flow rate, she finds how much water should be allocated to each canal. Then she moves on to each water level recorder at the diversion point to each canal. She said that she does this job of checking water level recorders every Saturday. When she was asked by authors whether she has had any complaints or problems on any of these canals, she said that she has not heard of any problems or complaints, except from the Logan Northwest Field canal company. She said that she heard of seepage loss problems from the water master of the Logan Northwest field canal, but that everything is fine with the present system.

Fig 7. Colleen Gnehm with one of the authors, checking a water level recorder

Fig 8. Colleen Gnehm replacing the graph sheet for a water level recorder

Measurement of Seepage Loss

Ryan Weber (2004), water master of Logan Northwest field canal prepared a report on seepage losses on three selected canals of Cache Valley, Utah. In this report, there are indications of significant seepage losses in Cache Valley canals. Surveys will be conducted by the authors on the reaches mentioned in the report and solutions will be proposed to minimize these losses, such as lining those canal reaches that are with the highest losses. Lining of canals is one of the best solutions to be applied to reduce seepage losses, stabilize channel bed and banks, avoid piping through and under channel banks, and control weed growth (Hill 2000). Seepage loss will be determined by selecting a typical reach and measuring the inflows and outflows. The difference between inflow and outflow measurements is the total loss and it is the combination of evaporation and seepage through the canal bed and banks. At the time of this writing, seepage loss measurements have been taken on three canals out of the nine canals. And the results obtained are shown in the results section.

Fig. 9. Current metering in a canal to determine seepage losses

Preparation of O&M Plans

One of the objectives of this study is to develop Operation and Maintenance plans for the selected irrigation canals. In this plan, all the practical problems witnessed during the present study will be shown with the remedies adopted to solve them. This plan will also present a set of guidelines for periodic maintenance of the system with active participation of all who are involved in this water delivery subsystem. This plan will comprise all the maintenance works classified according to their urgency of attention and economic considerations. Some of the main maintenance works are:

- Periodical removal of weed growth;
- Clearance of debris at the screens;
- Lubrication of outlet gates and head gates;
- Repair of flow measurement structures (where necessary);
- Removal of sediment from the canals; and,
- Repair of side walls damaged by trees growing near the canals.

The above-listed maintenance works were among those observed at the time of the *Diagnostic Walk-thru* surveys and they will be discussed in detail in operations and maintenance plans to be developed in the near future as a part of this study.

Calibration of Existing Flow Measurement Structures

A work schedule was made in order to define the steps to implement this study. Also, the required materials and instruments to develop the present study were prepared. These materials and instruments included:

1. Forms for recording current metering data;
2. Open-channel current meter;
3. Tape measures;
4. Topographic level;
5. GPS (Global Positioning System) unit; and,
6. Digital photographic camera.

The existing measurement structures were calibrated using a current meter to measure the flow rate, taking several measurements, such as upstream and downstream depths at the structure, water surface elevations, and the channel cross section downstream of the structure. For Parshall flumes, the authors checked to determine whether it has standard dimensions. Finally, all the data were processed and the results of the current metering was compared to the standard calibration of the measurement structures.

There are some non-functional flow measurement structures found in the canals. For instance, the Logan Smithfield-Hyde Park canal has three Parshall flumes and two broad-crested weirs. One out of the three Parshall flumes was observed to be operating under submerged-flow conditions, but the measurement arrangements at the structure were made only for free-flow conditions, thereby causing large measurement errors. Two of the broad-crested weirs appear to be newly built, but they are completely submerged, so their free-flow calibrations are not applicable and the structures serve no apparent purpose.

Fig 10. Taking measurements to check the calibration of a flume

Fig 11. Current metering to check the calibration of a broad-crested weir

Design and Construction of Flow Measurement Structures

Locations for new flow measurement structures were selected according with the results of the previous procedure. Some of these will replace existing flow measurement structures which are too deteriorated to repair, and are not currently functioning. The types of the new structures will be determined by taking in consideration the advantages and disadvantages of the different types measurement structures. In addition, to design these new structures, some calculations will be performed using spreadsheet or software such as the ACA program (Merkley 2004). Finally, these new structures will be build at the selected locations in the fall of 2005.

Operations

The terms “operations” and “water management” overlap in meaning when applied to irrigation canals. Thus, it is important to have an operations plan in order to achieve water management improvements, and it is equally important to have flow measurement capability in order to successfully implement an operations plan. The most significant operational problem for the Cache Valley canals in the Logan city is storm water drainage into the canals. The development of many new commercial buildings has including the construction of many parking lots which, by themselves, have very little capacity to retain rainwater. The collected storm water tends to gush into the irrigation canals which pass in the vicinity (or downhill) of the paved areas. The Logan Northfield canal in Logan City that conveys water to the Benson canal is one of the canals suffering from such problem. Because of this storm water drainage into the canal, the Canal Company does not have any control on the water flow in the canal when they have surplus water in the canal. There are many problems like flooding, channel bed erosion in the canal due to this storm water drainage.

So, in this regard, the canal companies should have an operational plan that can address these water management problems. To achieve this, the water flow in the canal should be regulated, monitored, and quantitatively measured, including water deliveries to individual users and secondary/tertiary channels. In this process, flow measurement structures, head gates, diversion gates, and outlet gates play an important role. Based on the demand and supply of irrigation water, a simple operations plan will be developed for the equitable distribution of available water to fulfill the requirements of the water-users. Operational monitoring includes periodically checking discharge rates and issues such as water-logging, seepage losses, and runoff inflows, and maintaining records for the improvement of the water delivery system in future. Flow measurement structures play an important role in the process of regulating and monitoring the water thus by ensuring equitable distribution and proper management of the canal system. The hydraulic data plays a major role in preparing hydraulic performance report based on which improvements in the canal system can be made and also maintenance works can be undertaken. These data helps to determine any losses, such as seepage, occurring in the canals.

The data collected by authors to measure the seepage loss and checking the calibration of flow measurement structures will help in preparing a structural maintenance plan and also an operations plan in near future.

Irrigation system mapping plays a vital role in understanding the system, and in developing and implementing operation and maintenance plans. Every irrigation system should have complete maps of that system depicting flow control structures, outlet gates, tertiary takeoff (if any), and water user information. The authors recorded the GPS coordinates at the noteworthy locations during the *Diagnostic Walk-thru* surveys. These GPS coordinates were then transformed to a UTM projection. Finally, this transformation was overlaid on aerial photographs of Cache Valley. Each canal and flow measurement structures have been labeled using ARCGIS software. The work of hyper-linking some selected photographs to this map is still in progress at the time of writing this paper.

Results

There are several hundred photographs with GPS coordinates of important locations in each of the nine canals that were surveyed. With the help of these photographs and comments, interviews with canal company personnel have been successful to obtain quality information about operations and maintenance issues, and provided a better understanding of the situations from which solutions could be proposed for each of the problems. Seepage loss measurements were taken on three out of the nine selected canals. The results of these measurements are shown below:

- The Logan North Field canal, which is also called the "Twin Canals," has been found to have a seepage loss of 7.7%. It showed a loss of 1.82 cfs from beginning of the canal where the flow rate was 23.7 cfs for a length of 1,450 ft.
- The Smithfield-Hyde Park canal was found to have a seepage loss of 6.5%. It showed a loss of 3.3 cfs from beginning of the canal where the flow rate was measured 50.5 cfs for a length of 1,440 ft.
- The Southwest Field canal has been found to have a seepage loss of 17%. The total flow at the upstream was found to be 2.3 cfs. It showed a loss of 0.41 cfs over a length of 1,470 ft in a reach where there is much vegetation.

All these seepage loss measurements were done by current metering by using a Pygmy meter and applying the velocity–area method. An electromagnetic current meter was initially used in some of the measurements, but the Pygmy meter was found to provide much more consistent and accurate results. The GPS coordinates were transformed to UTM values and plotted in a GIS over a background mosaic of aerial photographs of Cache Valley, highlighting all the flow measurement structures and also labeling all the different canal companies. Figure 1 is a simplified version of the final GIS product. The process of hyper-linking selected photographs to this GIS map was in progress at the time this paper was being prepared.

During the *Diagnostic Walk-thru* surveys, it was found that at many places along these canals there is no further access because some residential buildings have been built on the canal. This is also a problem for the canal company field staff to walk along the canal to perform operation and maintenance activities (Fig. 12).

Fig. 12. Obstructions along a reach of the Logan Northfield Canal

Conclusions

The *Diagnostic Walk-thru* Surveys on the canals helped the authors to better understand the current condition of the canals. The pictures taken during surveys gave an opportunity to view them and discuss proposed solutions to the problems which were identified. The GPS coordinates are useful for mapping the canals so that everyone can view and know about these canals when they are completed and placed on a website. PDF files of this study will be presented to the nine canal companies, the Logan River Commissioner, and the Utah State Division of Water Rights so that they can improvise and maintain the canal system with the guidelines provided. Seepage loss studies on this canal so far have not shown much since the work is in progress; however, depending on the seepage loss magnitudes, solutions to minimize these losses will be provided such as lining the canal if the reach is small, or lining the canal with plastic cover as done by Benson Canal company in Cache Valley.

Some of the canal company personnel are not familiar with the technical aspects of the flow measurement structures installed and functioning in their canals. For instance, the Parshall flume, a flow measurement structure installed and designed to work under free-flow conditions with only an upstream depth measurement was found to be working under submerged-flow conditions in the Smithfield-Hyde Park canal. At this location there is no provision to measure downstream depth to determine the flow rate under submerged-flow conditions. Thus, the assumption of free-flow at this flume yields large errors in the measurement of flow rate at that location.

When these observations were discussed during the interviews with canal company personnel, they were unaware of the situation and also they did not know how to respond to the problem. A maintenance and operations plan would definitely help canal company personnel to be aware of the canal management that yields better performance of the system. All the flow measurement structures were checked and most of them are working well. Based on the surveys conducted, the maintenance works can be classified into many categories and guidelines can be given to be followed in the operations and maintenance manual. The Logan Northern canal is the longest canal with an approximately 15-mile distance, yet it has only one flow measurement structure. The authors intend to build one flow measurement structure in this canal in the coming days.

Acknowledgments

Primary funding for this study was provided by the Utah Water Research Laboratory. Assistance with the coordinate conversions for map production was provided by Nat Marjang of the BIE Department at USU.

References

Hill, R.W. 2000. How well does your irrigation canal hold water? Does it need lining? Available at <http://extension.usu.edu/files/engrpubs/biewm03.html> (May 16, 2005)

Merkley, G.P. 2004. Irrigation Conveyance and Control: Flow Measurement and Structure Design (lecture notes for BIE 6300). Biological and Irrig. Engrg. Dept., Utah State Univ., Logan..

Skogerboe, G.V., and G.P. Merkley. 1996. Irrigation Maintenance and Operations Learning Process, Water Resources Publications, LLC, Colorado.

RICE EVAPOTRANSPIRATION ESTIMATION USING SATELLITE DATA

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ABSTRACT

An accurate measurement of evapotranspiration could lead to the development of improved rice irrigation water use efficiency. A study on evapotranspiration was conducted in the Tanjung Karang Rice Irrigation Project. An automatic meteorological station was installed inside the field to collect data for calculation of the crop water requirements using the CROPWAT software. Non-weighing lysimeters were installed to measure the crop evapotranspiration at five different locations. NOAA satellite data was correlated with field data. Results show that the satellite images can provide frequent field information for a large area and also reduce the error of missing data. The observed ET from the lysimeters ranged from 3.2 to 5.8 mm/day, while ET by calculation ranged from 3.2 to 5.7 mm/day. The corresponding ET values from satellite data were 4.0 to 6.5 mm/day. NOAA satellite data can be a convenient source of data for daily monitoring of irrigation water use by crops.

Keywords: paddy, evapotranspiration, remote sensing, lysimeters, Malaysia

INTRODUCTION

Increasing attention is being paid to irrigation water management of paddy fields, both because of its importance in food production and its huge water use. Meeting the physiological and ecological water requirements of rice is a prerequisite for effective irrigation scheduling of paddy fields. Beside the crop water requirements, water losses, which are not beneficial in crop production, can add a huge volume to the total water usage in agriculture. Based on this argument, there could be greater possibility to save water from agriculture, which can be used for other purposes thereafter. There is considerable scope for improving water use efficiency by proper irrigation scheduling which is essentially governed by crop evapotranspiration (ETc). Accurate estimation of crop ET is an important factor in efficient water management. Traditional ET measurements using lysimeters is accurate but time consuming and laborious. There is a need for a more rapid assessment of ET resulting from global environmental changes. The objectives of this work was to compute the evapotranspiration for the Tanjung Karang Irrigation Scheme using remote sensing and to validate the results with field measurements and meteorological computation.

EVAPOTRANSPIRATION BY REMOTE SENSING

Remote sensing can be applied to the management of irrigated agricultural systems either at a local scale or nationally. It has the possibility of offering important water resource related information to policy makers, managers, consultants, researchers and to the general public. Remote sensing, with varying degrees of accuracy, has been able to provide information on land use, irrigated area, crop type, biomass development, crop yield, crop water requirements, crop evapotranspiration, salinity, water logging and river runoff. This information when presented in the context of management can be extremely valuable for planning and evaluation purposes. Remote sensing has several advantages over field measurements. First, measurements derived from remote sensing are objective; they are not based on opinion. Second, the information is collected in a systematic way which allows time series and comparison between schemes. Third, remote sensing covers a wide area such as entire river basins. Ground studies are often confined to a small pilot area because of the expense and logistical constraints. Fourth, information can be aggregated to give a bulk representation, or disaggregated to very fine scales to provide more detailed and explanatory information related to spatial uniformity. Fifth, information can be spatially represented through geographic information system, revealing information that is often not apparent when information is provided in tabular form (Bastiaanssen, 1998).

Evapotranspiration is generally computed not for its own sake but for some other purposes and each method can be assessed for its usefulness in this regard. Traditionally, actual evapotranspiration has been computed as a residual in water balance equations, from estimates of potential evapotranspiration using a soil moisture reduction function or from field measurements by meteorological equipment. Previous work (Bastiaanssen & Molden, 2000), (Vidal & Perrier, 1989) used satellite data to estimate regional actual evapotranspiration. Granger (2000) studied evapotranspiration assessment using NOAA satellite image and AVHHR data with 1.1 km ground resolution, processed the data through radiometric calibration and geo-certified with ERDAS Imagine software. The satellite estimated evapotranspiration was calculated by multiplying potential evapotranspiration and the vegetation and moisture coefficient (VMC). The estimates compared to lysimeter measurements indicated successful estimates of regional evapotranspiration.

The application of surface energy balance algorithm for land (SEBAL) in Idaho indicates substantial promise as an efficient, accurate, and inexpensive procedure to predict the actual evapotranspiration fluxes from irrigated lands throughout a growing season (Droogers & Bastiaanssen, unpublished). Predicted evapotranspiration has been compared to ground measurements of evapotranspiration by lysimeters with good results, with monthly differences averaging +/- 16%, but with seasonal differences of only 4% due to reduction in random error (Allen et al, unpublished). The SEBAL method derives the evaporative fraction from satellite data. This is a measure of energy partitioning and a good indicator of crop stress. Actual evapotranspiration can be easily obtained from the product of the evaporative fraction and the net radiation. The SEBAL remote sensing technique is not restricted to irrigated areas, but can be applied to a broad range of vegetation types. Data requirements are low and restricted to satellite information although some additional ground observations can be used to improve the reliability.

A geographic information system (GIS) is a computer system that can store virtually any information found in paper map. A GIS can display maps on a computer screen, and it can provide detailed information about their features, including roads, buildings, and rivers. Moreover the computer can quickly search and analyze these map features and their attributes in ways not possible in paper maps. A GIS stores the topographic data for all types of map features, representing them as nodes, lines and areas. A GIS also stores the attribute data for all features. This paper reports work done at UPM in the use of remote sensing data for estimating evapotranspiration of rice.

THE STUDY AREA

The area chosen for this study is the Tanjung Karang Rice Irrigation Project (Fig.1). The site is located on a flat coastal plain in the Northwest Selangor Agricultural Development Project (PBLS) at latitude 3^{0} 35'and longitude 101^{0} 5' which covers an area of approximately 19,000 hectares extending over a length of 40 km along the coast with a width of 5 km on average. The main irrigation and drainage canals run parallel to the coast. The Bernam River, the water source for the project, meanders northwestward and forms the boundaries between the state of Selangor and Perak.

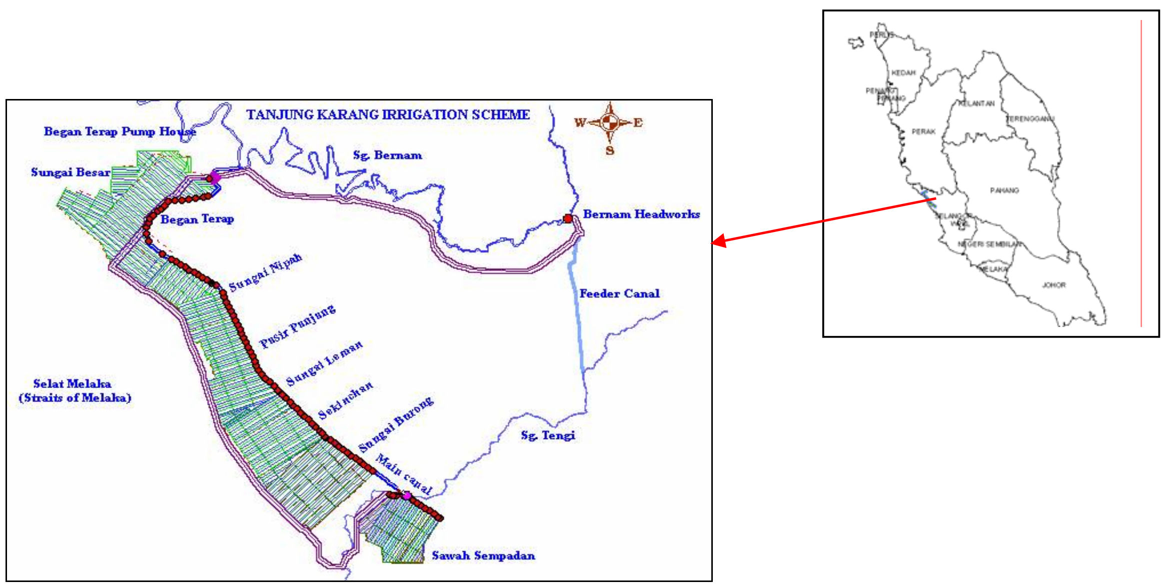
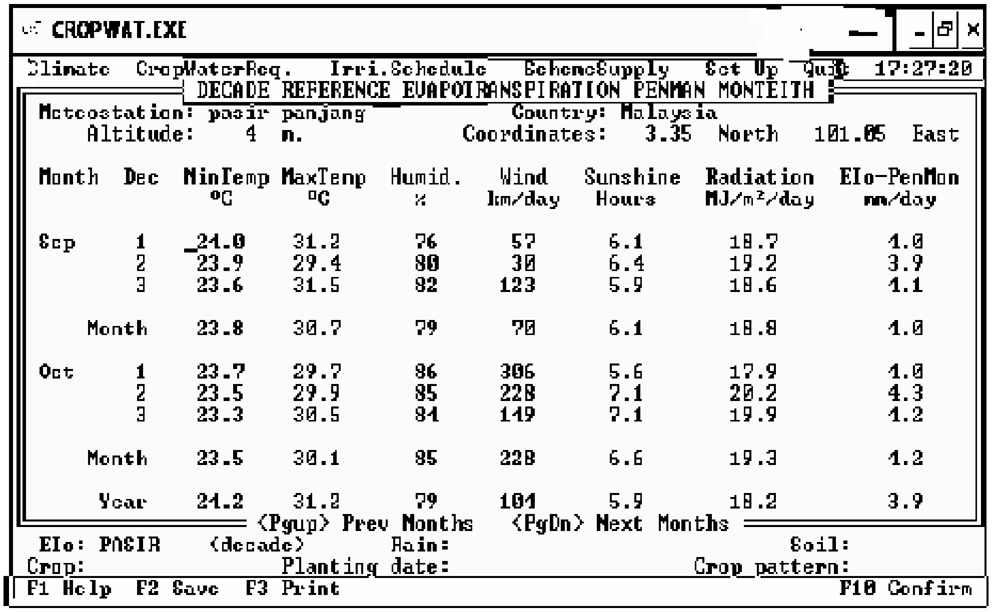


Fig. 1*: Location of the Study Area*

EVAPOTRANSPIRATION ESTIMATION METHOD

The evapotranspiration estimation method described here is based on the calculation of reference evapotranspiration (ET_o), to be multiplied by the crop factor (Kc), resulting in crop evapotranspiration (ETcrop). ET_o is defined as "the rate of evapotranspiration from an extensive surface of 5-15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water". ETcrop is defined as "the rate of evapotranspiration from a disease free crop, growing in large fields, under non restricting soil water and fertility conditions and achieving full production potential under the given growing environment". In this study the reference evapotranspiration was calculated using CROPWAT software version 7, (http://www.fao.org/ag/agl/aglw/ cropwat.stm). The method is applied using 10- day running average. All data were collected from the selected study area of the Tanjung Karang Irrigation Scheme. Figure 2 shows a typical result of CROPWAT.


CROPWAT.EXE

Climate CropWaterReq. Irri.Schedule SchemeSupply Set Up Quit 17:27:20

DECADE REFERENCE EVAPOTRANSPIRATION PENMAN MONTEITH

Meteostation: pasir panjang Country: Malaysia
Altitude: 4 m. Coordinates: 3.35 North 101.05 East

Month	Dec	MinTemp °C	MaxTemp °C	Humid. %	Wind km/day	Sunshine Hours	Radiation MJ/m²/day	ETo-PenMon mm/day
Sep	1	24.0	31.2	76	57	6.1	18.7	4.0
	2	23.9	29.4	80	30	6.4	19.2	3.9
	3	23.6	31.5	82	123	5.9	18.6	4.1
	Month	23.8	30.7	79	70	6.1	18.8	4.0
Oct	1	23.7	29.7	86	306	5.6	17.9	4.0
	2	23.5	29.9	85	228	7.1	20.2	4.3
	3	23.3	30.5	84	149	7.1	19.9	4.2
	Month	23.5	30.1	85	228	6.6	19.3	4.2
	Year	24.2	31.2	79	104	5.9	18.2	3.9

<Pgup> Prev Months <PgDn> Next Months

ETo: PASIR (decade) Rain: Soil:
Crop: Planting date: Crop pattern:
F1 Help F2 Save F3 Print F10 Confirm

Fig.2: CROPWAT output for calculating ET_0

REMOTE SENSING METHODS

Remote sensing method is attractive to estimate evapotranspiration as they cover large areas and can provide estimates at very high resolutions. Intensive field monitoring is not required, although some ground truth measurements can be helpful in interpreting the satellite images. The methods selected are varying in resolution and degree of physical realism.

SEBAL REMOTE SENSING TECHNIQUE

The Surface Energy Balance Algorithm for Land (SEBAL) developed by Bastiaanssen 1998 is a parameterization of the energy balance and surface fluxes based on spectral satellite measurements (Bastiaanssen, 1998). SEBAL requires visible, near-infrared and thermal infrared input data, which in this case were obtained from the free of charge data provided by NOAA AVHRR (National Oceanographic and Atmospheric Administration - Advanced Very High Resolution Radiometer). Instantaneous net radiation values were computed from incoming solar radiation measured at ground station, and the net radiation estimated from twenty six cloud-free NOAA images via surface albedo, surface emissivity and surface temperature. Surface albedo was computed from the top of the atmosphere broad-band albedo using an atmospheric correction procedure. Surface temperature was extracted from the images using an especial model developed for it. NDVI was calculated from the images using remote sensing software and the surface albedo was then calculated.

LYSIMETER METHOD

Non-weighing lysimeters were fabricated and installed inside the paddy fields to measure the crop evapotranspiration at four randomly selected plots in block C of Sawah Sempadan-Irrigation compartment PBLS. Four other sets of lysimeters were installed in Sungai Burung, Sekinchan, Sungai Leman and Pasir Panjang compartments. The lysimeters, 91cm x 91cm x 61cm, were attached with a casella hook to monitor the daily water level. The lysimeters were inserted into the soil to a depth of 30 cm. Lysimeters were planted with the same rice variety in the scheme which was MR 219. Readings from the lysimeters and calculated ET from weather parameters were compared with the remote sensing derived ET estimates.

DATA COLLECTION AND ANALYSIS

METEOROLOGICAL DATA

The following meteorological data were obtained: location of the scheme (coordinates and elevation), Maximum and minimum temperature, Relative humidity, Wind speed, Sunshine duration or radiation per day, Total rainfall and effective rainfall data, and Pan evaporation. Using meteorological and crop data, the crop water requirements were calculated using the CROPWAT software. The Penman-Montieth equation used in the software is being adopted by FAO as standard evapotranspiration equation to be used all over the world. The crop evapotranspiration, ET_{crop} can be expressed as

$$ET_{crop} = K_C \, ET_o \quad \text{................} \quad (1)$$

Where K_C is the crop coefficient and ET_o is the reference crop evapotranspiration. K_C values used were 1.3, 1.09 and 0.9 for the initial stage, the mid season stage and the end of the late season stage, respectively. These values were suggested by FAO (Paper No.56).

SATELLITE DATA

Satellite data was ordered from the Malaysian Center for Remote Sensing (MACRES) for the rice cultivation season. Images were registered, subset to the selected study area and analyzed. The evapotranspiration was calculated using the SEBAL model. The day net radiation is the electromagnetic balance of all incoming and outgoing fluxes reaching and leaving a flat surface for the daylight hours (Bastiaanssen 1995) obtained using the following equation

$$R_{n-day} = (1-\rho_0)\times(K^{\downarrow}) - 110\times\tau_{sw} \quad \text{W/m}^2 \text{.............} \quad (2)$$

where $K^{\downarrow}$ is the incoming short -wave solar radiation (W/m^2), ρ_0 the surface albedo (-), τ_{sw} is the day single way transmissivity t of the atmosphere (default = 0.7, or from meteorological data if available).

The calculation of evapotranspiration is including the transformation of day net radiation from W/m^2 to mm/day using the following equation

$$ET = R_n 86400\times10^3\left[2.501-(0.002361T)\times10^6\right]^{-1} \text{ mm/day}\ldots\ldots\ldots\ldots\ldots (3)$$

Using GIS, the data can be manipulated by digitizing the spatial data, entering the non spatial data and associated spatial attributes data, and linking between the spatial and non spatial data

RESULTS AND DISCUSSION

Lysimeter and Calculated ET

The daily evapotranspiration rates from Tanjung Karang irrigation compartments were estimated using different methods. The estimates from lysimeter and calculated ET from weather parameters using CROPWAT software is presented in Figure 3(a-e). The figure shows that the lowest lysimeter measured ET was 3.2 mm/day and highest ET was 5.8 mm/day, and occurred in the 13th week and 8th week after seeding, respectively. The figure also shows that the lowest and highest values for the calculated ET were 3.15 mm/day and 5.72 mm/day respectively.

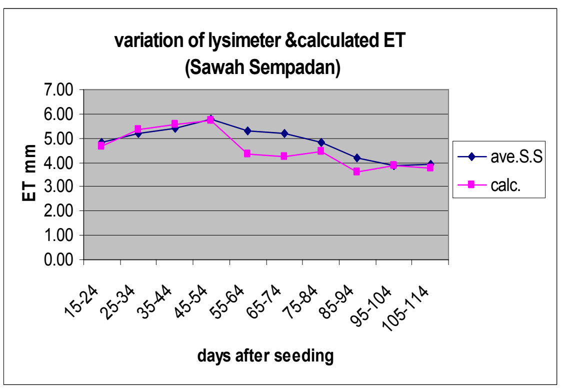


Fig 3a

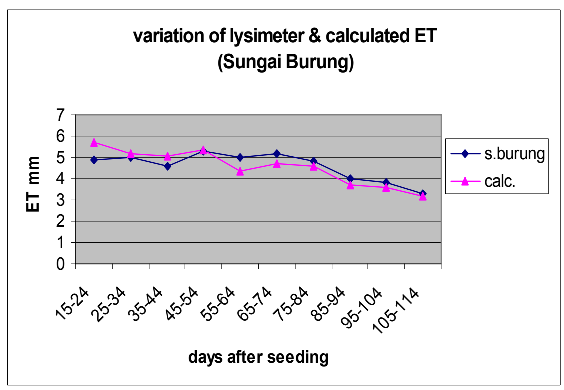


Fig 3b

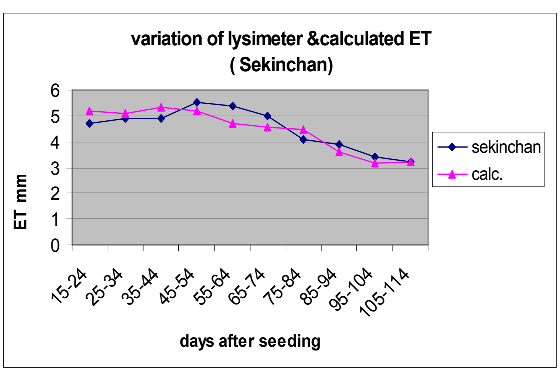


Fig 3c

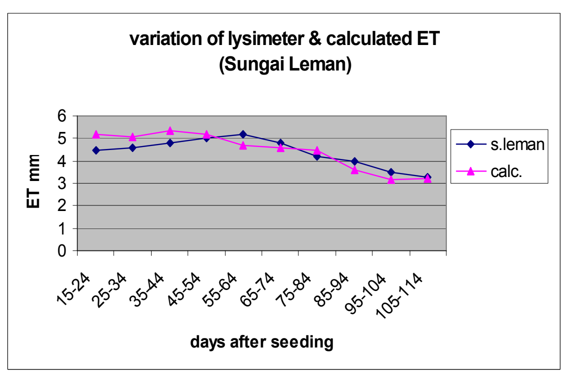


Fig 3d

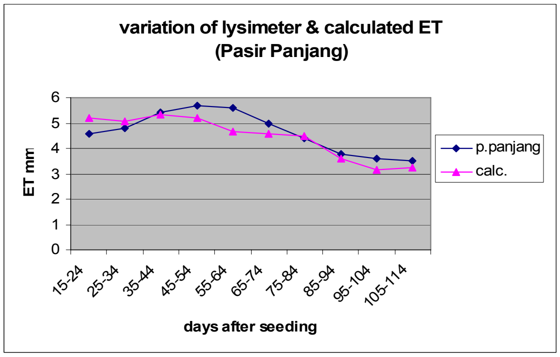


Fig 3e

Fig. 3. ET rate obtained by lysimeter and calculation for 5 locations within the irrigation scheme.

Figure 4(a-e) represents the comparison of measured and calculated ET showing the R^2 values ranging between 70-76%. Sawah Sempadan compartment shows the lowest R^2 because it is a result of average of four points.

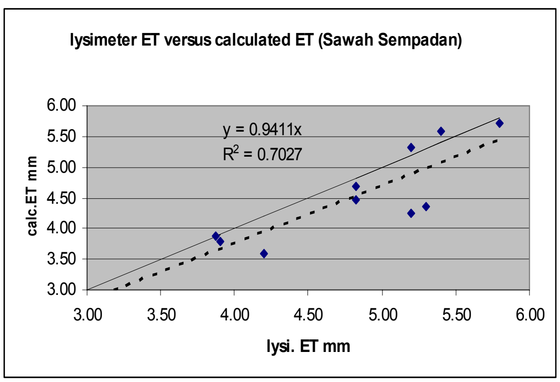


Fig 4a

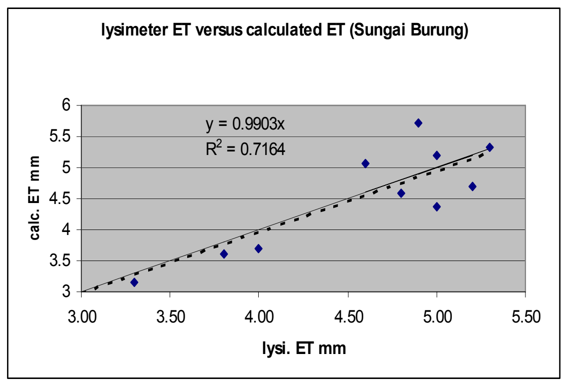
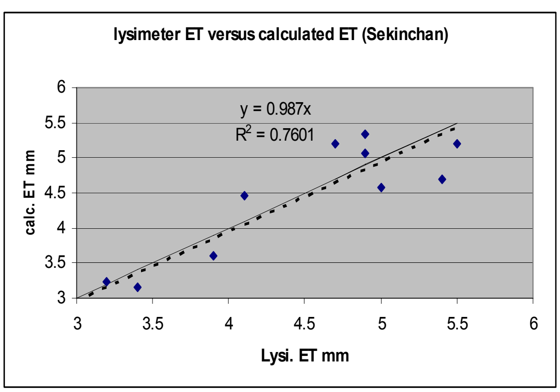


Fig 4b



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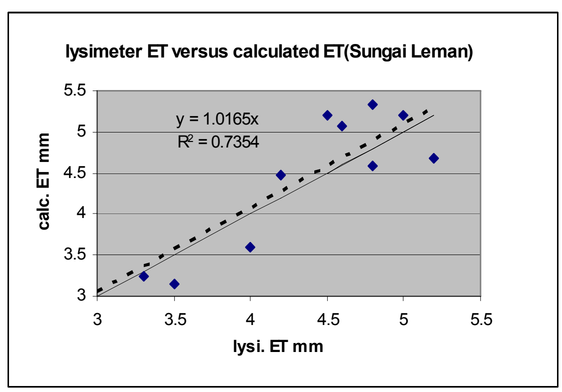

Fig 4d

Doppler Flow Instrumentation Upgrades within the Yuma Irrigation District

Dave Brooks, SonTek/YSI, National Sales Manager, 6837 Nancy Ridge Dr, Ste A, San Diego, CA 92121

Agriculture irrigation canals in the West tend to utilize an amalgamation of older technologies that struggle to attain the accuracies available with the new generation of Doppler flow instruments. Due to an ongoing effort by the Federal Government to increase flow accuracy and the timely transfer of discharge data to the end user, Doppler flow instruments are coming to the fore.

The proposed presentation shall cover the ongoing upgrades that are taking place within the Yuma Irrigation District, under the auspices of the USGS/USBR. The presentation will focus around the practicality, cost and benefit of replacing/augmenting aged equipment with highly accurate Doppler units.

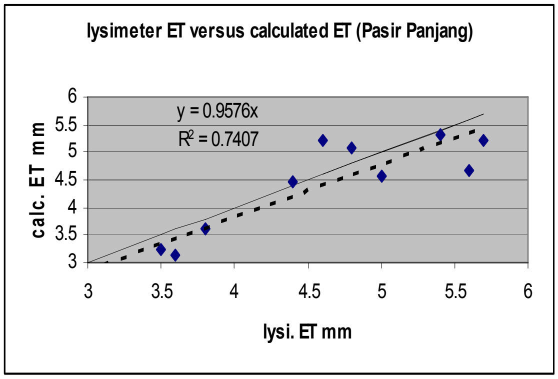

Fig 4e

Fig 4. Comparison of ET obtained by lysimeter and calculation for five locations.

Satellite Derived ET

Surface reflectance, red and near infrared band, was used to calculate the Normalized Difference Vegetation Index values (NDVI). It is defined as the difference between the visible (red) and near infrared (nir) bands, over their sum.

$$NDVI = nir\text{-}red / nir + red$$

The NDVI is representative of plant assimilation condition and of its photosynthetic apparatus capacity and biomass concentration (Groten 1993, Loveland et al 1991). The NDVI values range from -1 to +1 (pixel values 0-255). Calculated NDVI is used to estimate the emissivity values. Figure 5 represents the variations of NDVI between the different compartments obtained from the images. The values in December are low because it was the time of harvesting in the study area.

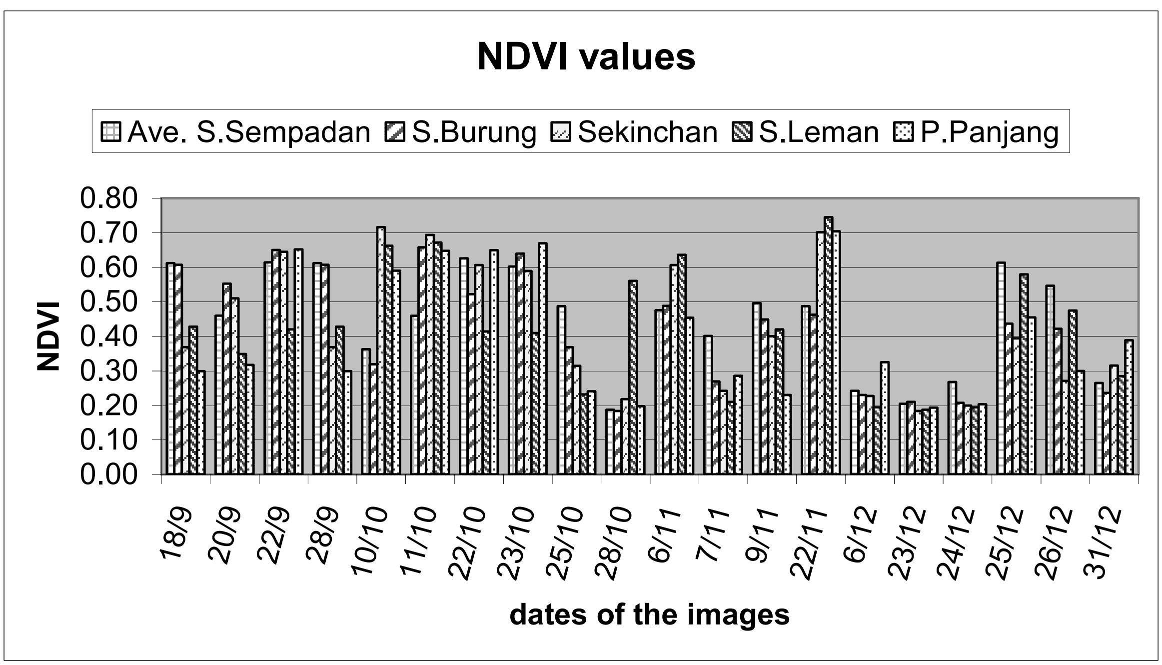

Fig: 5 NDVI values from satellite data

Figure 6 (a-e) shows the ET results obtained from satellite data calculation with the support of solar radiation data from the meteorological station. The images used were cloud free images and they were selected from a set of images taken from MACRES. The ET values from the images ranged between 4.04 mm/day to 6.54 mm/day.

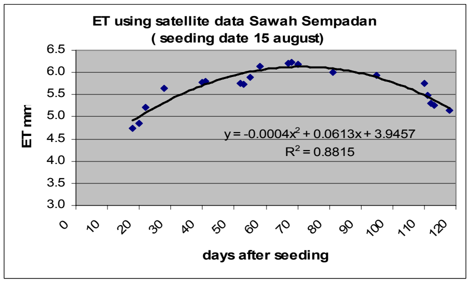

Fig 6a

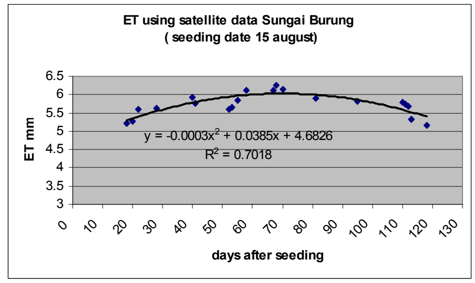

Fig 6b

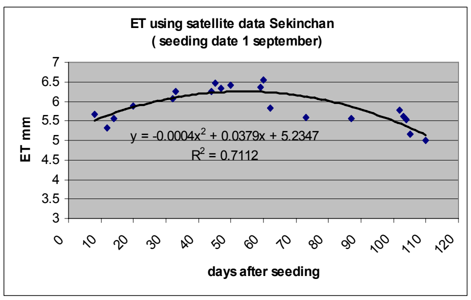

Fig 6c

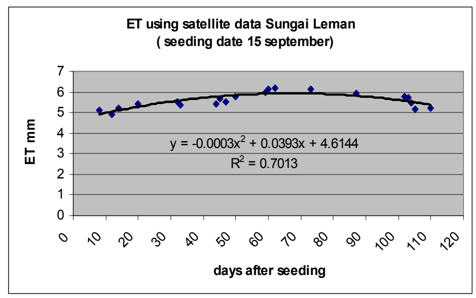

Fig 6d

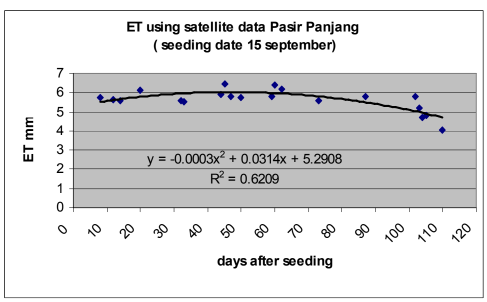

Fig 6e

Fig6. ET rate obtained by satellite data at 5 locations within the irrigation scheme

Twenty cloud free images were used in the study. The results obtained from all methods were compared. Evapotranspiration values from the NOAA data are generally 10% higher than the lysimeter data, but the ETcrop obtained from CROPWAT are generally 14% lower than those measured by lysimeter as shown in Figure 7(a-e).

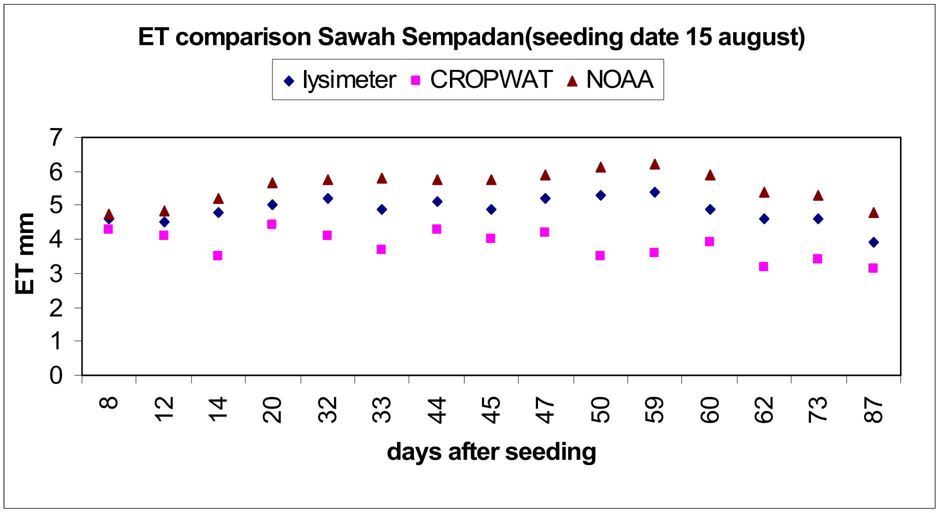

Fig 7a

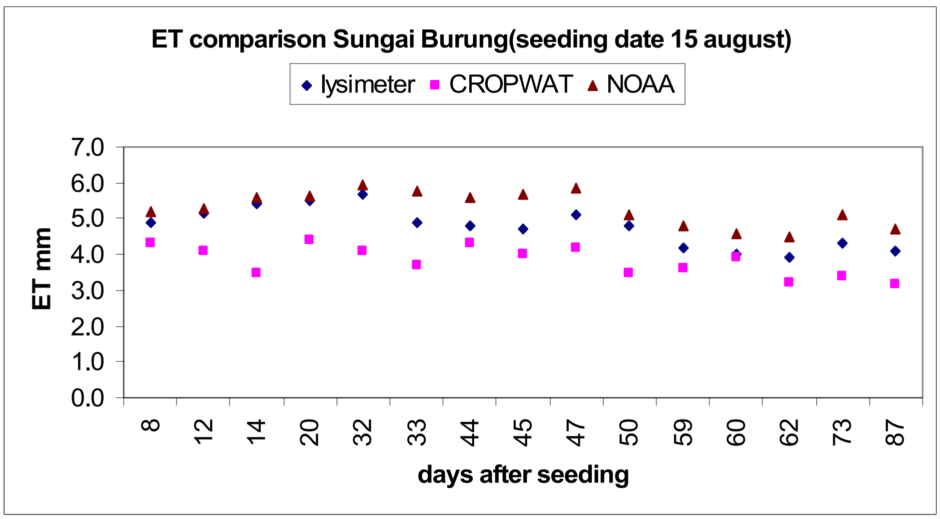

Fig 7b

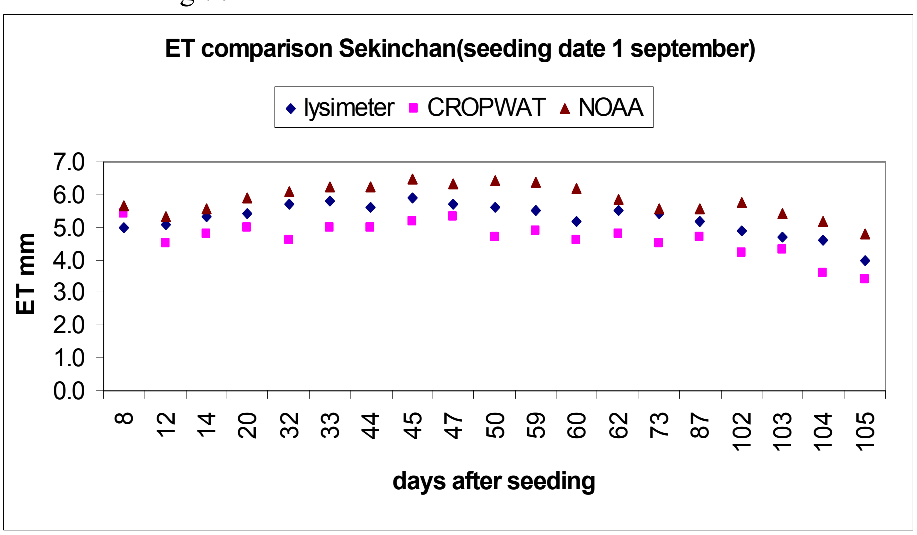

Fig 7c

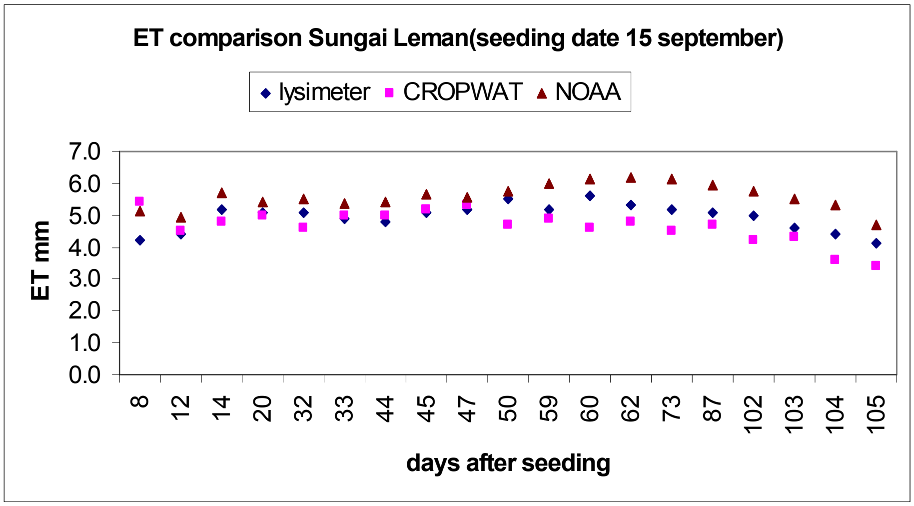

Fig 7d

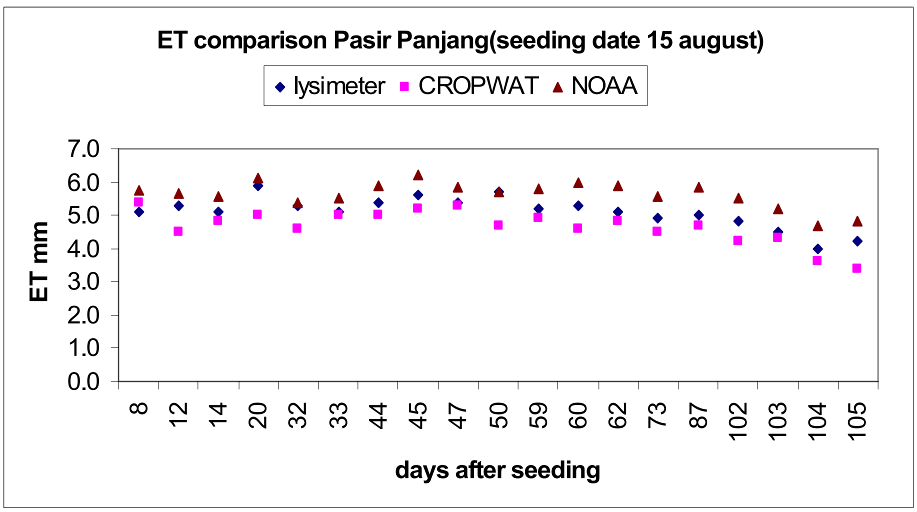

Fig 7e

The application of remote sensing needs highly trained workers and they will require some time to get the necessary skills. Consequently, it will be easy to apply the technique. The use of NOAA data with 1 km resolution is not the ideal for small areas because of its low spatial resolution, but the availability and cost of other data is the limiting factor. NOAA data is available daily even though a cloud free image may not be obtained easily in the humid tropics such as in Malaysia.

CONCLUSION

Estimates of evapotranspiration over the Tanjung Karang irrigation scheme were obtained using satellite-derived data and checked with lysimeters and calculation from weather parameters. Penman-Monteith equation through the use of CROPWAT software was applied to calculate ET. Considering ET obtained by lysimeters as the most accurate, the ET from satellite data overestimates ETcrop by 10%, while CROPWAT underestimates ETcrop by 14%. The availability of advanced very high resolution radiometer AVHRR data from

NOAA on daily basis is a cheaper alternative for evapotranspiration estimation. Satellite images can provide data and information about the paddy fields at any time, hence reduces the cost of taking field data and also reduce the error of missing data. Estimation of evapotranspiration using NOAA data will give good reflection of global changes. However, based on this study a factor of 0.9 needs to be multiplied to the satellite derived ET results.

ACKNOWLEDGEMENTS

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REFERENCES

Allen, G.R., A.Morse, M.Tasumi, Bastiaanssen W., H. Anderson. Evapotranspiration from Landsat (SEBAL) for Water Rights Management and Compliance with Multi-State Water Compacts. Unpublished.

Bastiaanssen, W.G.M., 1998. Remote sensing in water resource management: the state of the art. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Bastiaanssen W. G. M., David J. Molden, Ian W. Makin, 2000. Remote sensing for irrigated agriculture: Examples from research and possible applications. Agricultural Water Management 46 (2000) 137 – 155.

Droogers P., Bastiaanssen W. Evaporation estimates using a combined hydrological model and RS approach. Unpublished.

Granger.R.J, 2000. Satellite- derived estimates of evapotranspiration in the Gediz basin. Journal of Hydrology 229 (2000) 70-76.

Groten, S.M.E., 1993. NDVI – crop monitoring and early yield assessment of Burkina Faso. International Journal of Remote Sensing 14: 1495.

Loveland, T.R., J.W. Merchant, D.O. Ohlen, and J.F.Brown., 1991. Development of a land cover characteristics database for the conterminous U.S. Photogrammetric Engineering and Remote Sensing 57: 1453-1463.

Vidal, A., and Perrier, A., 1989. Analysis of a simplified relation used to estimate daily evapotranspiration from satellite thermal data. International Journal of Remote Sensing 10 (8), pp. 1,327-337.

http://www.fao.org/ag/agl/aglw/cropwat.stm

Lessons from Successful SCADA and Automation Projects

Charles M. Burt[1] and Xianshu Piao[2]

ABSTRACT

ITRC has designed, specified and assisted with installation, several dozen successful irrigation district automation and SCADA (Supervisory Control and Data Acquisition) projects in California, Oregon, Washington, Nevada, Arizona, and Colorado within the past 10 years. This paper is intended to acquaint people who are interested in SCADA with key concepts, to reduce their learning curve. The term "SCADA" encompasses many combinations and variations of remote monitoring and control. An emphasis on good planning, with the use of high quality equipment and expertise, will help guarantee a successful project.

INTRODUCTION

Irrigation Association members work predominately in the farm or landscape/turf aspects of irrigation. Another huge arena of irrigation involves irrigation districts, which obtain, convey, and distribute irrigation water to farmers. SCADA systems in irrigation projects have been in existence for several decades. However, the vast majority of functional SCADA systems in irrigation districts have been installed within the last 10 years. Many of the lessons learned are applicable to on-farm and municipal SCADA system applications.

Why SCADA?

There are probably three major reasons why so many irrigation districts are investing in SCADA:

1. Irrigation must retire "art" and shift to an industrial control process, in which real-time information is constantly used to make appropriate decisions. Reducing "art" in the process fulfills the need and desire to:
    a. Reduce diversions, to maintain in-stream flows in the rivers.
    b. Provide more flexibility in water delivery to farmers.
    c. Reduce pumping costs.
    d. Conserve water and sell the conservable water.
    e. Remove the mystery of operation details, so that new employees can be easily trained, and so that managers can establish clear and measurable performance guidelines for canal/pipeline operators.
2. There is often a need for automation that requires computers (Programmable Logic Computers, or PLCs) at remote locations. Because it is the nature of computers,

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electronics, sensors, and software programs to have occasional problems, it is prudent to remotely monitor their performance at such sites.

3. Some districts have key trouble spots where water levels or flow rates historically get too low or high. SCADA provides a means to remotely monitor those sites in real-time – minimizing labor, vehicle mileage, dust, etc. while improving response time to problems.

SCADA CHARACTERISTICS

Some SCADA systems will be quite elaborate and involve automation, and others will simply be able to transmit data from remote locations. However, all SCADA systems have the following components, at a minimum:

1. A sensor
2. Some type of on-site apparatus that creates an electrical signal that can be transmitted
3. A local power supply to power the sensor and transmission unit
4. Some type of communication system, such as hard wire, radio, satellite, phone, etc.
5. A receiving unit on the other end of the communications
6. Some mechanism to display the information – which may be a simple alarm bell, computer screen, message on a pager, etc.

The components listed above would provide "remote monitoring" – which is one-way communication only. However, many systems (e.g., Figure 1) also include some type of control capability – which requires two-way communication.

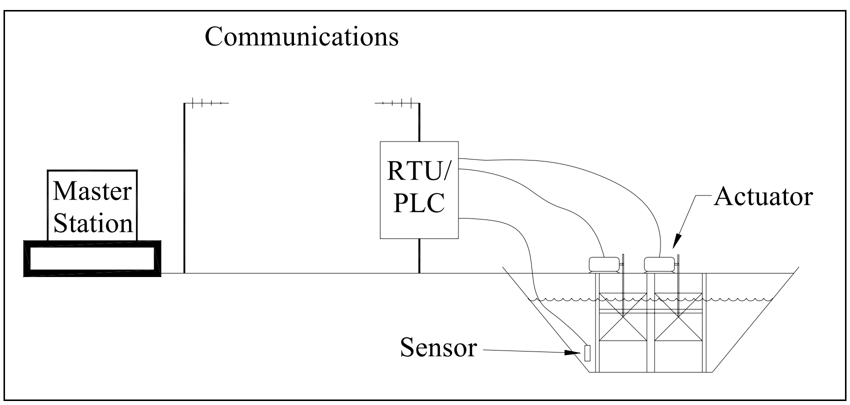

Figure 1. Conceptual elements of an irrigation district SCADA system that involves control.

Many people use the term "SCADA" to denote the collection and transmission of data, *plus* an automation process. An automation process may or may not require SCADA, so we prefer to separate the two (See Table 1). Not all of ITRC's SCADA projects involve automation, and not all of our automation projects involve SCADA. That said, all of ITRC's automation projects that use programmable logic controllers (PLCs) also incorporate SCADA for remote monitoring, alarms, and the ability to change target values.

Table 1. Variations between and within SCADA systems

Case	Basic Function	Frequency of Sensor Monitoring	Frequency of Data Transmission to Office
1 Monitor	Alarm for high/low values	Continuous	Only if alarm condition exists.
2 Monitor	Alarm for specific values such as height, position, temperature	As often as once/second, as seldom as once/15 min.	Only if alarm condition exists.
3 Monitor	Remote monitoring of specific values such as height, position, temperature. No alarming.	As often as once/second, and as seldom as once/day.	For river basins – often a few times/day. For irrigation districts – often once/minute.
4 Monitor	Cases (2) + (3)	1/sec – 1/day	Once/day remote monitoring can be over-ridden by an alarm exception at any time.
5 Monitor plus manual	Case (4) plus remote manual control of an actuator	1/sec – 1/15 min	1/30 sec – 1/30 minutes. Slower than 1/minute is outdated and cumbersome for operators.
6 Monitor plus Automation	Case (5) plus remote changing of target values for local, independent automation	1/sec – 1/15 min. With modern automation, 1/sec or more frequent is common.	1/30 sec – 1/30 minutes. Slower than 1/minute is outdated and cumbersome for operators.
7* Monitor plus Automation	Case (6) plus feed-forward between local controllers	1/sec – 1/15 min. With modern automation, 1/sec or more frequent is common.	1/30 sec – 1/30 minutes. Slower than 1/minute will often not work with feed-forward. ***This is rarely found in an irrigation district.***
8* Monitor plus Automation	Case (4) plus centralized computation of gate/pump movements	1/sec – 1/15 min. With modern automation, 1/sec or more frequent is common.	1/sec – 1/15 min. ***This is rarely found in an irrigation district.***

* - Denotes forms of automation with few examples of sustained success in irrigation districts.

It is common for one SCADA system to incorporate several of the cases in Table 1.

Overview of Building a SCADA System with Local Automation (Case 6)

An abbreviated flow chart for the process of building a SCADA system for Case 6 (of Table 1) can be seen in Figure 2. Within each of the action blocks are numerous steps. Within the box labeled "Perform Specific Field Tests", for example, ITRC has several pages of procedures. Likewise, for checking the wiring and calibration of the field PLCs alone we have 12 pages of flow charts.

Components versus Systems

Figure 2 illustrates that successful implementation of a SCADA system, especially one involving automation, is much more complicated than simply selecting a PLC and some sensors. SCADA systems are composed of components that have hopefully been selected and connected to work as a seamless system to satisfy specific objectives.

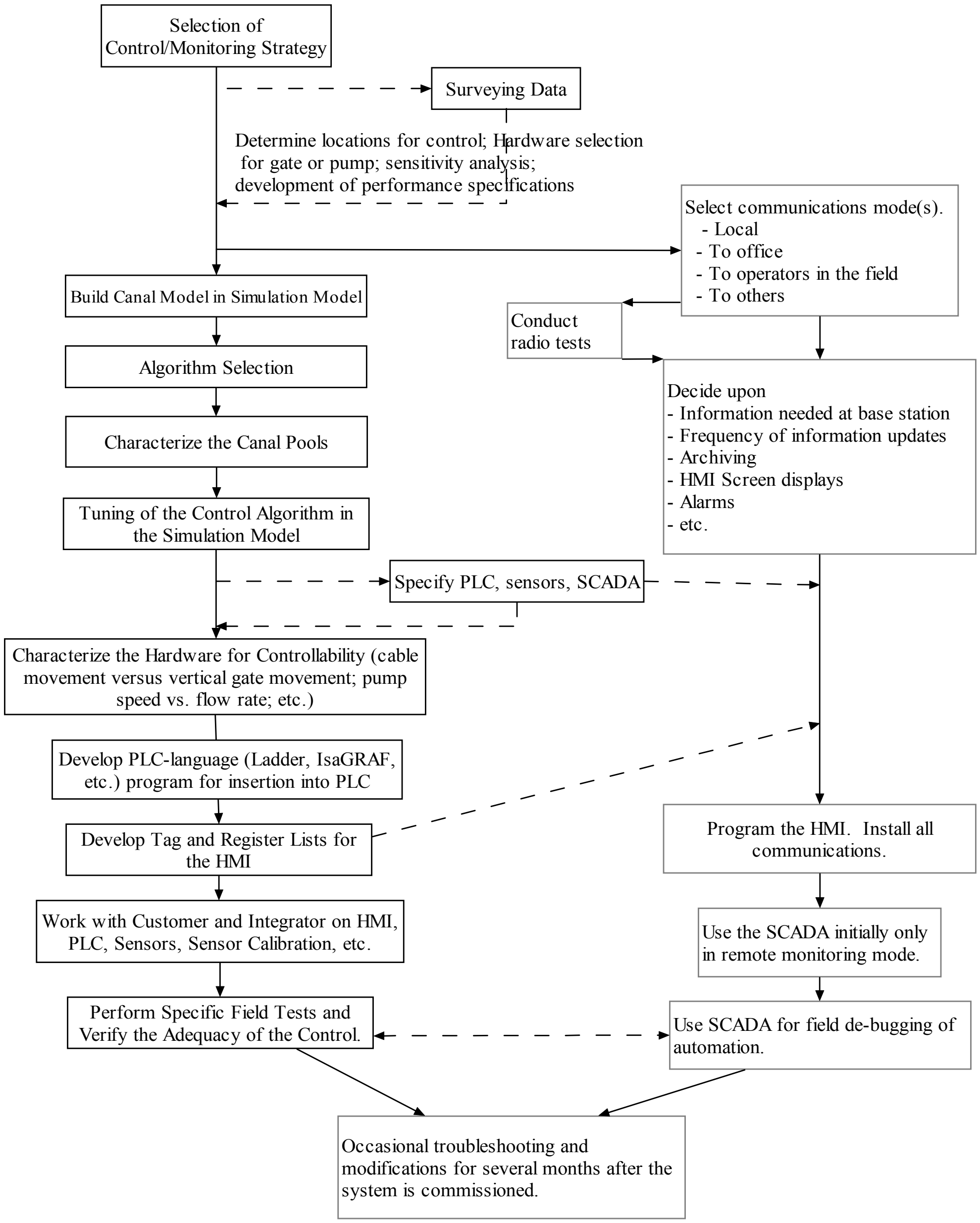

Figure 2. Outline for the Process of Design and Implementation of a Case 6 SCADA System.

The components must be carefully selected so that everything "matches". For example,

1. A very good sensor might output a voltage signal, but that might be completely incompatible with a requirement that the signal must be transmitted over a 3000' cable.
2. A specific brand of water level sensor may be excellent, but if a 10 psi sensor is selected when only a 1 psi sensor is needed, the resolution of the signal will only be 10% of what is possible.

3. 8-bit sensors connected to 16-bit computer input boards cannot give 16-bit resolution, or visa-versa.
4. If a control algorithm requires an average of 60 readings/minute, a PLC that is only capable of obtaining 60 readings in the last 10 seconds of the minute will provide different control capabilities than one that can obtain one reading each second during the 60-second period.
5. The power provided to a PLC must be capable of powering all the sensors, radio(s), PLC, heater, etc. in all weather conditions.
6. Sensors with proprietary software and communications won't easily fold into a complete system that can be updated and added to.

The examples show the following "matching" or "compatibility" requirements:

1. The hardware must be able to physically link together and communicate. This is the job of the "integrator".
2. The hardware must be compatible with the control/monitoring objectives. This is the job of an *irrigation* automation control specialist, who must provide specifications to the "integrator". Control specialists from the chemical, electrical, transportation, etc. industries have not been able to successfully apply their control logic to canal systems.

The emphasis with SCADA systems, in our opinion, is QUALITY, QUALITY, QUALITY – in specifiers, integrators, software, and hardware. Even in systems with the best-quality components, problems arise. The correct SCADA team can sort out those problems if there is a willingness to work together and an understanding of the system in its entirety.

Many of the components and "systems" sold for the farm irrigation SCADA market are one-of-a-kind, proprietary units of medium-low quality, that are not assembled or designed by a "team" that looks at the expanded needs for a farm. They are typically designed to measure/monitor/control one or two items that are sold by the same vendor that sells the communication system and office software. They are often not compatible with other brands; the result is that a farm may need many individual SCADA systems to accomplish what one good commercial, industrial SCADA system could provide.

Other Consideration

Irrigation districts that have successfully implemented them typically quickly expand them and wonder how they survived without them. But there are also many problem cases. Classic problems are:

1. Cost overruns
2. Failure to achieve performance expectations
3. Failure to reduce operating costs in order to meet payback expectations
4. The thing just doesn't work right

Secondary problems include:

1. Scheduling errors
2. Interfacing problems
3. Incompatible equipment
4. Lack of acceptance
5. Adverse publicity

In our experience, the problems in irrigation districts have arisen because of one or all of the following:

1. Entities are looking for a “silver bullet” that will cure problems quickly and with little effort.
2. People focus on a few components rather than understanding that they need to consider a system.
3. There is no clear plan for the present and future.
4. Irrigation districts decide to use the “local electrician” because he/she is a nice person and dependable, instead of hiring an experienced integrator with ample successful experience in irrigation district application.
5. Districts (or local government agencies) invent their own sensors, hardware, and software.
6. Districts start too big, too fast.
7. Not everyone accepts the fact that problems will occur, and that there must be qualified people to diagnose problems, service equipment and software, and stick with the problems until they are solved. This takes an on-going budget.

As with any process, there are logical steps to follow in designing and implementing a SCADA system. These include:

1. Master planning
2. Precise specifications
3. Vendor qualification
4. Vendor selection
5. Adequate training and documentation
6. User tools for future changes
7. Spares and warranties
8. Continuous and near-exhaustive testing
9. Realistic schedules

The process can take a long time before any actual installation begins. If the planning is done properly, the installation can be accomplished in a few months. If the wrong people and planning are involved, the installation may never be completed satisfactorily. A few of the points above are explained in more detail, below.

<u>Master Plan:</u> A master plan identifies the need for automation, the degree of automation required, what other features are desired, and the budget and cost justification. This represents the guideline for all the work, so it is necessary to carefully understand which options are desired and why. The plan must also consider the impact on operation, instrumentation, training,

installation, interfaces to other utilities (such as electric utilities), public relations, manpower requirements, future expansion, and expected life of the new system.

Integrator: The component selection, matching, installation, and troubleshooting are so complicated that most successful SCADA projects have utilized an “integrator” that assumes responsibility for the complete package. The integrator generally understands communications, sensors, human-machine interfaces (HMI), actuators, etc. and can make certain that everything physically moves, measures properly, and communicates. It is extremely important to understand that when SCADA is used in a canal automation scheme, the SCADA integrator will rarely, if ever, understand canal hydraulics, simulation techniques, and control algorithms and algorithm tuning. These are separate functions that require an additional expert.

HMI: The Human-Machine Interface (HMI) – the software and screens in the office - is important. How easy is the system to operate? Are control and monitoring screens straightforward and is information easily accessible? For example, an alarm condition that is missed because it is mixed in with many nuisance alarms is as bad as one that is missed by the instrumentation. Can in-house people make simple changes to the screen displays?

Reliability: Reliability is a measure of the system’s ability to minimize downtime by avoiding failure, or at least to keep operating in a degraded mode by using special software and hardware such as an uninterruptible power supply (UPS) and a redundant master computer. The tradeoff includes weighing the extra cost of the additional equipment against the value of this function and the likelihood of an outright failure. No machine will run forever and eventually you will have to shut down your master at least for occasional checkups and preventive maintenance – managers should be prepared to live with these tradeoffs or buy reliability up front. ITRC has decided that for control variables in automated systems, it is essential to have a high level of redundancy in sensors, power supplies, and A/D converters. Yes, this costs extra and may reduce the number of sites that can be automated, but it ensures a better chance of success.

Maintenance: Maintainability is the ease with which fixes or changes can be made to your system. In the case of hardware, consider what you can fix yourself, what spares you may need, and how accessible the vendor is for factory returns and for minor upgrade contracts. Modularity helps maintenance. Placing sensors so that they can be removed for cleaning/inspections, and be replaced in exactly the same location without new calibration, is important.

SUMMARY

The potential exists for new and expanded SCADA systems in their many combinations and variations of remote monitoring and control for irrigation districts and farms and large commercial/industrial/golf irrigation systems. However, in order for customers to fully utilize that potential, attention must be paid to all of the details – which, in many cases, can “make or break” a system. An emphasis on good planning, with the use of high quality equipment and expertise, will help guarantee a successful project.

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INTRODUCTION

The Government Highline Canal is part of U. S. Bureau of Reclamation (Reclamation) Grand Valley Project, Grand Junction, Colorado. The canal construction was started in 1910 and completed during the Great Depression. The canal diversion of 1620 CFS extends 55-miles from the Colorado River diversion and delivers water to four irrigation districts and a hydroelectric plant. Two Federal environmental programs spanning a 25-year period have had a dramatic impact in the modernization of the Highline Canal.

PROGRAM ONE

In the 1970's the Colorado River Salinity Control Program funded improvements to reduce canal and lateral seepage that was increasing the salt loading of the Colorado River. The cost effective portions of the canal were lined and most of the earth laterals were piped. These seepage reduction measures dramatically improved the delivery of irrigation water to the farmers.

General Description

The salinity control work was authorized for construction in 1974, amended in 1984. The purpose of the Reclamation's portion of the Grand Valley Salinity Project was to reduce the estimated 580,000 tons per year of salt added to the Colorado River as a result of irrigation conveyance system seepage. Salt loading to the Colorado River occurs when seepage from irrigation canals and laterals, irrigated fields, and irrigation return flows pass through highly saline underlying Mancos Shale Formation in the Grand Valley. By reducing the amount of groundwater percolating through these saline soils, salt loading to the Colorado River is decreased.

Reclamation's program in the Grand Valley primarily focuses on off-farm irrigation system improvements. Off-farm construction included lining portions of the main canal and piping the laterals that deliver water from the main canal to irrigated land. On-farm improvements were conducted by the Natural Resource Conservation Service, a.k.a. Soil Conservation Service, which includes upgrading irrigation systems through cost assistance and improving irrigation management to reduce deep percolation from farm operations. The improvements include installing underground pipelines, gated pipe, concrete-lined ditches, land leveling, drip irrigation systems, and a variety of other practices.

The Highline Canal is operated and maintained by the Grand Valley Water Users' Association (GVWUA). The Grand Valley Salinity Project was completed in two stages. Stage I was used as a test area to refine analysis and construction techniques used on the balance of the project (Stage II). Stage I construction began in October 1980. As part of the development, 6.8 miles of the Government Highline Canal was lined with un-reinforced slip-form concrete lining and four check structures were constructed in the canal. Thirty-four miles of unlined laterals were consolidated into 30 miles of close pipeline laterals. Construction of Stage One was essentially completed in April 1983. Beginning in November 1981, Stage Two investigations included re-evaluating various alternatives and analyzing salinity control measures other than concrete lining of the canals and laterals.

Stage Two improvements to the Highline Canal used a PVC membrane lining instead of concrete. Work in the canal included the construction of four check structures. Laterals in the Highline Canal systems were converted from open earth ditches to closed pipelines.

Construction

Improving the Highline Canal involved shaping the canal bottom and banks. After the canal was shaped, a 40-mil PVC membrane lining was pulled across the canal. A 15-inch-thick layer of gravel was placed over the membrane lining to protect it from the sun and canal maintenance. The laterals were a closed pipe design, with pipe sizes ranged from 6 to 48 inches in diameter. The individual deliveries have propeller type flow-meters and various valve schemes to deliver water to the on-farm irrigation system. Typically the user controls the delivery of water.

Benefits Salinity Control

The Grand Valley Salinity Project removes 115,700 tons of salt per year. The resulting annualized cost for the Salinity Project is $93 per ton of salt removed.

Consequential benefits for the GVWUA irrigators

The irrigation delivery system was changed from an open-flow supply-side system to a gravity pressured closed-pipeline demand-side system. The use of water orders went from water delivery accounting to canal monitoring. Water accounting is recorded with flow-meters, and the water orders are used to forecast the day-to-day demand on the canal. The increased flexibility in terms of rate and duration went from 24-hour blocks of water to whatever the irrigator desires. The down-side of increased flexibility at the deliveries is that the canal has the same limited capacity to deliver water to the laterals. The laterals no longer have tail-water spills. Changes in lateral demands are immediately reflected in the canal. Increased flexibility at the deliveries requires greater attention to the administrative spills or lack of spills to prevent the inadvertently de-watering and refilling of lateral pipelines.

PROGRAM TWO

In the 1990's The Recovery Implementation Program for the Endangered Fish Species in the Upper Colorado River Basin (Recovery Program) identified a 15-Mile Reach of the Colorado River between Palisade, Colorado and the confluence of the Colorado and the Gunnison Rivers at Grand Junction, Colorado as an area needing additional water supplies to maintain habitat conditions for several identified endangered fish species. The Colorado Endangered Fish Recovery Program needed to increase late season in-stream flows in the Colorado River through the Grand Valley. A cost effective alternative for accomplishing increased flows in the river was by modernizing the Highline Canal to reduce the late season administrated spills.

Historically the Highline Canal delivers 650 CFS to the GVWUA project area. The minimum flow to maintain a water surface in the canal to make the turnout deliveries is around 400 CFS. The canal is operated by starting out with 400 CFS in the spring and ramping up to 650 CFS within a month. The canal carries 650 CFS through most of the summer. Then as demand drops off in August through October, The canal is ramped down to 400 CFS. Demand decreases substantially below the 400 cfs needed to run the canal. In the very late season, demand can approach 25 cfs. Any water in the canal in excess of demand is released through administrative spills. Canal administrative spills are returned to the Colorado River through natural drains with little environmental impact, other than reducing the flows in the upper 15-mile reach of the river.

To deliver real water to the Colorado River from canal modernization is a complex problem which requires careful analyses. The Government Highline Canal Modernization Study was proposed, and a team was formed. The following were the cooperators in the study: Colorado River Fish Recovery Program (Recovery Program), USBR - Grand Junction Area Office (USBR), Grand Valley Water Users Association (GVWUA), and Cal Poly - Irrigation Training and Research Center (ITRC).

The study provided an analysis of structural and operational options that will permit the reduction of operational spills, a series of alternate designs that could achieve this effect, and a computer model of the Government Highline Canal. The problems with reducing canal flow rate requirement during periods of low user demand, is that the water level is too low to deliver adequate water to the canal turnouts, and secondly it is difficult to match canal flows to the flexible delivery demand. In addition, any canal modernization must maintain the current level of "service" to the irrigators in the GVWUA. The current system is characterized as having a simple and efficient operation as created by the flexible closed pipeline lateral systems from the salinity program.

The Salinity Control Program incorporated 8 new canal check structures in the portions of the canal that received lining. The modernization study recommended 7 additional check structures in the unimproved sections of the canal to permit reduced river diversion. The 7 new check structures were constructed in 2001. With 15 check structures operating in some kind of localized automation, the canal can operate with 150 CFS in flow in late season. Since the completion of the canal checks, river diversions have been reduced 30,000 to 45,000 acre feet per year.

The second part of the puzzle was to more closely match canal flows to the flexible demand. To quickly adjust canal supply, a pumping plant was constructed at Highline Lake. The canal is operated in an up-stream control strategy and has a major administrative spill into the lake. With the canal operated in up-stream control from the river diversion to Highline Lake, all the mismatches between supply and demand are accumulated at the Highline Lake spill. A pump back station was constructed at the spill to supply lake water to the canal during times when demands exceed the supply in the canal. The operation of the pump-back station allows the canal water diversions to more closely match the user demands, without the fear of shortages in the last 6-miles of canal downstream of the Highline Lake spill. The pump station is capable of delivering up to 75 CFS to the canal. The maximum down stream demand is about 150 CFS, and this 6-mile portion of the canal will be operated in downstream control mode to further reduce the tail-end spills. The pump station will reduce the attention required to the administrative spills to prevent the inadvertently de-watering and refilling of lateral pipelines on the tail end of the canal, and further reduce the required diversion from the Colorado River.

CONCLUSION

Irrigation districts and association are very interested in maintaining their agricultural water rights. Most districts and association would like to increase the reliability and flexibility of their delivery systems, but it is unlikely the profit margins from the collective irrigated lands within the projects are capable of funding a massive modernization project as described in this paper. The key to project funding is finding non-project partners to fund the modernization for their own benefits and create a win-win situation.

Moderately Priced SCADA Implementation in Northeastern Colorado

Stephen W. Smith[1]
Donald O. Magnuson[2]

ABSTRACT

In northeastern Colorado, more than 100 mutual irrigation companies have functioned very effectively in delivering raw water for agriculture since the late 1800's. As many of these canals are modernized, an appropriate technology for consideration is Supervisory Control and Data Acquisition System (SCADA) to provide either monitoring or both monitoring and control of canal operations from a centralized location. Canal flows and reservoir storage data can also be easily posted to the canal company's web site for management and shareholder access.

SCADA systems were once perceived to be too costly for most mutual irrigation companies but the hardware and software is increasing in function, decreasing in cost, and becoming much more affordable for these private enterprise situations. The opportunity, the costs, and the benefits of SCADA for mutual irrigation companies are explored in this paper.

Several case studies are cited. In particular, the efforts of the New Cache la Poudre Irrigating Company are described to include SCADA implementation for both initial monitoring of flows and later to include remote manual gate actuation. SCADA implementation by Riverside Irrigation District is also described in which a satellite uplink is used to keep costs reasonable to the District.

BACKGROUND AND INTRODUCTION

SCADA is an acronym for Supervisory Control and Data Acquisition. SCADA has been with us a long time but mostly with industrial process control and monitoring circumstances that could afford the technology. Irrigation, for many years, was not an industry that warranted the steep hardware cost until some irrigation manufacturers began to adapt their own proprietary hardware, and software, into a specialized type of SCADA. So, in the mid 1980's we began to see adapted SCADA systems that were specifically made for irrigation projects that could afford it -- golf irrigation, in particular. In golf and landscape irrigation, we referred to these systems as "centralized irrigation control." These early control systems were further adapted to accommodate distributed sites such as school districts or municipal park departments. In 1986, the City of Pueblo became the first city in the country to have centralized irrigation control for distributed park sites. During this period, specialized SCADA systems found a niche in irrigation and those systems, by a myriad of different proprietary names, have been with us for almost 25 years.

Where was agricultural irrigation to be found in this picture? There were a few irrigation central control systems to be found in agriculture, but not many if the total number of irrigation districts

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and mutual irrigation companies is considered. Agriculture could not afford the rather steep cost of SCADA. During the early 1990’s, the cost of implementing SCADA on a per site basis was generally in the range of $5,000 to $10,000 per site without gate actuation hardware. This cost was simply too high in comparison to the cost of a classic chart recorder installation on a weir or flume, or for that matter, the cost of manual actuation of valves, headgates, and checks by the canal company’s ditch rider.

The current cost of SCADA implementation has come down in recent years to a point where SCADA is affordable to mutual irrigation companies. Often smaller mutual irrigation companies do not have an office or a staff per se, but a SCADA central system can be located anywhere that is practical. This could be at the home office of one of the company’s officers. SCADA can provide smaller companies many cost effective features which result in significantly improved canal operations, improved deliveries to shareholders, and reduced liabilities.

SCADA CONCEPTS

Generic definitions are appropriate to help describe basic SCADA concepts. The “central system” is microcomputer based and interface software is used to communicate with remote sites. The software that provides and umbrella over everything is called a “human-machine interface” or HMI. The key hardware at remote sites is a “remote terminal unit” or RTU.

The HMI software can be proprietary and published by the manufacturer of the hardware or it can be more generic and published by software companies that purposely write HMI programs that are compatible with the hardware of all manufacturers. Software companies market programs that are known as Wonderware, Lookout, and Intellution, as examples. The SCADA industry has standardized largely on a communication protocol called “Modbus” which is quite flexible but also quite old being a protocol that was developed for hard wire circumstances.

The RTUs are essentially a small computer that can be programmed for the specific requirements at individual sites. The RTU is also the point at which sensors are connected. So, a site with only one requirement, often monitoring the water surface elevation in a flume or weir, would have a water level sensor wired to it. The RTU then communicates back to the central or conversely the central can initiate a call to the RTU. The preferred communication is full two-way communication. In other words, the central can call the RTU or the RTU can call the central. It is important to note that the RTU can be monitoring one or more sensors and perform logical operations and even create an exception report or alarm. If flows are excessive at a point in the canal system or if the water surface level is too high and freeboard too low, an alarm can be raised or action can be taken in the form of gate or check adjustments. Alarms can appear at the central computer or even be pager transmitted to an alphanumeric pager.

There are multiple levels at which SCADA can be implemented. Starting off with a “keep it simple” approach, monitoring water surface elevations only, for example, is sound and likely the initial system can be expanded to other sites and capability and features can be added to sites without a price penalty.

The four differentiating levels of SCADA implementation can be described by their respective function and utility to the canal company.

- Monitoring (only).
- Remote manual operations.
- Local control.
- Fully automated operations.

Each level results in increasing capability within the SCADA system, but each level costs more. The additional cost is largely at the remote sites, not at the central workstation. The central workstation becomes a fixed cost except for HMI upgrades and the inevitable computer hardware upgrades.

Figure 1 shows a simple SCADA monitoring site installed in a rated canal section historically used by the New Cache la Poudre Irrigating Company (NCLPIC) in Lucerne, Colorado. For many years, water surface elevations have been monitored at this location using a Steven's recorder and by manually reading the gauge twice per day by the ditch rider. With SCADA, data is transmitted by radio to the central computer on a frequent basis. At the central computer, the data is reported continuously on the HMI screen. NCLPIC is currently investigating full SCADA for improving canal operations and monitoring and reporting of the company's well augmentation plan.

The HMI screen can be, and should be, unique to the user and the circumstance. Figure 2 shows an example of the HMI screen in use by district staff at the Delores Project near Cortez, Colorado. This screen is simple and intuitive in nature. Radial gate (check structure) positions are depicted graphically, each in a somewhat lower position in the HMI screen, to indicate the canal itself. The operator may raise or lower gates, and therefore water surface elevations in canal pools, by using very small incremental gate movements. Interestingly, Delores Project staff can and do make changes in their own HMI software interface without assistance from an outside consultant or system integrator.

With simple monitoring using a SCADA system, sensors are installed that meet monitoring requirements such as water level sensors. Data is collected on the central system and can then be directly viewed by a system operator or plotted depending on needs and functional requirements.

With remote manual operations, as the name implies, the operator can raise or lower gates and thereby effect the canal operation from the central computer. This is called remote manual because gate movements are implemented by the canal company staff, just as if they were at the gate or check. But gate adjustments can be made much more frequently and therefore canal operations, overall, can become more real time and precise.

With control, the RTU at a particular site is programmed to maintain a set water surface level or to open a gate if a water surface level increases beyond a set point as with a storm event.

Full canal automation is possible. This ultimate benefit of SCADA has been widely discussed for two decades but there are actually very few canal companies that experience what would be called full automation. One semantical note is important here. Some would refer to a canal as being automated, with SCADA, but what they often mean is that the canal is operated under a remote manual scenario using SCADA equipment. Full canal automation which logically starts with irrigation order inputs and results in automated (algorithm driven) gate adjustments for the pending day is not an easily programmed process.

Figure 4 shows a fully automated canal check structure which is integrated with SCADA.

CASE STUDIES

Central Arizona Irrigation and Drainage District

The Central Arizona Irrigation and Drainage District (CAIDD) has implemented SCADA over much of the district's 60 miles of canal. CAIDD has utilized SCADA for many years but it is noteworthy that they have in recent years upgraded their old SCADA system at a very affordable cost. With the upgrade, using the existing gates, actuators, and other infrastructure, the district staff installed new SCADA equipment on 108 sites for an equipment cost of approximately $150,000.

Most of the district's checks are operated in remote manual mode. See Figure 3 which shows the day operator at the central system where the upstream water surface elevation at all 108 check structures can be viewed simultaneous with three side-by-side computer monitors. Using SCADA, gate adjustments can be made in increments of 1/8th inch which coincidentally equates to a change in flow of roughly one cubic foot per second through the check.

Additionally, a portion of the CAIDD sister district's (Maricopa Stanfield Irrigation and Drainage District or MSIDD) canal system is operated under full automation using a program that was developed by the Agricultural Research Service (USDA-ARS), Water Conservation Laboratory, in Phoenix, Arizona. SacMan, which stands for Software for Automated Canal Management, has been under development for approximately five years. SacMan runs in parallel with the HMI software and interface and is used to operate a key MSIDD canal in a fully automated mode.

A key approach to affordable SCADA for CAIDD was spread spectrum radios. These radios do not have a federal licensing requirement. The radios look for a clear frequency, use that frequency if it is unused, or proceed to another frequency if necessary. The line of sight range for a spread spectrum "loop antenna" is two miles and the line of sight range for a "directional antenna" is five miles. Of particular note, any one antenna can serve as a "repeater" radio to other radios. So, with a linear project like a canal system, communication can be achieved by using the radios in a daisy-chained fashion to increase the effective communication distance.

Figure 5 shows a spread spectrum radio and a directional antenna installed on a galvanized steel pipe at one of CAIDD's check structure sites.

New Cache La Poudre Irrigating Co. (Greeley #2)

New Cache La Poudre Irrigating Company (NCLPIC) operates one of the larger canal systems in northeastern Colorado which is known as the Greeley #2 Canal. The company holds decrees on the Poudre River and diverts approximately 600 CFS when all the decrees are in priority. In recent years, NCLPIC has also initiated a well augmentation plan for more than 100 member wells within the company's historic service area.

In 2003, the company commissioned an initial demonstration of SCADA (monitoring) with one of the key rated sections on the Greeley #2 system. This demonstration showed clearly that real time data could be effectively used and improved monitoring was a significant help in managing day-to-day operations as well as annual reporting of flows.

After considerable study, including tours of CAIDD, the Delores Project near Cortez, and Imperial Irrigation District in California, the Company elected to implement SCADA for further monitoring of flows as well as gate actuation at key checks and outlet gates. Rubicon gates were selected because of suitable flow measurement accuracy that is possible along with gate actuation. One existing radial gate was actuated with a Limitorque actuator. A UHF radio frequency was licensed to the company and the communications for the entire system are facilitated using a repeater on a grain elevator near the company's offices near Lucerne, Colorado.

Because Rubicon gates were selected, the Rubicon TCC (Total Channel Control) HMI was evaluated and ultimately selected. The system currently consists of six Rubicon gates, one actuated radial gate, and monitoring of one rated section. A key outlet used to waste excess water in storm events allows for 24/7 monitoring of canal water surface elevations and storm flows can be dumped to avoid some increased liabilities and risk of a canal breach.

Riverside Irrigation District

Riverside Irrigation District located in Fort Morgan, Colorado operates a canal that is more than 100 miles in length. The company delivers water to well recharge structures which must be monitored to meet the required reporting demands for flows and volumes associated with recharge. Automata RTU equipment, specifically the Automata Minisat, was used and linked to satellites. Data is accessed through an internet web page. Although there is an annual recurring cost for satellite communication (see Table 1), this approach allows a very low SCADA entry cost and minimal capital investment to meet the requirements of the site without travel to individual recharge sites for data collection as was required in the past. Currently six sites are in operation. Riverside Irrigation District has invested approximately $xx,xxx to date since early 2004 and expects to gradually expand the system as my be warranted and as can be afforded.

AFFORDABLE IMPLEMENTATION

Table 1 contrasts SCADA implementation costs at varying levels and compares those costs to collection of flow data using a Stevens recorder device, as might have been most common in the past. So, for example, if it were necessary to replace an existing Stevens recorder at a flume or weir at $2,450 (second column), the existing equipment might be replaced with an RTU using satellite communication at a cost of approximately $3,000 plus annual costs of $435 (third column). This incremental additional cost is likely quite palatable given the ease of data collection.

Additionally, assuming a central computer is already in place, the cost of real time assess to the additional site would be approximately $3,000 as well (fourth column). If the added features and sophistication of alarm condition reporting is desirable, then this cost increases to approximately $4,000 (fifth column).

SUMMARY

SCADA has become more affordable in recent years and is likely quite useful now to mutual irrigation companies for monitoring, remote manual operations, or even for full canal automation in the not so distant future. The technology has changed somewhat rapidly and can be expected to continue to change and become more flexible, more intuitive, and available at lower cost. This will encourage mutual irrigation companies to adapt to and adopt these technologies to the increasing demands of canal operations.

REFERENCES

Clemmens, A.J., R.J. Strand, and L. Feuer. 2003. Application of Canal Automation in Central Arizona. USCID Proceedings of the 2^{nd} International Conference on Irrigation and Drainage, Phoenix, Arizona. 12 to 15 May.

Clemmens, A.J., R.J. Strand, L. Feuer, and B.T. Wahlin. 2002. Canal Automation System Demonstration at MSIDD. USCID Proceedings of the 2002 USCID/EWRI Conference, San Luis Obispo, California. 9 to 12 July.

Hansen, R.D., B. Berger, and A. Hilton. 2002. www-Based Monitoring and Control for Over-Stressed River Basins. USCID Proceedings of the 2002 USCID/EWRI Conference, San Luis Obispo, California. 9 to 12 July.

Mareels, I., E. Weyer, S.K. Ooi, and D. Aughton. 2003. Modeling and Control of Irrigation Networks: A Systems Engineering Approach. USCID Proceedings of the 2^{nd} International Conference on Irrigation and Drainage, Phoenix, Arizona. 12 to 15 May.

Oakes, A., and B. Rodgerson. 2003. Advanced SCADA Networks Optimize the Operation of Water Resource Management Systems. USCID Proceedings of the 2^{nd} International Conference on Irrigation and Drainage, Phoenix, Arizona. 12 to 15 May.

Table 1
Cost Comparison for Various Means of Recording Flow Data at a Measurement Structure

	Chart Recorder[3]	Log Data & Upload to Satellite[4]	Log Data & Upload to Local Central Computer[5]	Log Data, Upload to Local Central Computer, and Create Alarm Condition[6]
Equipment Cost, $	$2,200	$2,500	$2,500	$3,500
Installation Cost, $	250	$500	$500	$500
Total Installed Cost, $	$2,450	$3,000	$3,000	$4,000
Monthly Recurring Cost, $	$0	$435 per year ($36 per month)	$0	$0

3 Presumed to be a Stevens Recorder type chart recorder device.
4 Presumed to be an Automata Mini-Sat device with a satellite uplink and no central computer. Data is accessed via a web site.
5 Presumed to be an existing SCADA implementation based on Automata equipment using spread spectrum radio communications.
6 Presumed to be an existing SCADA backbone installation with Motorola M RTU with either spread spectrum or UHF licensed radio communications.

Figure 1. An example of a rated canal section which is remotely monitored using a SCADA system. RTU equipment is 12-volt DC powered from a solar panel that maintains a charge on a battery. Communication with the site is via radio.

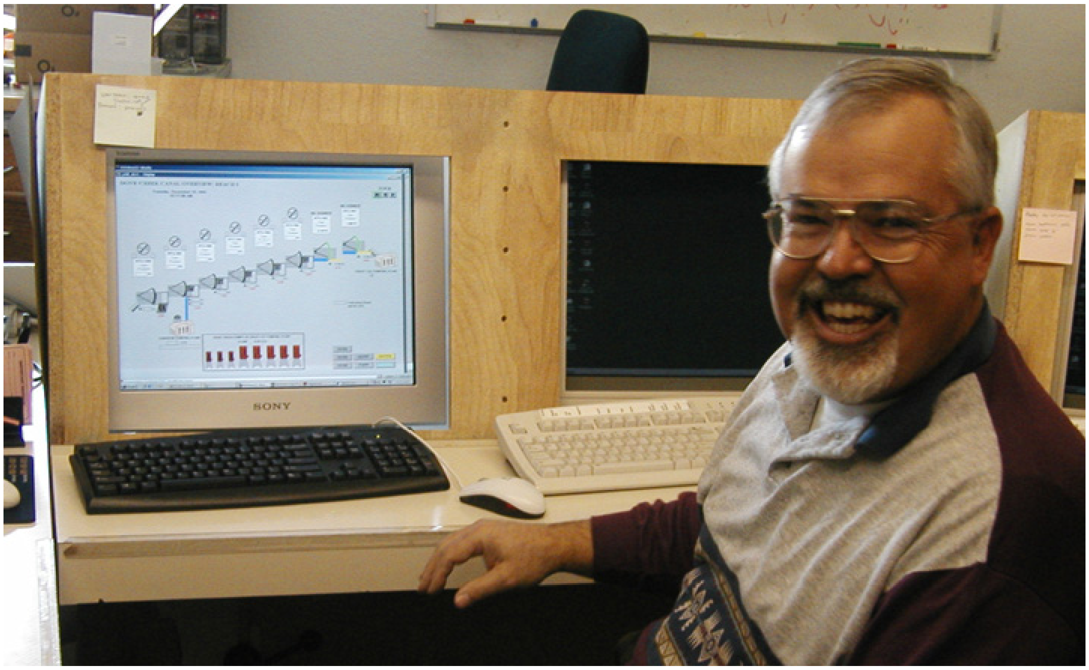

Figure 2. Chuck Lurvey, district engineer for the Delores Project in Cortez, Colorado, is sitting in front of the SCADA central computer. Radial gate icons on the HMI screen indicate the water surface level in the canal and the gate positions of the radial gates at checks along the canal.

Figure 3. An operator at the Central Arizona Irrigation and Drainage District (CAIDD) near Phoenix monitors primary flows and water surface elevations in the 60-mile canal. This SCADA system was implemented at relatively low cost using affordable RTU equipment and spread spectrum radios for communication.

Figure 4. This check structure is controlled by a Langemann gate and control is integrated with a SCADA system. Langemann gates function as a check structure and can be used for rough flow measurements.

Figure 5. The SCADA system at Central Arizona Irrigation and Drainage District (CAIDD) uses spread spectrum radio which is a relatively new type of radio system that does not require federal licensing. The spread spectrum radio is housed in the white enclosure and the directional antenna shown has a line-of-sight range of approximately 5 miles. The antenna is mounted on a 2-inch galvanized steel pipe.

ITRC Float Valve
Surge Pressure Protection Evaluation

Stuart Styles[1], Dale Brogan[2], Charles Burt[3], Franklin Gaudi[4]

Abstract: The Irrigation Training and Research Center (ITRC), California Polytechnic State University, San Luis Obispo, evaluated the performance of the ITRC Float Valve during several visits to Delano-Earlimart Irrigation District (DEID). The purpose of the trips was to evaluate the new ITRC Float Valve, investigate water hammer problems resulting from rapid valve closures, demonstrate the effect of water hammer to DEID operators, and provide recommendations for the current pressure surge problems. The results showed that a significant reduction in the water hammer potential to the DEID concrete pipelines could be achieved with the use of the new ITRC Float Valve design combined with educating operators to slow down the closure of on/off valves. The ITRC Float Valve minimized both pressure surges and the pressure fluctuations that are common with the existing on/off valves.

Keywords: float valve, water hammer, pressure surge, butterfly valve

Background

Pipelines and their fittings are designed to operate safely under certain specified pressures. Excessive high pressures, encountered as a sudden shock wave or continuously, will damage irrigation and water conveyance hardware (Figure 1).

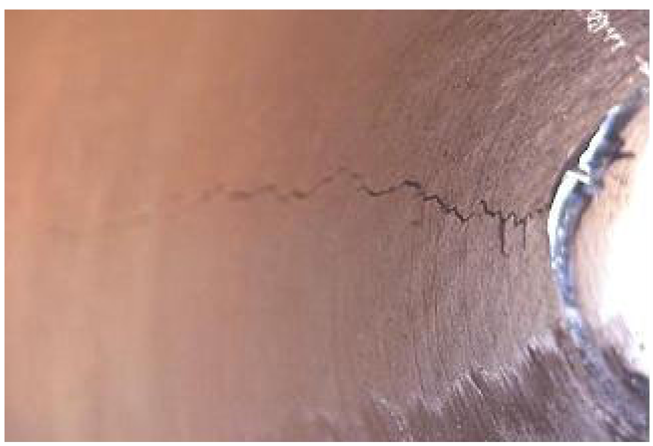

Figure 1. Water Hammer Damage in Concrete Pipeline

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These pressure surges are caused by a sudden change in the velocity of water in a pipeline, as is caused by the closure of a valve. The increase in pressure is a function of both the water velocity and the wave velocity. The wave velocity is the speed at which a pressure surge is transmitted by the pipe walls, and is dependent on the pipe material.

For several years, the Delano Earlimart Irrigation District (DEID) has been concerned about water hammer damage to their pipes. DEID distributes water through concrete pipelines in southern Tulare County and northern Kern County, California. Each turnout has a standpipe that is used as an air vent in the line to prevent back flow if a negative pressure occurs. Under a technical support agreement with the US Bureau of Reclamation (USBR), the Irrigation Training and Research Center (ITRC) has worked with DEID since 1999 to research and design a system to decrease the pressure in these pipes. The result of this research is the ITRC Float Valve.

The ITRC Float Valve has evolved through several stages of design. The final design and research results can be found at the ITRC website (www.itrc.org/reports/deidfloatvalve/floatvalve.pdf). The valve is designed to float as water in the standpipe rises. The float is connected to the valve through linkages. As the float rises the valve closes, regulating the flow into the standpipe to maintain a desired water level regardless of the pressure upstream of the valve.

ITRC personnel have tested and installed pressure regulating or float valves at a few sites within DEID. Figure 2 shows the turnout configuration showing the location of the ITRC Float Valve, the DEID operational (On/Off) valve, and Grower flow control valve. The ITRC Float Valve was installed at the inlet to the 36" inside-diameter concrete standpipe.

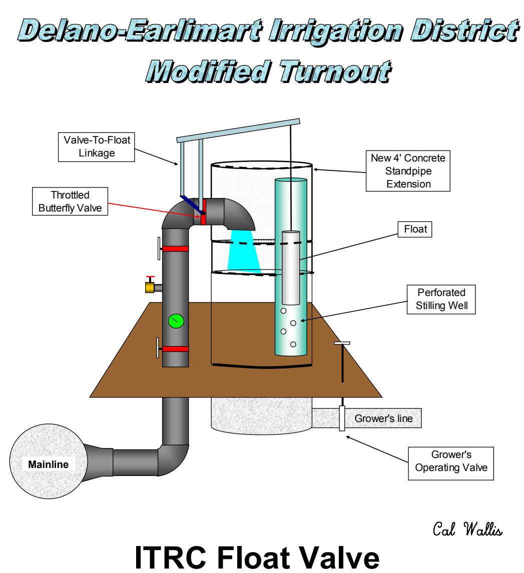

Figure 2. Turnout Configuration

After the ITRC Float Valves had been in place for some time at DEID it was determined that more research was needed on whether the speed of opening and closing valves (both ITRC Float Valves and the district's standard operational butterfly valves) has a significant effect on the pressure surges through the system. To this end, ITRC conducted two days of pressure tests in February 2004 to measure pressure surges created by different valve opening and closing speeds, and led a workshop with DEID operators to demonstrate proper techniques.

Pressure Tests

Two pressure tests were conducted at DEID to determine whether on/off valve closure speed will substantially affect surges in pressure. The flow rate was measured using a propeller flow meter upstream from the DEID operational valve. The pressure transducer for this test was installed upstream from the flow meter on the vertical section of the pipe.

The first test was performed during a preliminary test run by ITRC personnel. Five days later, ITRC personnel prepared and presented a workshop to the DEID operators. During the workshop each of the operators was allowed to close or open valves to demonstrate the effect on water hammer at different flow rates.

Pressure was measured for 55 seconds starting with the closing or opening of the valves. Throughout the test, the "standard" valve closing and opening represents the DEID accepted practice. Closing and opening of the operational (butterfly) valve and ITRC Float Valve were tested under the following conditions:

Field Check – Pressure Test 1

	Operational valve	**ITRC Float Valve**
Standard Closing	500 gpm	500 gpm
	1,000 gpm	1,000 gpm
	1,500 gpm	1,500 gpm
	2,000 gpm	2,000 gpm
Rapid Closing	250 gpm	
	500 gpm	
	1,000 gpm	
	1,500 gpm	
Rapid Opening	2,000 gpm	

Workshop – Pressure Test 2

	Operational valve	**ITRC Float Valve**
Standard Closing	500 gpm	500 gpm
	1,000 gpm	2,000 gpm
	2,000 gpm	
Rapid Closing	500 gpm	
Standard Opening	2,000 gpm	
Closing of the downstream On/Off valve		Standard closing (< 10 sec)
		Medium closing (10-30 sec)
		Very slow closing (> 30 sec)

Test Site

The pressure tests were conducted outside the DEID office from a turnout of a 30” diameter mainline. The DEID main pipeline elevation difference between the Friant Kern Canal and the district office is about 104 feet. The static pressure with no flow rate at this location is about 45 psi (conversion from 104 ft/2.31 ft per psi).

Pressure Test Equipment

Tests were conducted using a pressure transducer, scopemeter, and a portable computer. A 100 psig **Druck** pressure transducer (PDCR 900-0983) was used to measure the pressure in the inlet pipe to the standpipe. The sensitivity of the transducer is 0.10 mV/V/psi. The transducer was powered by a regulated DC power supply (Samlex RPS 1204) and the voltage adjusted to 10 volts using a potentiometer. The transducer was installed four feet upstream of the flow meter, float valve, and gear and handwheel butterfly valve.

The output signal from the transducer was recorded using the **Fluke ScopeMeter** Model No. 196. The ScopeMeter was set for amplitudes of 50 mV/division and 50 msec/division. The meter recorded data every 2 milliseconds (0.002 seconds) for a total time of 55 seconds (Figure 3). The data was transferred to a portable computer using the FlukeView program.

The **FlukeView** program Version 4.0 was installed in a portable computer connected to the ScopeMeter. The data was transferred to the computer after every run and Excel was used to process and plot the data.

Results

Data for pressure change with time were collected during each of the tests. Figure 3 is an example of the data collected from a test. Below is a description of what is happening at each of the points on the graph.

1. The test below started with a 1,500 gpm flow rate with a dynamic pressure of about 35 psi. Pressure readings were recorded every 0.002 seconds and can be seen on the graph as the blue dots. For this test, a DEID operator was instructed to close the butterfly valve located upstream of the ITRC Float Valve as quickly as possible (about 2-3 seconds). Immediately, there is a pressure surge caused by the closing of the valve and the velocity of the water that was moving down the pipeline from the source.

2. The pressure increased up to readings of 70 to 75 psi about 5 to 6 seconds after the valve was closed. These values may be too high for the concrete pipe and may be causing failures in the pipelines due to the high pressure. The maximum pressure surge was about 35 psi (75 psi-40 psi). Once the water

was stopped and the pressure surge reached its peak, the water moving towards the valve was reflected back, causing a decrease in the pressure.

3. At about 25 seconds, a severe pressure drop occurred in the pipeline resulting in a pressure that appears to be zero or even a negative pressure. Concrete pipes can handle negative pressure, but the large pressure changes may result in long-term fatigue failures in the concrete pipe.

4. At about 50 seconds, the pressures are starting to stabilize to reflect the static (no flow) pressure in the pipeline.

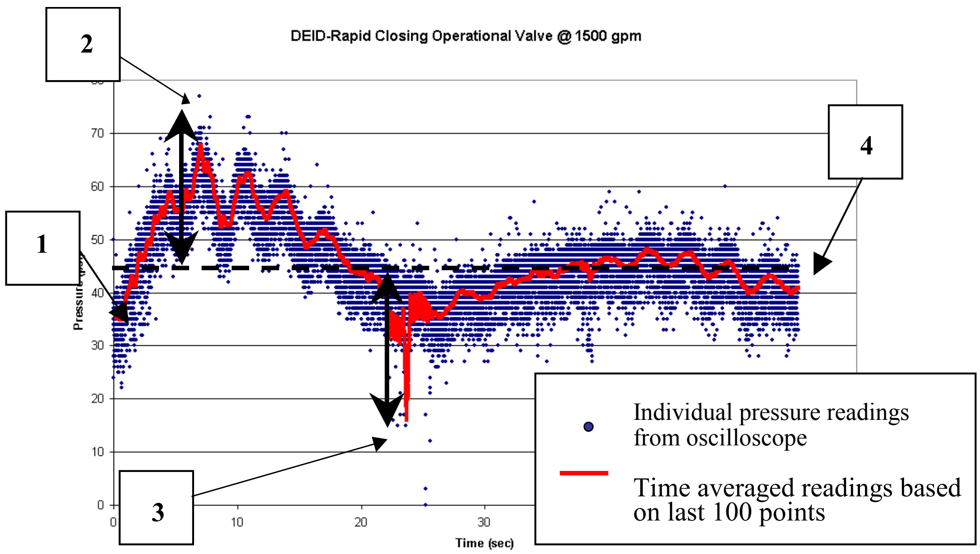

Figure 3. Graph of a Sample Test with Explanation of the Data

<u>The effect of the speed of closing a valve</u>

In order to compare the differences in hardware or the operation of the valves, several comparison graphs were created to look at two or three test results on the same graph. Figure 4 is an example of combining three field tests together on one graph. Below is a description of what is happening at each point on the graph.

1. The test below started with a 2,000 gpm flow rate with a dynamic pressure of about 25 psi. For this set of tests, a DEID operator was instructed to close the butterfly valve located downstream of the ITRC Float Valve at 3 different speeds (slow, medium, and fast). For the fast and medium closing speeds, a defined pressure surge occurs. For the slowest closing speed (the green line), there is a very small pressure surge.

2. The maximum pressure was about 68 psi when rapidly closing the line valve on the downstream side of the ITRC Float Valve. The maximum surge pressure was about 20 psi (68 psi-48 psi).

3. The maximum pressure was about 62 psi when closing the line valve on the downstream side of the ITRC Float Valve over a time period of about 15 seconds. The maximum surge pressure was about 14 psi (62 psi-48 psi).

4. At about 55 seconds, the pressures are starting to stabilize at 48 psi to reflect the static (no flow) pressure in the pipeline.

5. The pressure difference between the dynamic pressure at the beginning of the test (25 psi) and the static pressure at the end of the test (48 psi) reflect the friction losses (23 psi) at a flow rate of 2,000 gpm.

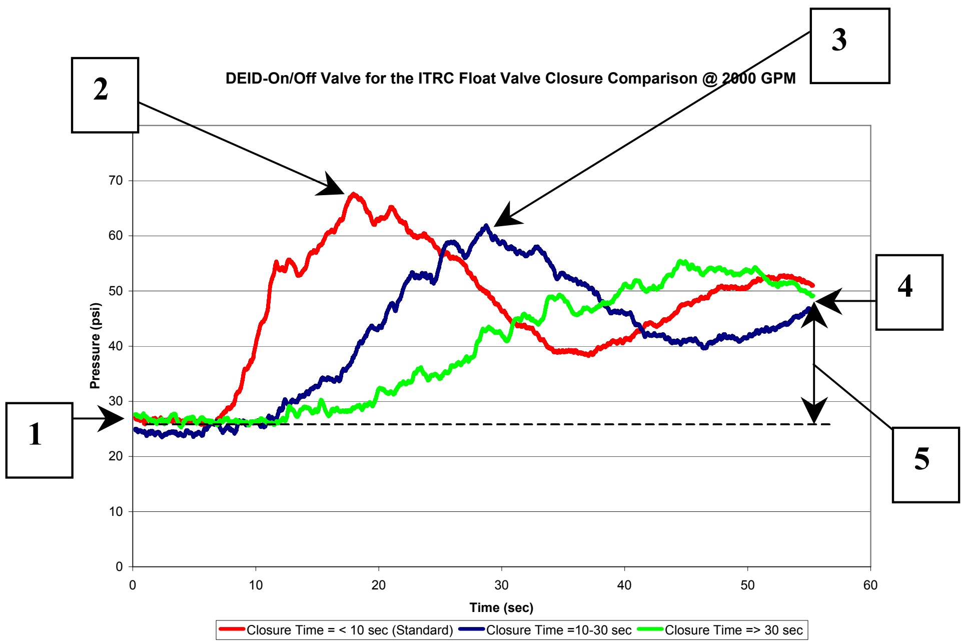

Figure 4. Comparison Between Different Times Required for the Closing of the On/Off Valve Downstream of the ITRC Float Valve. The Lines Represent a 0.2-Second Moving Average.

The graph shows a clear benefit of slowing down the closure of the valves. Even where an ITRC Float Valve has been installed, the grower should use at least 30 seconds in closing the flow control valve downstream of the Float Valve.

<u>The effect of flow rate on pressure surges</u>

The flow rate of water delivered to the farmer influences the pressure surges. Pressures were measured during standard closing of the operational valve at different flow rates (Figure 5). The results show that higher pressures and greater pressure differences were observed at higher flow rates. Note the surging of the pressure that takes place at 2,000 gpm as the valve is incrementally closed. At the end of the test, all of the lines reached a common static pressure even though they started at different dynamic pressures.

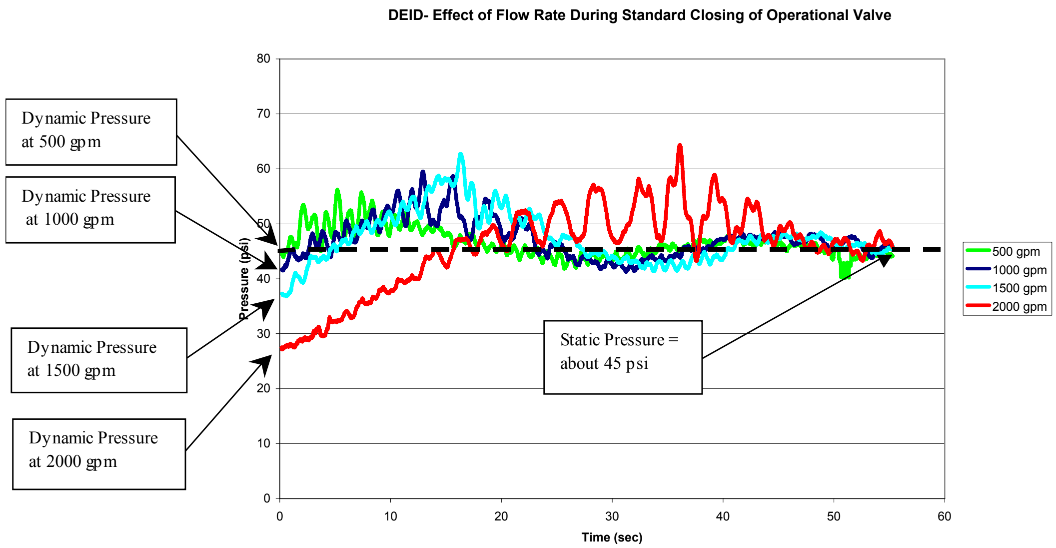

Figure 5. Comparison of Pressure Surges Caused by Different Flow Rates During Standard Closing of the Operational Valve Upstream of the ITRC Float Valve. The Lines Represent a 0.2-Second Moving Average. Operational Valve was Closed by DEID Operator.

The data indicate that much greater care must be taken at higher flow rates. The surge pressures generated at 2,000 gpm could be high enough to break a concrete pipe. The valve closure speed at 2,000 gpm should have been longer than 35 seconds.

<u>The effect of valve type on pressure surges</u>

The ITRC Float Valve reduced the rapid pressure fluctuations compared with the standard closing of the operational valve (green line in Figure 6). The ITRC Float Valve almost eliminated the rapid surge in pressure. The rapid closing of the operational valve caused high frequency (i.e. large number of waves per time) pressure waves, which continued for almost 30 seconds.

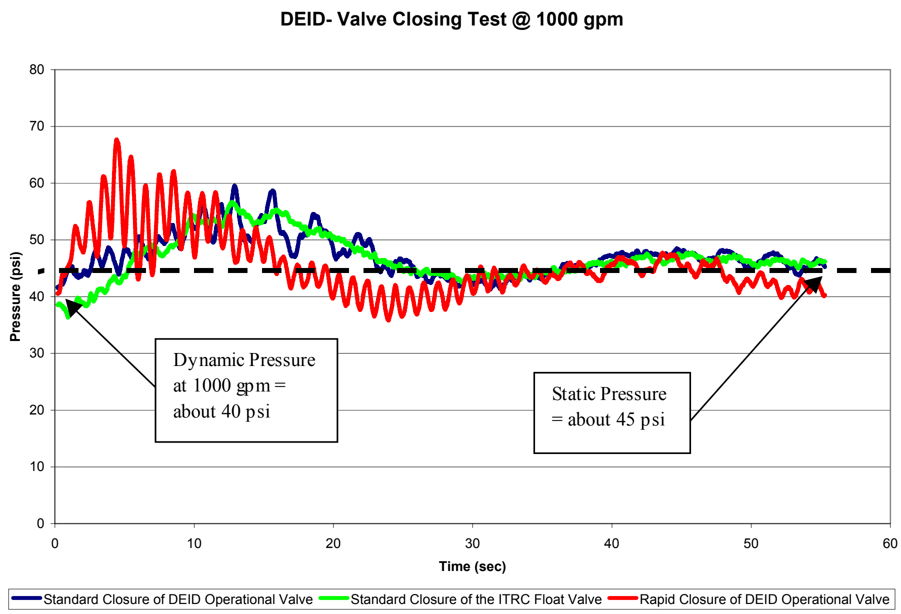

Figure 6. Comparison of ITRC Float Valve Closure versus Standard and Rapid Closure of the Operational Valve. The Lines Represent a 0.2-Second Moving Average.

The results show that the ITRC Float Valve helps to minimize pressure surges especially when an inexperienced operator closes the valve too quickly.

<u>Human operator effect on pressure surges</u>

Operators also have a significant effect on the pressure surges in the pipe (Figure 7). Two operators closed the operational valve at standard closing speed. However, one of the operators closed the valve slower (green line) than the other operator, with a closing time of almost a minute. The slower closing speed eliminated the pressure surges even at the high flow rate of 2,000 gpm.

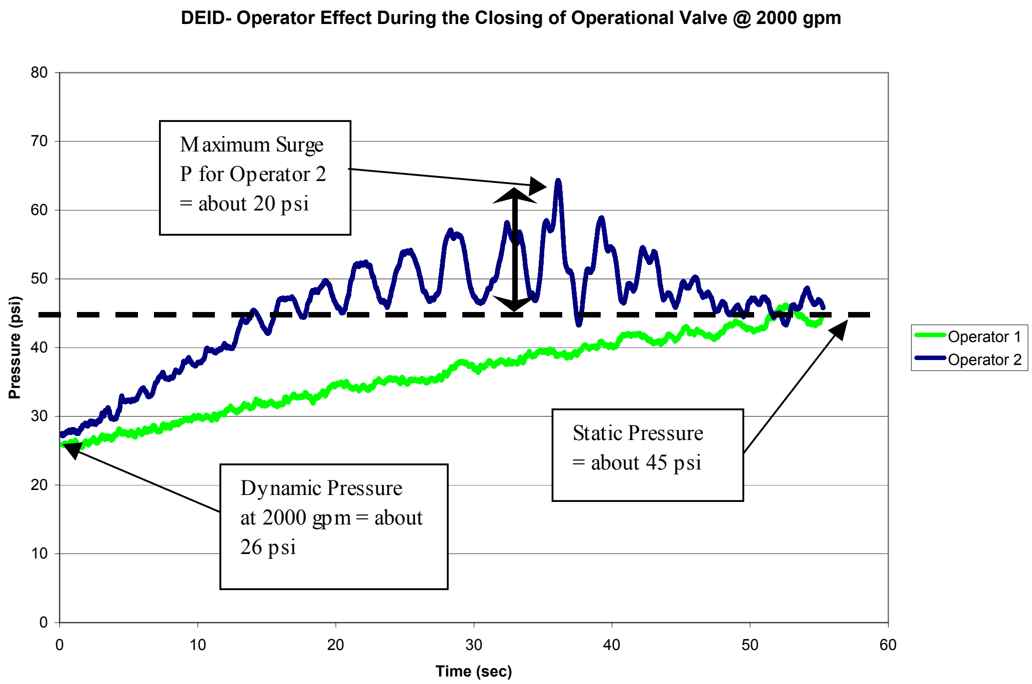

Figure 7. Comparison of Two DEID Operators During the Closure of the Operational Valve at a Flow Rate of 2,000 gpm. The Green Line Indicates a Slower Closing Speed. The Lines Represent a 0.2-Second Moving Average.

The data indicate Operator 1 probably has seen a line break due to water hammer pressure surges and took a much greater time period to close the valve. The results would tend to indicate that for high flow rates, the minimum closure time should be at least 1 minute for turnouts that do not have an ITRC Float Valve installed.

Conclusions

From this set of tests run at DEID, the following conclusions were made:

- Rapid closure of either the grower flow control valve or the DEID operational on/off valve will cause pressure surges high enough to create damage to the concrete pipelines at DEID. Care should always be taken when closing the manual valves at DEID even if an ITRC Float Valve has been installed.

- Based on the pressure tests conducted at DEID, the ITRC Float Valve significantly reduced the pressure surges during water deliveries. The ITRC Float Valve eliminated the high frequency pressure surges. The overall pressure surge was further reduced by increasing the time required to close the On/Off valve downstream of the ITRC Float Valve.

- The rapid closure of the DEID operational valve caused high frequency pressure surges even at flow rates as low as 500 gpm. Standard DEID closure time caused some pressure surges at the turnout. The pressure surges were considerably reduced when the operator took more than a minute to close the valve.

- Pressure tests conducted during the opening of the DEID operational valve also recorded pressure surges and significant negative pressures within the line. The opening of a valve should follow the same rules as the closing of a valve.

Recommendations

ITRC recommends the following items to minimize water hammer pressure surges and to reduce the pressure variations during the closing or opening of the valves:

1) ITRC Float Valves should be installed at turnouts where growers want to operate their own valves for flow rate control. The district operational on/off valve handle should be locked or removed to prevent being used by unauthorized personnel.

2) The time required for a grower closing or opening the flow control valve downstream of the ITRC Float Valve must be at least 30 seconds. The grower should use his watch to time the valve movement.

3) For those sites with only a standard operational valve, the time required for closing or opening the valve must be at least 1 minute. The operator should use his watch to time the valve movement.

Reference:

Gaudi, Franklin. 2001. Evaluation and Modification of a Float Valve for the Delano Earlimart Irrigation District (DEID). Senior Project. California Polytechnic State University. San Luis Obispo, CA 93407.

IRRIGATION INFRASTRUCTURE REHABILITATION IN ALBERTA; 35 YEARS OF GOVERNMENT/INDUSTRY COOPERATION

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ABSTRACT

Alberta has 1.63 million (661,000 ha) of agricultural irrigation (over 60% of Canada's total) with 1.34 million acres (542,000 ha) in 13 irrigation districts. The districts are privately operated and under the control of the irrigators who pay water rates based on the acres assessed for irrigation. The irrigators elect a Board of Directors to manage the district.

Since 1969, the Government of Alberta's Department of Agriculture, Food and Rural Development (AAFRD) and the irrigation districts have participated in a unique cost shared program to rehabilitate the irrigation water delivery infrastructure, some of which was initially constructed over 100 years ago. Over $630,000,000 (Cdn) has been allocated to cost shared projects within the districts under this program.

In addition to the benefit of grants to the irrigation districts, these programs have allowed Alberta to develop a world-class water distribution system that serves the needs of the irrigation districts as well as municipalities, industries, recreation users and wildlife. Innovative design and construction technologies and products have been developed that are now in common use in Alberta and other areas of the world.

Irrigation districts and contractors have developed methods of rehabilitation that conserve water, improve management and can be constructed in the adverse weather conditions common during Alberta's fall and winter construction periods. Manufacturers developed products to fit the industry, such as large diameter PVC pressure pipe, automated gates and specialized precast concrete structures. Engineers developed unique technologies such as overshot gates, remote control and data collection systems for level control, flow control and canal automation. Some of these products have also found applications in industries other than irrigation.

The assurance of a dependable and efficient water delivery infrastructure has not only benefited the primary producers but also the economy of southern Alberta in particular, and Canada in general, with large agri-business ventures locating new or expanded facilities within the irrigated areas of southern Alberta. Organizations such as Ducks Unlimited reaped the benefits of an assured water supply as they developed areas for wildlife habitat.

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INTRODUCTION

In order to understand irrigation in Alberta, it is important to understand the area, the historical background of irrigation and the evolution of the present legislative, financial and administrative confines under which irrigation districts operate.

Alberta accounts for over 60% of Canada's agricultural irrigation. Irrigated land in Alberta currently totals over 1.63 million acres (661,000 ha) with over 80% of that contained within irrigation districts. This area represents only about 4% of Alberta's cultivated land but is responsible for approximately 20% of the province's gross agricultural production.

Alberta's cultivated soils are generally well suited to agriculture, but unique in that the underlying parent material is glacial till, this being one of the few areas of the world where these soils are irrigated. Topography varies from a rolling terrain in the area near the mountains to relatively flat plains in southeastern Alberta.

The region is classed as semi-arid. Sunshine is one of the more stable climatic features, with southeastern Alberta having the most hours of sunshine in Canada. Although this is one of the drier and hotter areas of Canada, only one crop per season is possible. The crops grown under irrigation are shown in Table 1.

Table 1: Irrigated Crops in Alberta's Irrigation Districts (acres)

Crop	1979 [a]	2004 [b]	Change
Wheat (soft, durum, hard spring, CPS, winter)	220,127	229,130	4.1%
Barley (grain, silage & malt)	199,004	255,004	28.1%
Canola	66,233	114,541	**72.9%**
Other grains & oilseeds	77,770	22,759	-70.7%
Corn (silage, sweet and grain)	22,610	42,380	**87.4%**
Alfalfa & hay (all types for feed)	224,943	318,782	41.7%
Pasture (all types)	86,166	138,263	60.5%
Other forages & silages	7,383	27,258	**269.2%**
Alfalfa & grass seed	6,546	14,346	**119.2%**
Potatoes (including seed)	11,396	41,095	**260.6%**
Sugar Beets	32,474	34,993	7.8%
Peas & beans	25,350	63,033	**148.7%**
Other specialty crops (turf, nursery, mint, market gardens, sunflower, etc.)	3,079	11,715	280.5%
Miscellaneous or unspecified	4,994	17,917	258.8%
Total crops	**988,075**	**1,331,216**	**34.7%**
Summer fallow or non-crop	21,878	8,545	-60.9%

a) Source: Thiessen & Smith, 1981

b) Source: AAFRD Irrigation Branch, "Alberta Irrigation Information", 2004

Alberta has 13 irrigation districts, all in southern Alberta, ranging in size from less than 1,300 acres (500 ha) to over 360,000 acres (146,000 ha). In 2004 there were 1,339,760 acres (542,190 ha) on the assessment rolls. The six largest districts account for over 90% of the total. Each district is independently controlled by the irrigators (farmers) and operates as a quasi-municipal body. The provincial *Irrigation Districts Act* sets the framework under which irrigation districts operate and each district holds a water license issued according to the provincial *Water Act*.

The irrigators elect a Board of Directors who hires staff to operate and maintain the district. The larger districts also maintain an engineering and/or construction department to do design and construction work.

This paper describes how, over the past 35 years, the Government of Alberta, the irrigation districts and private industry (consultants, manufacturers, contractors) have worked together to create world-class water distribution infrastructure for the benefit of all Albertans.

HISTORY

Western Canada has a long history with irrigation. Books by Gilpin (2000), Topham (1982) and Freeman (1994) and papers presented by Thiessen & Smith (1981) and Craig (1987) document that history very well. The historical summary presented here draws extensively on those three documents.

The first irrigation in western Canada was in 1858 out of Humbug Creek in British Columbia. Alberta followed in 1877 with a private scheme from Fish Creek, now in the south part of Calgary. Southern Alberta, because of its harsh climate and sparse vegetation was slow to attract settlers, and it was not until the completion of the transcontinental railroad that much development occurred.

The first major “project” to be developed was in the Raymond/Magrath/Lethbridge area from a diversion on the St. Mary River at Kimball. Between August 1898 and July 1900 approximately 115 miles (185 km) of canal were dug, moving over 1.1 million yd^3 (840,000 m^3) of earth. Prospective settlers were assured that a two-room house could be built for $150, that land was available for $5/acre and that there were employment opportunities with the local coal company. By 1911 about 50,000 acres (20,000 ha) were irrigated.

The Canadian Pacific Railway (CPR) completed Canada’s trans-continental railway in 1885 and received a land grant of 25 million acres (10 million ha) for doing so. In 1903 William A. Pearce, Superintendent of Mines for the Dominion Government, convinced the CPR to select the remainder of the land grant earned for railway construction in one large block between Calgary and Medicine Hat. By 1910 the CPR had developed irrigation works in the Western section (east of Calgary) and by 1914 in the Eastern section (surrounding Brooks).

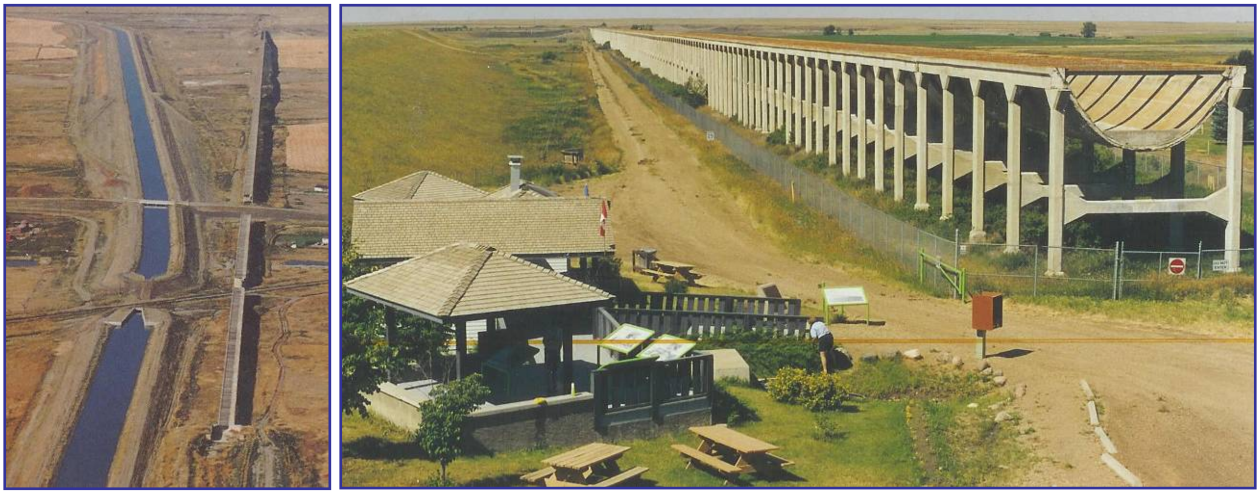


Figure 1: Brooks Aqueducts (Original on the right of each photo. Replacement on the left)

One of the most significant irrigation structures in North America was built in the Eastern section during that time. The Brooks aqueduct was perhaps the greatest challenge faced by the CPR engineers. Built across a two mile wide, 60-foot deep (3.2 km wide, 18 m deep) valley, this reinforced concrete barrel flume, interrupted in its middle by an inverted siphon to accommodate the railway line, was beset by problems from the beginning. It was later described by R.T. White, former Eastern Irrigation District (EID) General Manager as ".... an engineer's dream and an operator's nightmare". In 1979 the concrete aqueduct was replaced by a canal, constructed in a huge earth fill built across the valley (Figure 1).

Another significant irrigation structure was built in the Western section during that time. In 1904 construction began on a diversion weir across the Bow River in what is now Calgary.

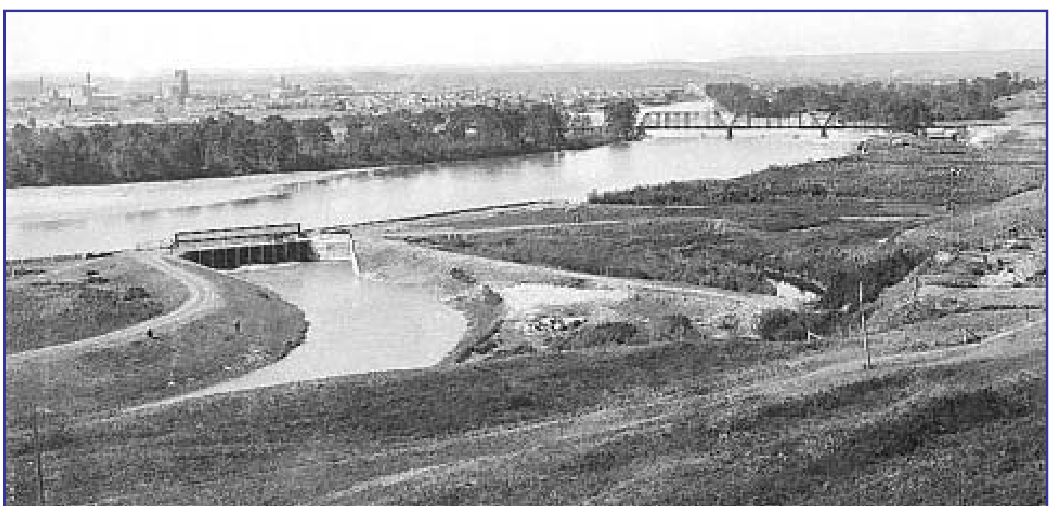


Figure 2: Bow River Diversion (Glenbow Museum Photo)

It has been said that, at the time, this diversion was the second largest in the world, second only to a diversion on the Nile River in Egypt. Work progressed on this diversion weir and the main canal (Figure 2) for what is now the Western Irrigation District and in 1905 Reservoir #1 (Chestermere Lake) was filled with water for the first time.

Figure 3: Irrigation Construction in the Early 1900's (Glenbow Museum Photo)

In his 1994 book documenting the history of the Western Irrigation District George Freeman stated:

> *"It is of interest to consider this situation in today's terms. With modern equipment we would have quite a problem accomplishing what had been done with horses and fresnos. At one time during the peak of the irrigation construction there were 450 men and 400 teams of horses employed on contract work while a further 300 men and 60 teams of horses were working on operation and maintenance of the ditches. With modern bureaucracy, we would still be staggering through the mountains of paperwork which would have developed and, in that time, we would not have moved a shovelful of earth. It must be remembered, however, that there were no obstacles other than the topography to interfere with the construction and it was possible to proceed across the terrain under the direction of the contours only, without interference from man-made impediments or government bureaucracy."*

Starting with the formation of the Taber Irrigation District in 1915 and the Lethbridge Northern Irrigation District in 1919, farmer owned organizations were the dominant force for the next three decades.

Following World War II, the era of government involvement in irrigation development began. In 1935, the federal government formed the Prairie Farm Rehabilitation Administration (PFRA) and it assumed a dominant role. From 1948 to 1972 the PFRA built eight large dams (Shady, 1989) including the St. Mary Dam, creating the first major on-stream irrigation storage reservoir.

The role of the provincial governments in water management is significant in Canada. In 1930, Canada turned over all interests in natural resources to the provinces. This included water, forests, coal, oil and natural gas. Therefore, responsibility for water resources falls on the provinces, not the federal government. The federal government retained jurisdiction for matters of navigation, fisheries and international treaties governing watersheds. In Alberta, ownership of the oil and natural gas reserves has had significant financial benefit.

With the provinces having the responsibility for water, they are very active in irrigation. On the Canadian prairies (Alberta, Saskatchewan and Manitoba) much of the natural water in the rivers begins as snowfall on the east slopes of the Rocky Mountains and flows easterly to Hudson's Bay. The Prairie Province Water Board, formed in 1948, insures that each province gets its fair share of the water available. By agreement, 50% of the water available in one province (e.g. Alberta) must be allowed to flow to the neighboring province (e.g. Saskatchewan).

IRRIGATION REHABILITATION PROGRAM DEVELOPMENT

Up to the late 1960's, irrigation development had gone through three phases: Company, Irrigation District and Government. The Prairie Farm Rehabilitation Agency (Agriculture and Agri-Food Canada) participated to a large extent in irrigation rehabilitation in Alberta until 1973.

This paper concentrates on the newest "fourth stage". The self-managed irrigation districts, governed by Provincial legislation, operate and maintain irrigation works and rehabilitate these works, with Alberta Agriculture, Food and Rural Development (AAFRD) providing the major share of rehabilitation funding.

Alberta Environment (AENV) owns and operates many multi-purpose water resource projects (head works, dams, reservoirs and canals). These head works also provide water to the irrigation districts that own and operate the downstream infrastructure. The Alberta government, on behalf of AENV, has constructed many major provincially owned and operated works as well as some irrigation district owned main canals and storage reservoirs. The last major AENV projects completed were Oldman River Dam and the St. Mary Dam spillway replacement. The province is currently invested millions of dollars annually in the rehabilitation of the Carseland-Bow River Headworks system, another key AENV owned and operated system.

Figure 4: Old Wooden Control Structure

In the late 1960's, the province and the irrigation districts started to rebuild the irrigation distribution systems owned by the districts under cost sharing agreements. The need for a rehabilitation program with a major contribution from a senior level of government was clearly demonstrated by the deteriorated condition of irrigation works, partly due to inadequate or lack of maintenance.

Many canals were eroded while others had siltation or weed and tree growth, which restricted the flow carrying capacity. It was estimated that up to 10% of the total irrigated area was affected by salinity due to seepage from canals. Wooden drop and check structures were badly deteriorated (Figure 4) and there were periods of interrupted water delivery due to failure of some portion of the distribution system. The irrigated acreage had increased significantly which created capacity problems in many areas.

A 1967 federal Agriculture Rehabilitation and Development Act (ARDA) study showed that the benefits of irrigation accrued 14% to the irrigation farmer, 41 % to the surrounding municipality and the province (Alberta) and 45% to the country (Canada) as a whole (Freeman, 1994). Based on this study and, with Alberta assuming the governments' role, the first cost shared Irrigation Capital Works (ICW) Program was based on an 86% contribution by Alberta. The districts (farmers) provided the other 14% from their general revenues. A unique aspect of the program was that it was to fund rehabilitation of both large and small projects in all 13 districts.

In the first year, AAFRD allocated $584,000 to the districts. The money was distributed among the districts on the basis of acres on the assessment rolls. AAFRD engineers provided the engineering for all projects in the early years. In the years following the program continued in various forms for 5-year increments. A later economic study (AIPA, 1984) suggested an 85/15% ratio and was instrumental in convincing the government to continue the cost-shared program. Methods of allocating the funds among districts varied over the years. The annual grants have varied from under a million to $30 million (Figure 5).

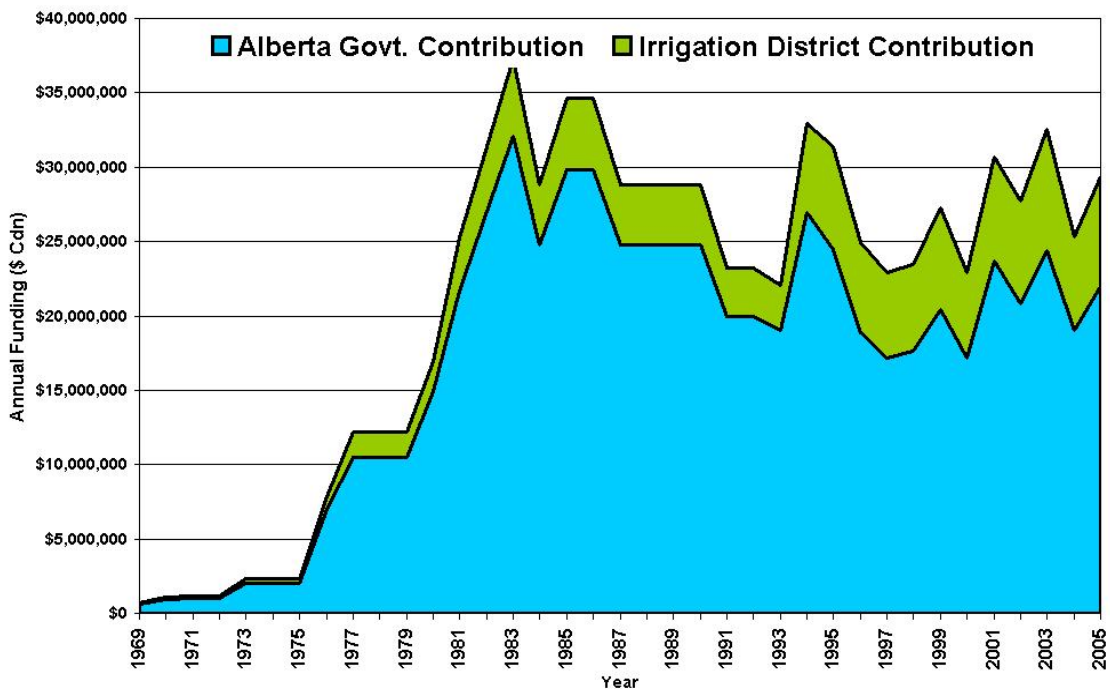


Figure 5: Historical Levels of Irrigation District Rehabilitation Funding

Prior to 1995 rehabilitation programs were for five-year intervals with no assurance that they would be renewed. This made long range planning difficult for some districts. In 1995 a new era of irrigation rehabilitation began. After public consultation by a legislative committee, the provincial government adopted the current Irrigation Rehabilitation Program (IRP). The program became long range in nature with the cost sharing changed to 75/25%, similar to other Alberta government cost shared infrastructure programs. One senior government official is said to have made the comparison that funding this infrastructure is like funding highway construction, since these canals and pipelines deliver water to our communities, just like highways deliver other commodities.

The present level of funding is $22 million annually. The available base funding is distributed among the 13 irrigation districts based on the number of acres they serve and the amount of infrastructure (replacement value) they own and operate. In some years, special capital funding is provided to individual districts for special projects, which address critical and/or unique issues.

Funds are dispersed according to Irrigation Rehabilitation Financing Agreements entered into annually by each district and the Alberta government. Engineering is now done by private consulting engineers or by irrigation district engineering staff according to standards developed by the industry (Alberta Agriculture, 1991).

Annual Rolling Three-Year Plans are prepared by each irrigation district and submitted for approval to the Irrigation Council. In those plans the districts provide detailed information on the projects they plan to start during the upcoming construction year, and those “New Year One” projects are reviewed and approved for funding by the Irrigation Council. The Irrigation Council is a body appointed by the Minister of AAFRD and is currently made up of five public members (generally farmers with irrigation district experience) and one representative each from AAFRD and AENV. Once approved, the new projects may proceed with design and construction by private contractors or the district.

TECHNICAL EVOLUTION AND INNOVATION

Figure 6: Centre Pivot System on Canola

Before one considers the improvements made within the irrigation districts, it must be acknowledged that in Alberta, as in many other parts of the world, the irrigation farmer himself has adopted many technical innovations. Mechanization replaced labor, with sprinkler irrigation now used on 83% of the area within the districts (up from 70% in 1999). Center pivots account for over 61 % (up from 40% in 1999) of the irrigation in the districts. More land is irrigated with less water and less land is damaged due to over irrigation or salinity.

The irrigation district’s responsibility for water supply ends at the farm turnout. No funds from the government are used for the operation and maintenance of the districts and these grants are not given to individual farmers. Cost shared funds are only used to rehabilitate the water delivery infrastructure within the districts.

Early district rehabilitation projects consisted mainly of rebuilding the canal banks or opening up the canal cross-section by cleaning and replacing critical control structures. Few projects included seepage control, gravel armour slope protection or pipelines because of the cost. With no guarantee of funding beyond the five-year intervals, efforts were often concentrated at fixing the worst spots here and there, rather than rehabilitating complete laterals in a planned fashion.

As the rehabilitation program matured into a long-term program, and after most of the large capacity problems were handled, the standards used for rehabilitation design and construction (Alberta Agriculture, 1991) were improved. Control structures were upgraded, many with electrically operated gates, some automated. Pipeline systems were introduced. These improvements were an attempt to make the projects last 50 years and improve water and land use efficiencies and, where possible, align canals along legal boundaries.

Membrane Lined Canals

Originally, little was done to control seepage from canals. The build up of saline soil and waterlogged conditions adjacent to canals prompted the development of seepage control methods.

The first attempts at linings involved polyethylene (PE) membranes but extensive damage resulted from the loss of cover due to erosion, livestock, external hydrostatic pressures and by mechanical equipment during installation and maintenance. Weeds established themselves on the liner cover and maintenance costs related to aquatic and canal bank weed control were not reduced.

Experience has shown that, where membrane linings are needed, they must be protected by non-erosive cover materials. Modern reinforced PE or a poly-vinyl chloride (PVC) liners use gravel armour slope protection for erosion control.

Numerous methods of installing liners have been used. The two most common are:

1) The canal is over-excavated, and the liner is installed and covered with gravel (Figure 7). This method has proven to work very well where the canal banks are good and where gravel is readily available.

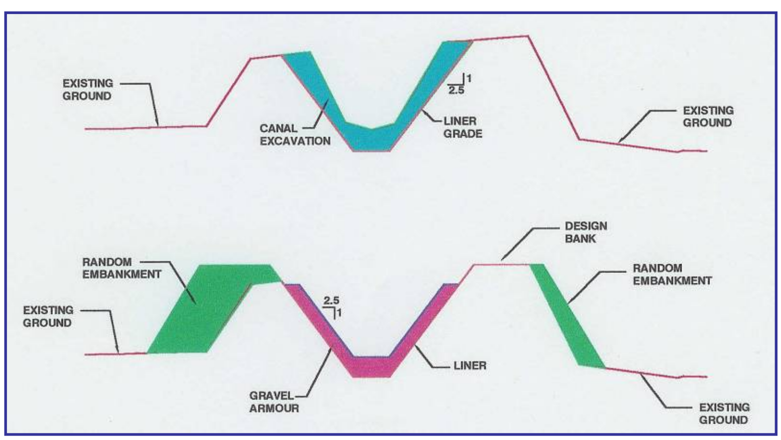


Figure 7: Gravel Armour Placed Directly Over the Liner

2) The canal is over-excavated using this material to rebuild the outside half of the canal banks. The liner is then installed and a compacted clay fill material placed on the liner with dozers and compactors. The canal side slopes have gravel armour slope protection placed on them (Figure 8). This method is preferred but costly if the banks are in good condition. If the existing banks are in poor condition, this method can be cost effective.

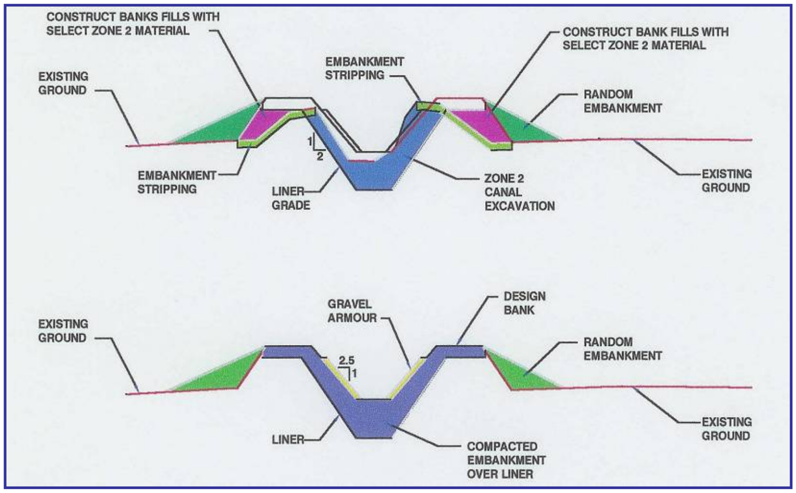


Figure 8: Gravel Armour Over Compacted Fill Over Liner

Other exposed liners have been tried including synthetic rubber, prefabricated asphalt or aluminum sheeting and fiberglass-reinforced polyester. Spray-on asphalt and sulphur have also been tried on an experimental basis. Tests have shown that, for a variety of reasons, these materials are not a practical method of seepage control.

Interceptor Drains

Where high groundwater is present, vertical plastic cutoff curtains and tile drains have been effectively used. Open interceptor drains are not practical due to extensive land requirements and high maintenance costs. Interior and/or exterior cutoff walls utilizing plastic lining and gravel chimneys with tile drains are used. On those areas involving high water tables, interceptor drains control seepage to adjacent lands, whether it results from natural flows (high water tables) or canal seepage.

Concrete Lining

Concrete lining was installed in about 180 miles (300 km) of irrigation canals from 1970 to 1988. In Alberta, un-reinforced concrete lining proved unsatisfactory due to extensive cracking which occurred as a result of wet soil conditions in the fall, followed by the cold winter and corresponding frost action (Figure 9). In the late 80's, methods of adding reinforcing to the concrete lining (Figure 10) were developed and these proved effective. However with the advent of larger diameter pressure rated PVC pipe, concrete lining is no longer used in Alberta.

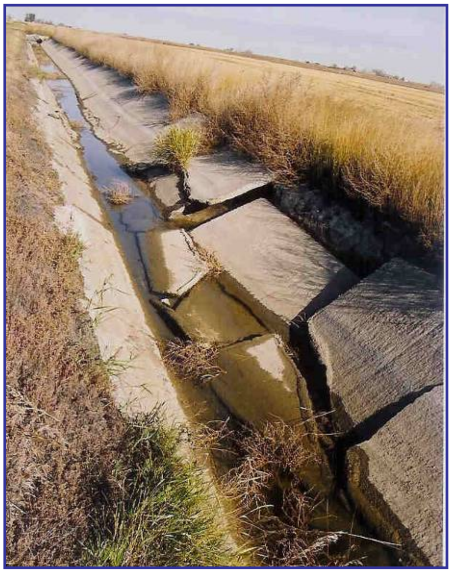


Figure 9: Failed Concrete Lining

Figure 10: Installing Reinforced Concrete Lining

Gravel Armour (Slope Erosion Protection)

Most canals that are rehabilitated today have gravel armour slope protection included, whether or not liners are used. This is expensive (\$20-\$26/yd^3, \$15-\$20/m^3) but is likely the best utilization of funds on a project. Figure 11 shows a 20-year-old canal that was only partially armoured. The portion with armour is in excellent shape while the rest is not. Gravel armour at least doubles the life expectancy of a canal.

Numerous studies have been done with gravel armour to determine what side slopes can be used. It was found that 2.5:1 (H:V) to be the optimum; 3:1 was better but only marginally and at a high cost. While 2:1 worked in many cases in small canals, the potential for slope failure on large canals may be too great to be acceptable. Depths of armour vary from 6-8" (150-200 mm) for armour on earth material to 8-12" (200-300 mm) for armour placed directly on membrane liners.

Figure 11: Armoured and Un-armoured Portions of a 20-Year Old Canal

Studies have been done to determine the acceptable gradation of gravel. It has been found that material with too many fines does not work well. Some geotechnical people believe there should be some fines but the districts have found that if the material below 1/4" (6 mm) and above 8" (200 mm) is screened out from a well graded pit run gravel, the armour produced will work very well and is affordable because it can be produced by simply screening the raw product.

CANA Construction[5], a Calgary contractor, designed a large machine for placing membrane liners and gravel armour at the same time in large canals (Figure 12). The machine was effective, but was limited in its application, so now all canal work is done with large backhoes (see Figure 20: Winter Construction).

Figure 12: Canal Liner/Armour Placement Machine

Control Structures

Historically, gates on irrigation structures have been undershot gates. Small flows were controlled with cast iron or fabricated steel gates and large flows were controlled with radial gates. This worked well for flow control structures such as reservoir outlet structures and canal turnouts, but worked poorly for canal check structures where upstream water level control was required. Operators wrestled with the problem of using radial gates as check structures. These have the disadvantage of not passing flood flows easily and thereby there is the danger of overtopping canal banks when flood or surge flows arrive at a structure.

To allow for flood flows, radial gate check structures were often constructed with stop log side bays to assist in level control. This was an improvement in level control but required a much wider structure and created the additional operational problems common with the use of stop logs.

To overcome the limitations of undershot gates for upstream level control two “overshot gates” were developed; the drop leaf gate and the Langemann Gate. These have the advantage of allowing surge or flood flows to pass through the structure without overtopping the canal banks while checking water. They work well for upstream level control, and it is now standard practice to use overshot gates for level control and undershot gates for turnout flow control. This combination has the advantage of maintaining a relatively constant main canal level and delivering relatively constant delivery flow rates to the laterals (and hence the irrigators), regardless of the flow rate in the main canal.

[5] Note: The use of brand names and company names is for the convenience of the reader and does not imply any endorsement by the authors.

Drop Leaf Gate: The overshot drop leaf gate (a modified crest gate) was first used in Alberta in 1983. It was developed to simplify the control of the upstream water level at check structures. The gate is a flat panel that is hinged on the bottom and a twin cable hoist is used to raise and lower the top edge. Drop leaf gates have been typically fabricated using welded steel (painted or galvanized), but some have been fabricated using aluminum or stainless steel. Typical drop leaf gates (Figure 13) are fabricated using a steel faceplate, wide flange or channel top girder, angle bottom girder and HSS or channel beams. A fabricated hinge with a bronze hinge rod is bolted to the structure sill. Local steel fabricators can easily manufacture drop leaf gates.

Figure 13: Typical Drop Leaf Gates

Figure 14: Large Drop Leaf Gate Hoist

Armtec Water Control Products markets hoists and drop leaf gates. Other suppliers have occasionally supplied hoists, but Armtec have developed a standard line of single and double gearbox hoists.

Cost of the drop leaf gate is affected greatly by the size of the gate hoist (Figure 14). Traditional hoists with large drum-cable ratios (greater than 24:1) are expensive due to the large torque generated by the drum. Standard practice is to use a 12:1 or 16:1 drum-cable ratio. Ratios as small as 10:1 are being used and the first drop leaf gate used an 8:1 drum-cable ratio. A manually operated drop leaf gate and hoist costs approximately $100/ft^2 ($1,100/m^2). The same gate with a 120VAC electric hoist (Rotork actuator) costs approximately $140/ft^2 ($1,500/m^2).

The drop leaf gate has been very successful and most check structures are now constructed with drop leaf gates. Older check structures with radial gates have been retrofitted with drop leaf gates. Initial concerns about silt deposition upstream of the gate, cable corrosion and weed buildup have been shown to be unfounded. At high flows (low gate positions), bed load travels over the gate and does not accumulate. Cable life has been very good. Galvanized cables will last in excess of 20 years. Aquatic weed accumulation on the cables has been a minor problem, but the gate typically passes weeds over the gate rather than accumulating at the gate.

The drop leaf gate has also been utilized for flow measurement. It provides reasonably accurate flow values but needs to be calibrated. The main difficulty is the error induced by cable stretch, top beam deflection, and inaccuracies in the gate position measurement (potentiometer and analog/digital conversion). The discharge co-efficient changes as a function of gate angle but research in Alberta and Arizona has developed calibration equations based on the gate angle.

Figure 15: Langemann Gate in an 800 cfs (23 m^3/s) Canal – Upstream & Downstream View

Langemann Gate: The Langemann gate (named after its inventor, a southern Alberta irrigation farmer) is a modification of the drop leaf gate. It was originally developed as a flow control for turnout applications. Whereas the drop leaf gate uses a single hinge with the top edge traveling in an arc as the gate rises, the Langemann gate uses two hinges and the top edge travels in the vertical direction only (Figure 15). This provides better control of the gate height and improves the flow measurement accuracy. It also requires less power as the gate does not have to lift the mass of water that exists on top of a drop leaf gate. Aqua Systems 2000 Inc. has marketed this gate since 1995.

This gate can be configured to operate for upstream level control (with or without automation) but it can also be configured for flow control with a patented flow controller. Since it requires little power to raise the gate, it is ideally suited for solar panel/battery operation. It is also especially well suited for retrofitting into the stop log guides of an existing structure and can replace radial gates in existing structures with minimal need for structural modifications.

Precast Concrete Structures

The IRP has provided Alberta precast concrete firms with the opportunity to develop precast irrigation structures. With construction restricted to late fall, winter and early spring, contractors are required to maximize productivity during adverse weather. Freezing conditions favor rapid construction techniques.

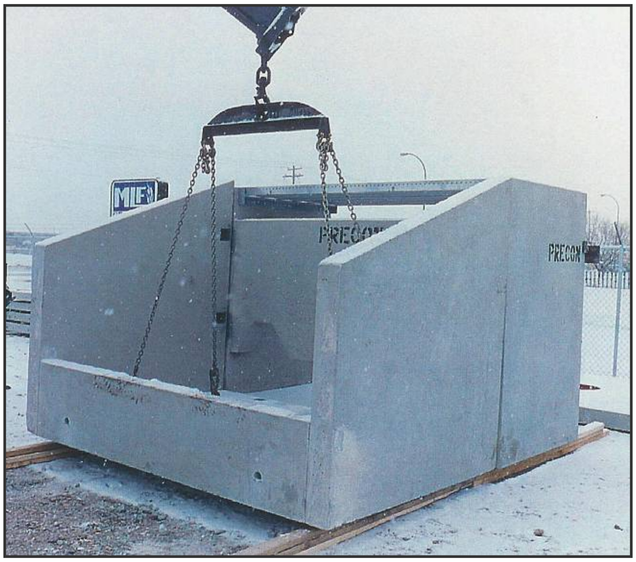


Figure 16: Precast Impact Baffle

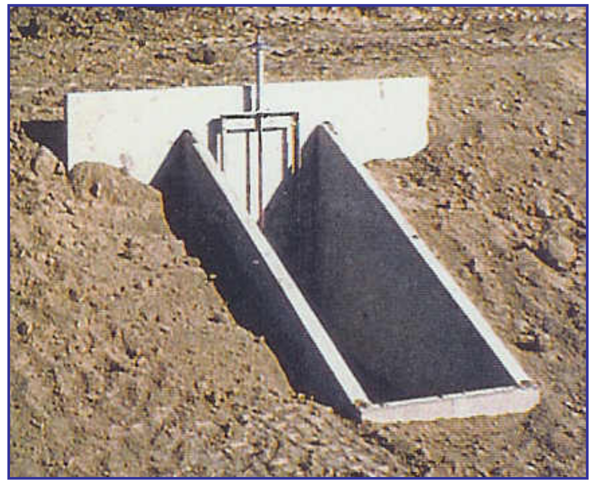


Figure 17: Precast Turnout Structure

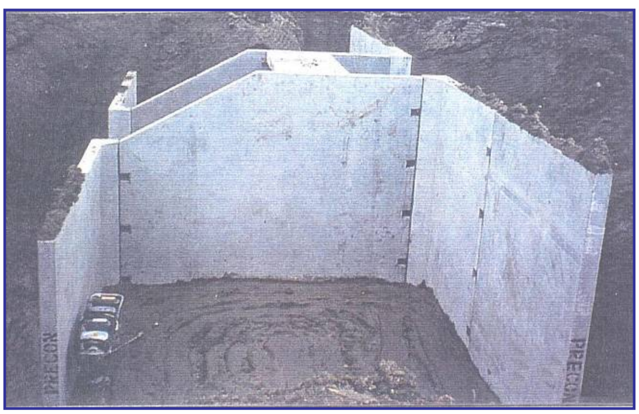


Figure 18: Precast Check/Drop Structure

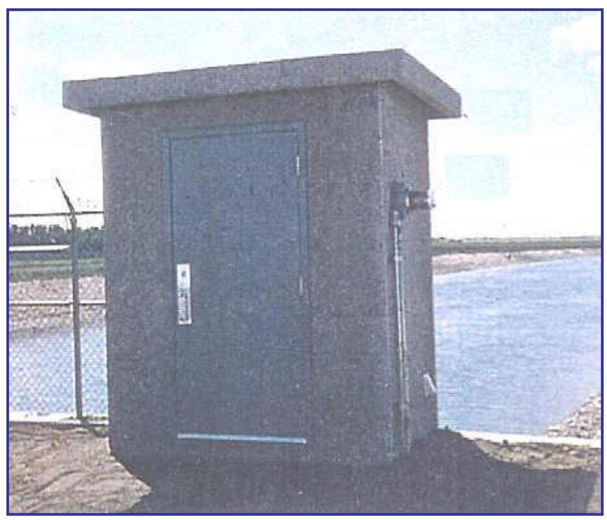


Figure 19: Precast Control Building

Precast concrete is well suited to this type of working environment since the concrete does not have to be poured in freezing weather and most precast structures can be installed and backfilled in one or two days instead of weeks for cast-in-place structures. For smaller structures (<150 cfs, <4.2m^3/s), precast structures are also significantly less expensive than cast-in-place structures.

The major supplier of precast concrete irrigation structures, Precon Precast Products has developed standard control buildings, check structures, check-drop structures, drop structures, impact baffles structures, turnout structures, multi-panel vaults, pipeline inlets, pump stations, and vaults (Figures 16 to 19).

Cold Weather Construction Methods

Cold weather construction in very wet environments and at remote locations can be trying and expensive. Since the canals are in use from May through October, construction generally cannot start until November and must be completed by April. The cold, wet environment in which rehabilitation takes place necessitates both special construction techniques and design considerations.

Figure 20: Winter Canal Construction

Winter construction of reinforced concrete structures requires heated or insulated enclosures. Earth canal construction is often done quickly in small reaches (Figure 20). The canal is over-excavated and work is completed on each short reach within 24 hours so that frozen material is not being worked with.

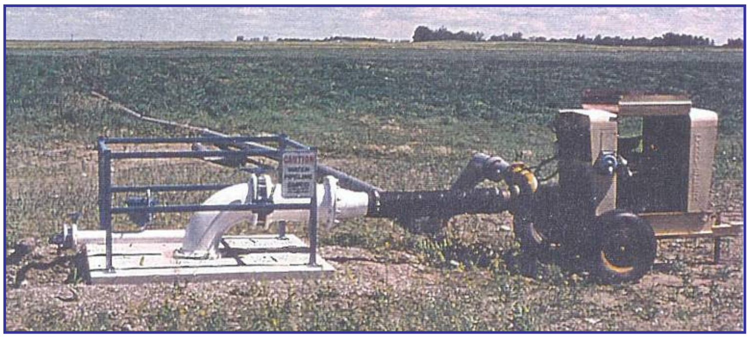
Pipelines

Pipeline water distribution systems are the logical choice for the smaller supply laterals, particularly where steep topography works to the disadvantage of canals and to the advantage of pipelines. Where steep slopes were the biggest problems in the early years (erosion, numerous drop structures, etc.), those districts with the steep slopes are now the ones best able to use pipelines. In many cases pipelines are even a cheaper alternative. The farmer on the bottom of the ditch who used to have to deal with all of the variations in flows now usually has the highest pressure available at his turnout. Common materials for pipelines include concrete, reinforced concrete, steel cylinder concrete, high-density polyethylene (HDPE) and poly-vinyl chloride (PVC).

Pipelines have become the preferred method of rehabilitation because they reduce operational spills, control seepage, eliminate farm severance and bring more land under production, thereby increasing the production and cash value of farmland.

PE and PVC pipe came on the scene in the early 1980's. Initial problems with excessive deflection in PE pipe resulted from poor backfill methods. However, once proper backfill methods were developed the problems were overcome. Both PE and PVC proved successful for pipelines but the technology of manufacturing PVC pressure pipe in sizes up 48" (1,200 mm) has offered the industry the most economical piping option, when the total cost of materials and installation are considered.

With PVC pipelines being used almost exclusively, the irrigation districts asked PVC manufacturers to make larger PVC pipe available, so that larger canals and canals with flatter grades could be converted to pipe, and the industry responded (see Program Benefits section).



Steel farm turnouts were designed which allowed pumps to be connected directly to the pipeline (Figure 21). The farmer takes advantage of any pressure that is supplied. Some districts levy a surcharge (e.g. 12¢/psi, 1.7¢/kPa) for the pressure supplied to the irrigators.

Figure 21: Combination Pump Turnout (right) and Household Turnout (left)

In a few cases, centralized pump stations supply sufficient pressure to operate all the sprinkler systems on a particular lateral (Figure 22).

Figure 22: Centralized Irrigation District Pumping Station

Some districts use standardized turnout designs (Figure 21), ordered in mass each year to reduce cost. This standardization also has advantages when future maintenance is required. The standard design has a small outlet for household deliveries on all turnouts. This has proven to be a very successful option, as users often want a household delivery at some future date.

The turnouts are often equipped with combination air/vacuum valves and thermally activated valves to prevent frost damage in the spring and fall. Initially epoxy coated steel fittings were used but these corroded. Now cathodic protection (sacrificial anodes) and tape wrap are used on almost all buried steel fittings. Engineers developed design and construction methods to ensure high quality pipelines. These involve pressure tests after construction, use of accurate roughness coefficients for design purposes, settling reservoirs and trash racks at inlet structures.

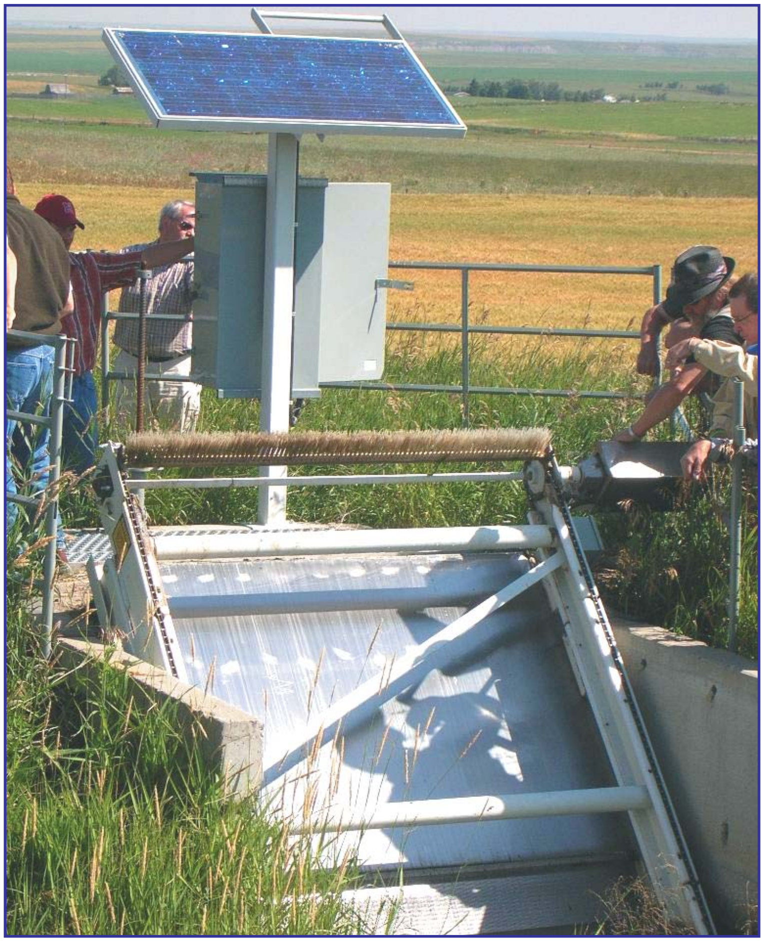


Figure 23: Solar Powered Pipeline Self-cleaning Inlet Screen

Settling reservoirs remove silt and debris before water enters pipelines and are sized according to the particle settling requirements. Trash racks often have automated solar powered weed screens to keep them cleaned off. (Figure 23)

Low head C361 reinforced concrete pipe is used for some irrigation pipelines. This initially proved unsuitable due to problems with bell and spigot joints. Manufacturers developed the R4 joint, which involved reinforcing extending into the bell and spigot. This has proved satisfactory for low-pressure applications.

Pipelines have also been used successfully for spillways. Two types of energy dissipaters are incorporated; one utilizes a hanging baffle concrete structure and the other involves an open-ended vertical steel or concrete riser pipe.

Change in Rehabilitation Methods

Over the years, many types of rehabilitation have been and are being used. Figure 24 shows how buried pipelines have become the rehabilitation method of choice with over 80% of the annual rehabilitation (by length) now done with pipelines.

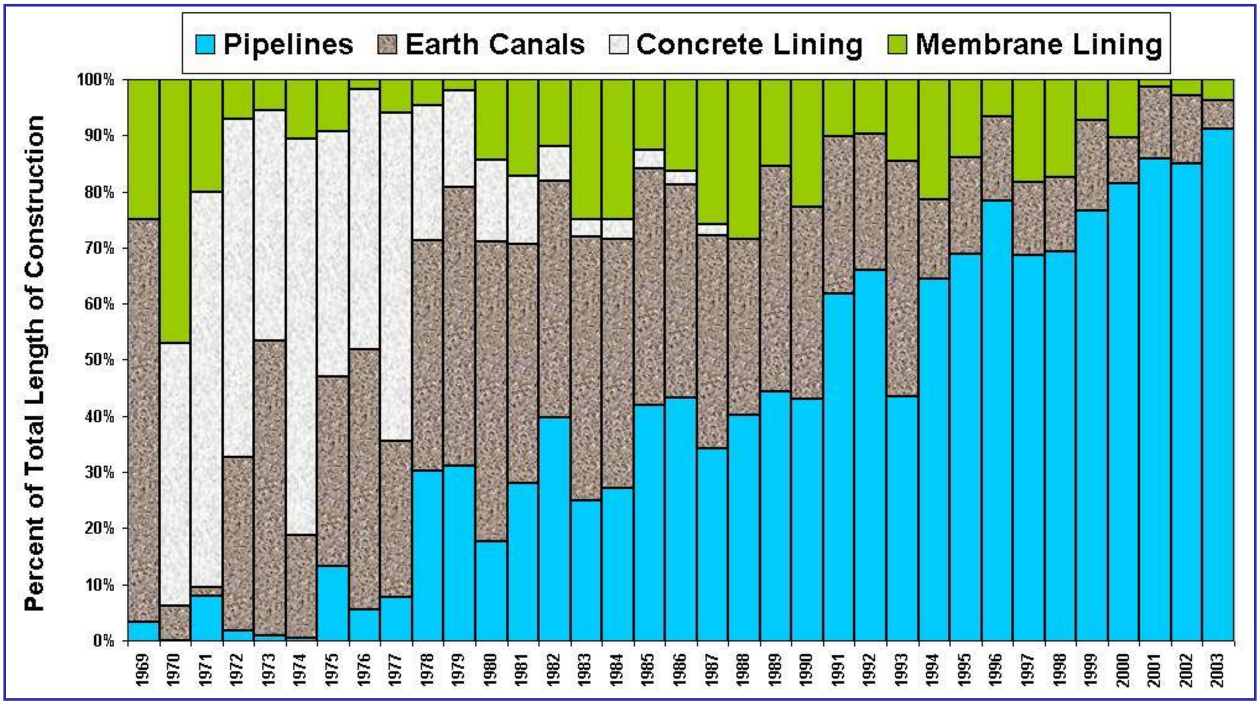


Figure 24: Rehabilitation Methods Used in Alberta

Remote Control and Automation

In this paper "remote monitoring" refers to systems where the conditions at a site (flow, gate position, water level, etc.) can be monitored from a remote location by radio, telephone or other method. "Remote control" is an added level of control and allows an operator to control devices from a remote location. Remote monitoring and remote control systems are both common in irrigation districts.

"Automation" refers to devices, which are controlled automatically, without human intervention, according to defined algorithms and make adjustments according to changing conditions. This may occur on-site, or may be controlled by a remote computer or other control system that is in communication with the site. The latter case results in a "remote control, automated site" where the control settings can be changed from the remote location.

Often irrigation district personnel can operate a remote control site (automated or not) from home or from the field using a modem equipped laptop computer.

Automation has been an integral part of irrigation rehabilitation in Alberta and has included pump control, reservoir control, upstream level control, downstream flow control, and

Supervisory Control and Data Acquisition (SCADA). Current trends are towards more central control and automated water ordering systems.

Figure 25: Automated (120VAC) Check/Drop Structure

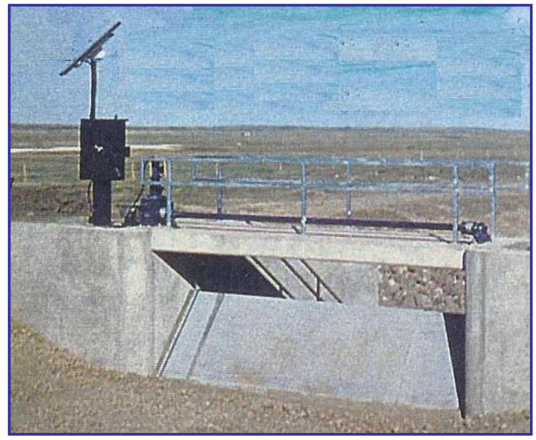


Figure 26: Automated (24VDC Solar) Check/Drop Structure

The first irrigation remote control was implemented in 1980 at an irrigation pump station. Controls consisted of remote access to the site with capability to turn pumps on and off and determine pump status. This was followed in 1982 with reservoir level control at Stafford Reservoir and then rapidly followed with upstream level control automation at drop leaf gate structures.

Early automation efforts utilized simple control algorithms and lookup tables due to hardware limitations. Subsequent efforts, using powerful control hardware, utilized Proportional Control and Proportional Integral Derivative (PID) control loops for better control response.

Considerable effort was spent optimizing the control algorithms to minimize gate movements and still achieve desired control limits. This is particularly important when using the limited energy available at solar powered sites (Figure 26). Best results were obtained where scale models were tested hydraulically to see how well they fit the proposed control algorithms, prior to implementation in the field.

The greatest success has been achieved with the simplest automated sites. All complex installations have suffered from development problems, control algorithm behavior and nuisance alarms. C.M. Burt (2004) documented similar experiences in the U.S.A. and as he stated: "*. . . more than anything else, perhaps the failures were caused by lack of attention to detail. In irrigation automation, the devil is in the details.*"

Programmable logic controllers (PLC's) and personal computers (PC's) are both being used for irrigation control. Gate positions are usually measured using multi-turn potentiometers with 12 bit analog-digital (A-D) converters. A few gates have been installed with optical encoders. Water level is measured with differential pressure transducers or ultrasonic level transmitters. Many districts monitor all return flow and inflow channels using Lakewood data loggers and

Miltronics probes. Even small irrigation districts have made use of this automated data collection technology (Figure 27).

Figure 27: Return Flow Monitoring: Mountain View Irrigation District

Inter-site and central site communication has typically been via telephone lines or radio links where sites are relatively close. SCADA systems have been developed utilizing radio, phone line and Internet data transmission and control. Consideration is now being given to data transmission via satellite. Both real time control and periodic communication connection have been used between sites and central offices. Graphical User Interfaces (GUI's) have been used to simplify information presentation and display site information.

Gate automation usually utilizes fail-safe alarm systems. Several efforts were made to achieve downstream flow control but to date; none have been satisfactory due to control algorithm limitations.

Equipment reliability has been a big issue and the major problem has been power surges due to lightning storms. A present trend is to use solar-cell-recharged 12 or 24 VDC batteries for powering gates and control equipment (Figure 26). This may improve equipment reliability and has the advantage of lower cost at small sites, especially those return flow measurement sites that are at remote locations.

BENEFITS OF THE IRRIGATION REHABILITATION PROGRAM

Farmers

The irrigation farmers benefit greatly. They have a reliable water distribution system that is effective and efficient. More land is in production as pipelines replace canals. As canals are relocated along legal boundaries, larger more effective irrigation and other farm equipment can be used. The amount of land affected by seepage and salinity has been greatly reduced. More land is served with the limited water supply and farmers who have pressurized water available see their annual pumping energy bills reduced. Closed pipelines also give irrigators more flexibility in how the water is delivered to them. This is a key need for modern automated farm irrigation farmers, as documented by C. M. Burt (2004).

Irrigation Districts

Irrigation districts have a system in place that is easier to operate, less expensive to maintain and makes more efficient use of water. Irrigation districts can now serve more acres with the limited amount of water they are allocated. These improvements were made possible, partly as a result of funds provided by the province.

Public at Large

Many communities rely on irrigation districts to supply their municipal water. They benefit from a more reliable water supply. Industry has located in Alberta providing jobs and value added processing. Water based recreational facilities abound in southern Alberta, most of which rely on irrigation water. Fish and wildlife groups have water in areas of the province, which previously had none. The North American Waterfowl Management Program bestows its “Blue Heron Award” on those who make a great contribution to the protection of waterfowl in North America. In Alberta, only four groups have received that award. They are the Western, Eastern, Bow River and St. Mary River Irrigation Districts, a testament to the fact that in addition to delivering water, Alberta’s irrigation districts are also faithful stewards of the environment.

Private Industry

The benefits of the IRP extend well beyond the irrigated area of Alberta and many Alberta companies have benefited directly from the IRP. Precast concrete manufacturers, suppliers of raw materials, earth moving and pipeline contractors, consulting engineers and many others have a significant portion of their annual income from irrigation district rehabilitation.

The case of an Alberta manufacturer of PVC pipe could be used as a case study of what the program means to industry.

IPEX Inc. is a manufacturer of, among other things, PVC pressure pipe. IPEX was formed in 1992 with the merger of Scepter Mfg. and the pipe division of Canron. An IPEX vice-president saw opportunities in larger diameter pipe and surveyed Alberta’s irrigation districts and responded to a challenge by the Eastern Irrigation District, which was basically “Build it, and we will buy it!” (Swihart, 1997)

As a result the company began making 30" (750 mm) pipe in 1987, 36" (900 mm) pipe in 1989, 42" (1,100 mm) pipe in 1998 and 48" (1,200 mm) pipe in 1999. Irrigation districts in Alberta have utilized all these sizes (Figure 28).

The large diameter pressure pipe, born to serve the irrigation market, now serves a varied market in North America and the world. The manufacturing of this large pipe aids greatly in keeping the plant, which has expanded from 75 to 130 employees, running year round and provides additional security to those employed at the plant. Without the large diameter pipe used by the irrigation districts, some of the employees would be laid off at certain times of the year.

A study prepared for IPEX showed the significant impact irrigation construction in general, and pipeline purchases in particular, has in Canada. For every $1 spent purchasing pipe, Alberta’s gross domestic product increased by 82 cents and Alberta’s labor income increased by 39 cents. Every million dollars spent on PVC pipe annually supports 12 jobs, half in the Edmonton manufacturing plant and half in associated industries. For every $100 spent on PVC pipe it was estimated that direct and indirect personal taxes paid to the province increased $5 and those personal taxes paid to the federal government increased $9.

IPEX's pipe manufacturing plant is located in Edmonton, over 250 miles (400 km) from the center of irrigation in Alberta. Edmonton is the site of the provincial government where the decisions regarding funding are made and it helps to have this excellent example of the economic impact of irrigation in the city.

Figure 28: Installing Large Diameter PVC Pressure Pipe

Another example of private industry involvement involves two of the North America's largest produces of frozen french fried potatoes. Within a period of months, Lamb Weston (a ConAgra company) and McCain Foods Limited, both announced they were building new french fry processing facilities in southern Alberta. Lamb Weston built its $100 million facility east of Taber and McCain Foods followed with its $94 million facility located between Coaldale and Taber. An example of the spin off benefits of these two plants is demonstrated by a Taber trucking firm purchasing 14 new semi-trailer units and the opening of a new truck-trailer repair business in this town of 8,000 people. In addition, Rogers Sugar Co. has recently invested tens of millions of dollars upgrading its sugar beet processing facilities, also in Taber.

The world class water distribution system, created in part with funds provided by Alberta's IRP, ensures that irrigation farmers will have the water to grow the crops needed by the local food processing facilities and ensures that these facilities will also have a suitable supply of water for use in processing the products.

Well aware of agriculture's contribution to the history of Alberta and its future contribution to the economic well being of the province, Premier Ralph Klein was on hand to officially help turn the sod for the Lamb Weston plant. At the time, he indicated that rather than enticing industry with direct grants, Alberta prefers to market what has commonly been called the "Alberta Advantage". By that we mean Alberta has a skilled, technically trained work force, the infrastructure (including water distribution infrastructure) and affordable energy necessary for industries to compete on the world scale and a tax structure that promotes private enterprise.

The Fraser Institute (established in 1974 as an independent public policy organization in Vancouver, BC) added data on the 10 Canadian provinces to data on 46 states contained in a US study conducted by the Cato Institute to monitor the fiscal performance of those states and provinces. The study focused on fiscally effective government, the general economic climate and assessed the tax and expenditure behavior of those governments in North America. Of the 56 jurisdictions monitored, Alberta finished in first place. Perhaps Alberta's commitment to assisting to provide a reliable and effective water distribution system to the irrigation districts, communities, recreational facilities and wildlife habitat in southern Alberta played a small role in Alberta's placing in that study.

OTHER ALBERTA INITIATIVES

"Water for Life" Strategy

Recognizing the importance of its water resources, Alberta has gone a long way towards developing a comprehensive strategy that will identify short, medium and long-term plans to effectively manage the quantity and quality of the province's water systems and supply.

In Alberta, like most irrigated areas of the world, irrigation is by far the largest consumptive user of water. Therefore the results of this strategy could have a major impact on the irrigation industry.

Water for Life: Alberta's Strategy for Sustainability develops a new water management approach and outline specific strategies and actions to address the province's water issues.

The *Water For Life* strategy is based on three key goals, or outcomes:

- Safe, secure drinking water supply,
- Healthy aquatic ecosystems, and
- Reliable, quality water supplies for a sustainable economy.

The latter outcome is of particular interest to the irrigation industry. In order to achieve that goal, Alberta is inventorying all potential water storage sites that have been studied in the past and using tools included in the *Water Act* to achieve efficient and effective use of water.

Because water is vital to all Albertans, in all areas and communities across the province, the Government of Alberta consulted with Albertans on the challenges and priorities for water management and supply, and sought fresh ideas for responsible solutions to those challenges.

This process is very similar to that suggested by Smith (2004) in a paper presented at the Irrigation Association's Technical Conference that year.

The consultation process had three major components. The first phase was completed in early 2002 when a small, diverse group identified the challenges associated with managing water in the province and several opportunities for improving it. These ideas provided the framework for the second stage of the process, where key stakeholders and all Albertans were invited to respond to the initial directions proposed by the ideas group. The third stage in the process was a Minister's Forum on Water, held in June of 2002. The forum involved 108 invited Albertans and experts.

Working with a panel of experts on water issues, Alberta Environment compiled the ideas and feedback heard through all three levels of the consultation process and developing a series of recommendations and a framework that serve as the provincial water strategy for sustainability.

As part of implementing the Water Strategy, the province has created the Alberta Water Council to advise the government on water management issues. At the basin level, Watershed Planning and Advisory Councils have been created and local Watershed Stewardship Groups are also active making improvements to their local lakes and streams.

Throughout the process the irrigation community has been well represented and, in many ways, been leaders in educating the public as to the value of water and the need to use it as efficiently and effectively as possible. With the improvements made both on-farm and in the irrigation infrastructure, the irrigation industry can show how they are now irrigating far more acres and producing far more crops while, at the same time, taking less water per acre out of the rivers than they did 20 years ago.

More information on "Water for Life – Alberta's Strategy for Sustainability" can be found at:

www.waterforlife.gov.ab.ca

Capital Planning Initiative (CPI)

Another unique Alberta initiative resulted from its decision, beginning in 1997, to develop a provincial wide capital planning strategy. Almost all governments are being subjected to increasing demands for funding for major physical infrastructure (roads, schools, health facilities, colleges & universities, water management infrastructure, etc.). The common issues of aging infrastructure and growth pressures (particularly in Alberta) might suggest the simple solution is simply to spend more money. However funds, in all jurisdictions are limited, so it is imperative that a systematic approach be used to identify the needs and plot a suitable course of action.

The key component of the CPI is to look at all types of infrastructure whether it is government owned (highways and major water resource infrastructure) or government supported (schools, health facilities and irrigation district infrastructure). This was viewed as a much better approach than just targeting the "big ticket" items (e.g. health and education).

All participants in the process were asked to develop an Infrastructure Management System (IMS) for their infrastructure. Again the irrigation districts of Alberta answered the call and, with assistance from AAFRD's Irrigation Branch, they developed and completed a complete IMS which not only catalogued all of the infrastructure owned and operated by the 13 irrigation districts, they also determined the infrastructure replacement cost, condition, utilization and functional adequacy of that infrastructure. The irrigation district IMS database is updated annually. In this way the funding needed to maintain the $2.5 billion worth of infrastructure can be calculated and the needs of irrigation infrastructure (even though it makes up less than 3% of the total infrastructure included in the CPI) is being adequately considered, along with the huge needs of schools, highways and health facilities.

In addition to assisting the irrigation industry in documenting its needs, the CPI process has proven to be a valuable way to shown other Albertans, most of who are not familiar with irrigation, what the value of that infrastructure is and what a large segment of the population it serves in one way or another.

CONCLUSION

This cost shared Irrigation Rehabilitation Program has worked extremely well over the years and provided the irrigation districts with the means to develop world-class infrastructure. Technology developed and used in Alberta has been exported to other areas of North America and the world.

The irrigation districts and Alberta Government have worked together for 35 years to develop that system, but much is still to be done. Some districts still have much of the district to rehabilitate and some work that was done (e.g. un-reinforced concrete lining) needs to be redone as better technology becomes available.

In many different ways the Government of Alberta has recognized the value of irrigation and took on the challenge issued by the irrigation districts. The road has not been easy and with fewer Albertans involved in agriculture all the time (even far less in irrigated agriculture), there were detractors along the way. As Alberta celebrates it centennial in 2005, our faith in irrigation seems to have been justified as we see crop production and processing of produce that is far beyond what our forefathers may have envisioned. The long-range program that is now in place has served us well and will continue to serve Alberta, and all of Canada, into the future.

REFERENCES

AAFRD Irrigation Branch, May 2005, “Alberta Irrigation Information – 2004”

Alberta Agriculture, October 1991, “Engineering Standards for Design and Construction of Projects Funded Under the Irrigation Rehabilitation and Expansion Program”

AIPA (Alberta Irrigation Projects Association), April 1984, “Irrigation Development in Alberta - The Economic Impact”, by Underwood McLellan Ltd., Lethbridge, AB

Burt, C. M., 2004, “Completing the Connection Between Irrigation Districts and On-Farm Irrigation”, Irrigation Association, 2004 Conference Proceedings

Craig, K. R., June 1987, “Irrigation in Alberta: Past, Present & Future”, Presented to the Annual Convention of the Association of Professional Engineers, Geologists and Geophysicists of Alberta (APEGGA).

Freeman, George, 1994, “Flow Beyond the Weir”, Written on the 50th anniversary of the Western Irrigation District

Gilpin, John F., 2000, “Quenching the Prairie Thirst – A History of the Magrath Irrigation District, Raymond Irrigation District, Taber Irrigation District, St. Mary River Irrigation District”

Shady, Aly M., June 1989, “Irrigation, Drainage and Flood Control in Canada”, Canadian International Development Agency, Hull, Quebec

Smith, MaryLou M., 2004, “Consensus Building as a Primary Tool to Resolve Water Supply Conflicts”, Irrigation Association, 2004 Conference Proceedings

Swihart, Ric, May 9, 1997, Lethbridge Herald news article, Lethbridge, AB

Thiessen, J. W. and Smith, R. F., 1981, “Modernizing Irrigation Systems in Alberta, Canada”, Presented to the 11th Congress on Irrigation and Drainage, Grenoble, France

Topham, Harvey L., 1982, “History of Irrigation in Western Canada”, Prairie Farm Rehabilitation Administration, Agriculture Canada

RELATED INTERNET SITES

www.agric.gov.ab.ca	AAFRD "Ropin' the Web"
www.waterforlife.gov.ab.ca	Alberta Environment's Water Strategy
www.aipa.org	Alberta Irrigation Projects Association
www.aquasystems.com	Aqua Systems 2000 Inc.
www.armtec.com/watercontrol	Armtec: Water Control Products
www.brid.ab.ca	Bow River Irrigation District
www.eidnet.org/local/aqueduct/	Brooks Aqueduct Official Home Page
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www.glenbow.org	Glenbow Museum
www.ipexinc.com	IPEX, Inc.
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www.smrid.ab.ca	St. Mary River Irrigation District
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ECO-IRRIGATION: AN EBB AND FLOW SYSTEM FOR LARGE SCALE COMMERCIAL APPLICATIONS

From the dawn of civilization until slightly over a century ago, the sole form of irrigation was subsurface. Water was allowed to enter a planted field, and then drained. From Mesopotamia to the Nile Valley to the plains of India, food supplies were irrigated by drainage ditches and natural flooding. Surface water from accumulated rain or snow was the only water source. During the last hundred years, with the advent of deep wells, pumps, and engines, mankind gained the ability to remove vast quantities of aquifer water. This technology has allowed for various types of high-pressure irrigation systems, such as micro- and spray irrigation. Until the last two decades, the aquifer was generally considered an inexhaustible source, and the use of surface water assumed a secondary role in many areas. Now that worldwide population has exploded and water consumption has dramatically increased, fresh water supplies are becoming very taxed. Because agriculture consumes the majority of the world's fresh water, it is essential to reconsider any method of conserving water in crop production.

The single largest limitation for the application of modern irrigation technology, from a water source point of view, is the fact that most water applied to crops is not utilized by the plant; the excess water either evaporates, runs off into surface water, or slowly leaches back into the aquifer system. This water is unavoidably contaminated by agricultural runoff or non-point-source pollution.

Seven years ago, after spending several years in the containerized horticultural nursery business near Orlando, Florida, I was feeling very unhappy with our systems of microjet and overhead spray irrigation. These systems presented so many difficulties with pumps, filters, emitters, and water distribution that I began to explore the possibility of locating another, better method. I reviewed the practice of sub-irrigation in ancient times, recalling as I did that my mother had watered her patio plants from the bottom up, by pouring water into the saucer every several days.

In order to test this method of irrigation, three baby swimming pools were set up for experimentation; and large containerized plants were placed in two of the pools, while a water source was established in the third pool, or reservoir. A small pump was used to fill the plant-containing pools nearly to the tops of the containers, and then the water from the plant-containing pools was drained back into the reservoir. To my great surprise, plants irrigated by this technique required markedly less frequent irrigations; the plants not only thrived, but appeared to grow more quickly than with the conventional overhead or micro-irrigation systems that we employed at our tree farm. All sub-irrigated plants were wetted equally, and the medium was saturated with each irrigation event.

In order to evaluate the saturation of the containers in the three methods of irrigation—sub-irrigation, microjet, and overhead—the plants were weighed before and after irrigation. The plants that were sub-irrigated consistently gained more weight during the irrigation cycle than did those that were microjet or spray irrigated. Interestingly, those plants that were irrigated by microjet or spray were then sub-irrigated, with a significant increase in weight. These facts convinced us that field capacity was not being reached with our current irrigation practices. With a subsurface irrigation cycle, there was no maldistribution of water, and each plant container weighed the same after an irrigation event. Rather than watering twice a day, we used this irrigation technique about every two or three days; and the plants thrived.

While exploring the idea of rain harvesting and water reuse as an alternative irrigation method, I designed a system of rain harvesting by covering a five-acre contoured field with polyethylene liner, and separating the area into several irrigation beds along with a large collecting reservoir. Rainwater accumulated over the entire polyethylene-lined area and drained into the lined reservoir, from which a low-pressure pump supplied water to the plant bays. Gravity was used to drain the water after the desired depth was achieved. This created a closed-loop system that harvested and stored rain, and prevented non-point-source pollution.

For the next two years, data was carefully collected. To my surprise, rain harvesting resulted in more collected water than the plants on the system could use; and we began to supply other portions of our nursery with this surplus water. Even though all the agricultural effluent was collected, there was no significant increase in total dissolvable solids, and no accumulation of toxic herbicides, insecticides, heavy metals, or other byproducts. Algae growth was intermittent; and since we had introduced herbivorous fish—tilapia—into the reservoir, there were no weeds and the algae was quickly consumed. Ospreys and herons were noted to harvest the fish, and have continued to do so. This, we believe, completed the cycle of the removal of any increased salts or nitrates.

Because of the excellent results on the smaller five-acre system, this rain harvesting and sub-irrigation system has been increased to approximately sixteen acres, and several plant crops have been raised and harvested.

In Florida, we have rainfall of about 53” per year; and even during our severe drought that ended about two years ago, we had no need of aquifer water to irrigate our plants on the subsurface system. Where rain exceeds 30” per year, no other water source is considered necessary. Even though we have heavy evaporation losses in Florida, those losses are essentially confined to the surface of the reservoir, allowing a huge net increase in the water surplus from rain harvesting.

The amount of water necessary to irrigate, by conventional methods, an acre of ornamental horticultural product in containers, is between three and six million gallons per acre per year. Six million gallons of water is a cube measuring approximately 90’ per side.

The amount of rainfall over a small area is astounding. As an example, on a 200-acre farm in Central Florida, enough rain falls annually to float ten large aircraft carriers. This rain-harvested water can be repeatedly re-used by either subsurface technology, microjet systems, or overhead sprays. We prefer subsurface irrigation, for reasons that I shall explain in a moment.

Some may ask whether aquifer recharging is prevented by covering a recharge area with a polyethylene liner, thus preventing a certain percentage of rainfall from returning to the aquifer. In Florida, where annual rainfall per acre is about 1½ million gallons, approximately 20% of the rainfall, or 300,000 gallons, reaches the aquifer. When the land is covered by an impermeable membrane such as that used in this system, the tradeoff is greatly in favor of rain harvesting, which prevents the withdrawal of some 3 to 6 million gallons of water per acre per year from the aquifer—the approximate amount used for micro-irrigation or overhead spray systems.

The advantages of sub-irrigation include: 1) reduction in weeds (because the top layer of soil is wetted only by rains, and not by irrigation water); 2) reduction in fungal foliage disease because of reduced foliar wetting (and therefore a dramatic reduction in the necessity for fungicides); 3) marked reduction in insects because of reflected light from the white liner (thus reducing the necessity for insecticides); 4) a dramatic savings in labor when contrasted to micro-irrigation, since there are no emitters to check or repair, no filters to change, and no small pipes and tubes (which in our area are likely to be chewed open by rabbits); 5) more uniform crops than with conventional irrigation methods, since the containers are all equally saturated with each irrigation event. In addition, we believe that fertilizer use will be reduced: the reason for this is that with each sub-irrigation event, the water in the container rises and falls, carrying with it the fertilizer molecules that—instead of constant leaching from top-down irrigation—are made more accessible to the plant roots. Perhaps as great an advantage as any is that a grower can be guaranteed of 100% effectiveness of the irrigation, by simply looking across the field, noting the water level, and knowing that all plants are equally irrigated.

The disadvantage of the system lies primarily in two areas. The first, and perhaps most important, is the necessary change in farming habits. The second is the expense of the initial installation of the system.

During the years that we have been developing our technology, we have gained the grant support of the state water districts, the Environmental Protection Agency, state departments of Environmental Protection and Agriculture, and the United States Congress. Four years ago, the University of Florida invited us to be a research partner; a two-year study has just been completed, and a Ph.D. thesis has been written comparing the results of sub-irrigation, micro-irrigation, and overhead spray irrigation on our farm..

The process of change is sometimes agonizingly slow; but more and more agencies realize that in order to stem the huge waste of agricultural water, it will be necessary for governments to supply a majority of the funding for the changeover. This has been occurring in Florida for a number of years, and has almost reached the acceptance point that water saved is less expensive than is any alternative water source, even if the agencies fund 80-85% of the initial installation cost of the rain-harvesting system. Since plant growth is more efficient with sub-irrigation, the grower makes a higher profit than with conventional systems. Energy savings are between 50-75%, as documented in the University of Florida's independent study. Huge amounts of aquifer water are saved for the needs of an ever-increasing urban environment.

The system has not been proven in arid climates; but water from snow melts and seasonal river excesses can be harvested and stored much as they are today in many areas of the country, with the added advantage that agricultural runoff can be almost eliminated.

Since the water shortages resulting from seasonal droughts can be mitigated, thus making water available for irrigation to the grower in all seasons, production of all plants—whether food or ornamental—can be assured.

The key to water conservation, in my opinion, is the combining of agriculture, government, and academia into a single force. With this combination working together, vast quantities of currently-wasted irrigation water can be saved to insure fresh water resources for generations to come.

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Vadose Zone Monitoring of Fields Irrigated with Recycled Processing and Municipal Wastewaters.

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Abstract

Irrigation of fields with recycled municipal wastewater and effluent from wineries allows for the beneficial reuse of nutrients and water, while utilizing the soil profile to treat the process water and prevent degradation of groundwater. However, some constituents may pass through the soil profile and detrimentally impact groundwater. In our current research, we are using soil solution samplers, often referred to as suction lysimeters, installed at various depths within the vadose zone to monitor subsurface water quality at sites receiving the recycled wastewaters. Analysis of soil solution samples collected from fields irrigated with winery stillage indicated that there is a high degree of spatial and temporal variability in the amount of total dissolved salts, total suspended solids, and inorganic nitrogen levels which is closely related to the hydraulic loadings and application cycles of the wastewater. Soil solution samples collected below 4 feet in the area treated with tertiary level municipal wastewater had relatively lower nitrate and concentrations than the water collected with the 0-4 feet depth, which may be indicative of the soil's potential denitrification capability.

Introduction

Land application of process winery stillage has been practiced for several decades at the Fresno/Clovis Regional Wastewater Reclamation Facility (RWRF). This disposal technique allows for the beneficial reuse of nutrients, organic matter, and water, while utilizing the soil profile to treat the process water. However, application of winery stillage can lead to subsurface and ground water degradation, because these waters typically contain elevated levels of organic carbon, total suspended solids, nutrients, and minerals. Groundwater quality at disposal sites has primarily been assessed through groundwater monitoring well studies. However, little information is available on the quality of subsurface water as it migrates through from the soil through the soil profile commonly referred to as the unsaturated or vadose zone.

In order to prevent any additional degradation of groundwater, the California Regional Water Quality Control Board (CRWQCB) has been decreasing limits on hydraulic, nitrogen, and Biological Oxygen Demand (BOD) loading during permit renewals. The CRWQCB has set limits of 300 lb/acre instantaneous BOD loading and

100 lb/acre average loading. The new permit limit reduces the ability to surface irrigate, because application depths in range of three to six inches exceed the instantaneous BOD loading for common BOD concentrations in food process wastewater.

In Phase 1 of our research, the Center for Irrigation Technology (CIT) and the California water Institute (CWI) assisted the City of Fresno's Public Utilities in monitoring subsurface water quality at a winery stillage disposal site. Vadose zone monitoring at the site was required for compliance with the CRWQCB Monitoring and Reporting Program, as stipulated in the RWRF's Waste Discharge Requirements. The objective of the work with the City was to collect soil water (vadose zone) samples at 2 and 4 ft depth in stillage disposal areas and evaluate the concentrations of chemical constituents in those samples. The 2nd phase of the research which is currently in progress, involves the monitoring of soil and solution samples within the top four feet of fields planted with two forages- Sudan grass and Elephant grass. The major objectives in this phase of the project are: (1) to examine the effectiveness of the two forages to act as scavenging crops for the organic and nitrogen loading from the winery stillage application; and, (2) to assess the ability of these crops to alleviate any soil salinity build up associated with the application of the winery stillage (Cassel S., 2005). In a related study, we are conducting a soil water quality monitoring under ponding basins containing tertiary treated municipal wastewater. The primary objective of this study is to estimate potential denitrification losses during percolation.

In this paper, we present an overview of the installation and sampling plan used for monitoring the soil solution within the vadose zone, data depicting the trends in the spatial and temporal variability for the constituents in samples collected at the winery stillage site, and some preliminary soil solution data from the site treated with the municipal wastewater. The presentation concludes with an outline of proposed future work aimed at assessing how well solution samples obtained from lysimeters represent the actual field conditions.

Materials and Methods

A. Stillage site

The Stillage Disposal Site is located at the Fresno/Clovis Regional Treatment Facility, CA. The site was used for disposal of winery stillage waste since 1974. It was originally 95 acres, but was later expanded to about 145 acres and the area received between 500,000 and 1,000,000 gallons of waste per day. Stillage wastes were disposed at the site until the end of 2003, then the practice ceased. The disposal site was comprised of 6 sections, categorized as A through F (Figure 1).

Before winery stillage application, the beds were plowed to 6-8 inch depth, and then leveled to a 0.1 percent slope. Then long and narrow checks/curbs were prepared around each bed. At the time of application, stillage was distributed / spread with the use of splash plates to prevent the formation of holes at the bed inlet. During 2003, Sudan grass was planted in section A and irrigated with secondary effluent because well water was not available at the time of application.

Soil water quality in the vadose zone was monitored using suction lysimeters in all six sections. Since the maximum rooting depth of Sudangrass is around three feet, lysimeters were installed at 2 and 4 feet. Vadose zone monitoring at those two depths was valuable to assess solute movement through the soil profile and determine the role of Sudangrass in reducing water contamination below the root zone.

Nine pairs of lysimeters were installed in sections A through E following the manufacturer's procedure (Soilmoisture Equipment Corp. 1999). A pair consisted of one lysimeter installed at 2 ft depth and another lysimeter placed at 4 ft with a nearby soil moisture access tube. Figure 2 shows the relative positions of the monitoring devices installed at a given location. To ensure adequate sample volume for laboratory analyses, a Diviner 2000 soil moisture probe (Sentek Environmental Technologies, 1999) was used to determine the position of the wetting front following stillage application. Vadose zone samples were collected when the wetting front reached the depth of the lysimeter porous cup. Soil moisture readings were taken every 1-2 days after stillage application depending on loading of the beds and measurements continued until the vadose zone sample was collected.

Sampling in the E-W direction allowed us to examine the impact of stillage application at the eastern, middle and western parts of each section. Each row consisted of three pairs of lysimeters, spaced evenly across the north-south (N-S) direction. The suggested placement of the lysimeters is presented in Figure 1. The N-S sampling provided additional data in an effort to account for any spatial variability in soil hydraulic properties. Additionally, the primary purpose of the Vadose Zone Monitoring Program is not to compare the loadings between sections but to evaluate the loadings in each section. One pair of lysimeters was also installed at 2 and 4 ft at a location that never received stillage for background reference.

B. Municipal Wastewater

The municipal waste water site is located in the city of Madera, CA. The City owns and operates the wastewater treatment plant (WWTP). The WWTP effluent discharge and ultimate sludge disposal are regulated under WDR Order No. 95-046. This order currently limits the plant to a maximum permitted flow of 7 MGD. Final disposal of the treated effluent takes place on City-owned lands located adjacent to the WWTP. The City owns fourteen 20-acre plots. Some of these plots are leased to farmers for growing fodder crop while the rest of the plots are used by the city as ponding basins either for effluent and sludge disposal or for sludge drying purposes. Sometimes, these holding ponds are drained and farmed every one to two years with wheat followed by corn for fodder.

In one of the ponding basins, suction lysimeters were installed at two locations at depths of 2, 4 10 and 15 feet below the soil surface. Vadose zone monitoring at these depths was important in order to assess the movement of the solute through the soil profile and at depths generally greater than the root zones of any crops traditionally grown on these fields.

Results and Discussion

A. Stillage site

The stillage constituent loadings were calculated based on the stillage quality data and the records for hydraulic loadings. In all beds, total biological oxygen demand (BOD) loadings exceeded 1000 lb ac^{-1} and reached very high values (>10,000 lb ac^{-1}) in sections C, D, and F during the second applications. These very high loadings were mostly explained by the elevated BOD concentrations of the stillage as well as the large volume of stillage applied. The lowest BOD loadings were found in sections A and E. During the first applications, BOD loadings were less variable among beds. Average BOD loadings ranged from 34 to 320 lb ac-d^{-1} during the first applications and from 17 to 280 lb ac-d^{-1} for the second applications. Although BOD loadings were very high in sections C and F for the second applications, the corresponding average BOD loadings did not exceed 100 lb ac-d^{-1} due to the long drying cycles between stillage applications. This indicated that drying time was a very important factor to reduce average BOD loadings. The total dissolved (TDS) and suspended (TSS) solids, nitrate-N (NO_3-N) and ammonium-N (NH_4-N) loadings were also very high and variable among beds.

The pH of the solution samples was relatively neutral and ranged from 5.3 to 8.7. For most beds, the pH of the solutions collected at 4 ft was slightly greater than that of samples taken at 2 ft, with sections C and D showing the highest pH values (Table 1).

The EC of the lysimeter solutions were high and varied from 1,936 to 10,437 µmho cm^{-1} (Table 1). Section A, planted with Sudan grass, had the lowest EC among all beds. Low EC values were also observed in section F during the first sampling events. In most beds, the EC of the solutions collected at 4ft was lower than that of samples obtained at 2 ft. Sections B, D, and E were characterized by the highest EC levels in the lysimeter samples.

The TSS concentrations were lower than TDS concentrations in the collected solutions (Table 2). During the first samplings, the TDS of the solutions were higher than that of the influent stillage, except in beds B21 and F90. An opposite trend was observed for TSS. The TDS of the 4-ft depth samples were lower than that of the 2-ft solutions in most sections. For beds E68 and E71, the TDS of the 4-ft solutions were very high in spite of a relatively low level in the influent stillage. The elevated TDS in section A could negatively affect Sudan grass growth.

The NH_4-N concentrations were relatively low in most samples (Table 3). The NO_3-N levels were less than 1 mg L^{-1} in many beds (Table 3). The NH_4-N concentrations were greater than the NO_3-N levels in sections A through E during the first samplings. The higher NO_3-N concentrations observed in solutions collected in section F suggested that nitrification might have started at the time of sampling, i.e, 3-4 days after stillage application, and that some of the NH_4-N had been oxidized to NO_3-N. Basic summary statistics conducted on the lysimeter solution data, indicated that among all constituents analyzed, NO_3-N displayed the greatest spatial variability on a per section basis. For example, in section A, coefficient of variability (CV) values of 230% and 249% were obtained for NO_3-N at 2-ft and 4-ft depths during the first sampling, respectively.

B. Municipal Wastewater

Most of the data collected at the Madera waste water site is currently being analyzed. Examples of the spatial and temporal variability in chloride (Cl), nitrate (NO_3) and ammonia (NH_3-N) concentrations in the lysimeter samples are shown in Figures 3, 4, and 5 respectively. Generally, the Cl concentrations at the four depths were similar to that measured in the pond's surface water throughout the entire monitoring period. This is most likely due to the fact that the chloride ion is acting as a non-rective tracer as it moves through the soil profile with the percolating water. However, in the case of the NO_3 (Figure 4) and NH_3-N (Figure 5) ions, there were differences between the levels in the pond and those samples collected within the profile. More importantly, no inorganic nitrogen (NO_3-N and NH_3-N) levels were detected at the 15feet depth during the monitoring period. These results may be representative of the nitrogen dynamics, such as the degree of nitrification and denitrification, occurring within the soil profile.

Conclusions and Future Research

Analysis of soil solution samples collected from fields irrigated with winery stillage indicated that there is a high degree of spatial and temporal variability in the amount of total dissolved salts, total suspended solids, and inorganic nitrogen levels which is closely related to the hydraulic loadings and application cycles of the wastewater. Soil solution samples collected below 4 feet in the area treated with tertiary level municipal wastewater had relatively lower nitrate concentrations than the water collected within the 0-4 feet depth, which may be indicative of the soil's potential denitrification capability.

In the sampling plan currently in use for the vadose zone monitoring at the stillage site, soil water quality in the vadose zone is monitored using suction lysimeters in all six sections. In our, future work, we intend to examine the spatial correlation between soil solution samples installed along a transect to find out how representative of the field are the solution sample obtained by the various lysimeters. This statistical characterization of the spatial distribution of the organic and nitrogen loading will be useful: in designing and implementing future monitoring sampling networks; modeling the overall flow and transport rates of the various stillage constituents; and, providing important information on how different stillage discharge regimes affect the loading rates at various locations in the field. In the case of the municipal wastewater site, it is suggested that soil cores from the area be tested under ideal laboratory conditions to determine the potential denitrification rates of these soils.

References

Cassel F. S., D. D .Adhikari, and D. Goorahoo 2005. Salinity mapping of fields irrigated with winery effluents. Presentation at the technical session of the 26th Annual Irrigation Show, Phoenix, AZ.

Sentek Environmental Technologies. 1999. *Diviner 2000 User Guide Version 1.0.* Sentek Pty Ltd. South Australia. Internet: http/www.Sentek.com.au

Soilmoisture Equipment Corp. 1999. 1900 Soil water sampler – operating instructions. Santa Barbara, CA. 16 pp.

Table 1. Average pH and EC in lysimeter samples

pH

Bed	First sampling		Second sampling	
	2 feet	4 feet	2 feet	4 feet
A4s	6.0	6.2	6.2	6.6
A8s	6.0	6.6	6.8	8.1
A12s	5.7	6.3	7.2	-
Average A	*5.9*	*6.3*	*6.8*	*7.3*
B21n	8.0	8.1	6.2	7.8
B25n	6.7	6.7	6.1	6.7
B29n	7.0	7.3	6.4	6.9
Average B	*7.3*	*7.4*	*6.2*	*7.1*
C38n	5.3	5.3	7.8	7.4
C42n	7.4	6.5	8.2	7.9
C46n	5.5	7.2	5.2	6.1
Average C	*5.8*	*6.5*	*6.9*	*7.1*
D54n	7.9	7.9	8.1	7.8
D57s	8.2	7.4	7.7	7.6
D61n	8.7	8.3	8.0	8.0
Average D	*8.1*	*7.9*	*7.9*	*7.8*
E68n	7.8	7.6	7.1	7.8
E71s	8.3	7.5	7.2	7.4
E75n	8.2	8.1	8.1	7.9
Average E	*8.1*	*7.7*	*7.5*	*7.7*
F84	6.7	7.0	6.7	6.9
F90	6.6	6.9	5.5	6.7
F96	6.9	7.3	5.7	6.3
Average F	*6.7*	*7.1*	*5.8*	*6.6*
Average of all beds	7.0	7.1	6.7	7.2
Average of all beds except F	7.0	7.2	7.1	7.4

EC (µmho cm^{-1})

Bed	First sampling		Second sampling	
	2 feet	4 feet	2 feet	4 feet
A4s	4413	2463	4647	1936
A8s	3755	3877	3490	3000
A12s	3917	3990	3383	-
Average A	*4063*	*3389*	*3884*	*2468*
B21n	8120	5340	8515	8527
B25n	7280	6790	7090	7063
B29n	5847	4850	7103	7800
Average B	*7058*	*5519*	*7451*	*7797*
C38n	3780	3381	6480	5990
C42n	15290	9563	7615	7737
C46n	3970	4343	5743	6650
Average C	*6158*	*6060*	*6490*	*7021*
D54n	6730	4915	6573	4800
D57s	6663	6987	5793	6303
D61n	8730	10193	9653	8793
Average D	*6987*	*7671*	*7340*	*6861*
E68n	8060	8183	7430	6570
E71s	10127	10437	8247	8030
E75n	7250	6910	6877	5830
Average E	*8714*	*8710*	*7518*	*6933*
F84	4703	4240	8025	5692
F90	3264	3560	6407	6295
F96	3830	3381	6473	6213
Average F	*3938*	*3727*	*6757*	*6146*
Average of all beds	5608	5394	6631	6498
Average of all beds except F	6562	6270	6584	6653

Table 2. Average TDS and TSS in lysimeter samples

TDS (mg L^{-1})

Bed	First sampling		Second sampling	
	2 feet	4 feet	2 feet	4 feet
A4s	4536	3952	3110	1560
A8s	3157	3947	2929	2325
A12s	4320	2456	1860	-
Average A	*4080*	*3451*	*2788*	*1943*
B21n	7761	4956	-	8916
B25n	-	7247	9643	8003
B29n	-	4529	8857	8374
Average B	*7761*	*5577*	*9250*	*8431*
C38n	4381	2844	-	4652
C42n	15844	11151	7104	6429
C46n	4251	4073	5763	-
Average C	*6621*	*6420*	*6210*	*5985*
D54n	6140	4281	-	4095
D57s	8100	4328	5229	6003
D61n	-	5724	8914	7984
Average D	*6793*	*4654*	*7072*	*6269*
E68n	6916	10446	8001	4652
E71s	-	11433	9103	7341
E75n	6387	5811	6805	5931
Average E	*6652*	*9395*	*8302*	*6423*
F84	4481	3740	11009	7036
F90	2899	3468	8711	6769
F96	3324	2632	9467	8550
Average F	*3616*	*3246*	*9472*	*7852*
Average of all beds	4726	4942	7751	6991
Average of all beds except F	5836	6017	6986	6634

TSS (mg L^{-1})

Bed	First sampling		Second sampling	
	2 feet	4 feet	2 feet	4 feet
A4s	47	4	12.0	2
A8s	420	32	2	-
A12s	7	205	7	-
Average A	*142*	*80*	*7*	*2*
B21n	78	52	-	229
B25n	-	200	542	282
B29n	-	20	134	221
Average B	*78*	*90*	*338*	*244*
C38n	6	55	-	28
C42n	1030	54	350	199
C46n	328	132	156	-
Average C	*340*	*84*	*220*	*157*
D54n	481	38	-	17
D57s	366	45	110	124
D61n	-	67	181	148
Average D	*443*	*47*	*146*	*106*
E68n	251	482	307	226
E71s	-	344	138	307
E75n	453	265	494	407
Average E	*352*	*341*	*261*	*327*
F84	47	47	212	44
F90	43	17	68	154
F96	6	25	153	47
Average F	*32*	*30*	*134*	*73*
Average of all beds	147	92	180	163
Average of all beds except F	257	131	201	201

Table 3. Average NH_4-N and NO_3-N in lysimeter samples

NH_4-N (mg L^{-1})

Bed	First sampling		Second sampling	
	2 feet	4 feet	2 feet	4 feet
A4s	43	24	19	10
A8s	-	25	33	0
A12s	12	36	23	-
Average A	*22*	*30*	*25*	*6*
B21n	22	79	78	84
B25n	54	102	177	110
B29n	18	123	53	142
Average B	*32*	*101*	*83*	*108*
C38n	5	34	-	165
C42n	21	78	36	54
C46n	21	53	71	-
Average C	*14*	*58*	*54*	*82*
D54n	11	21	8	22
D57s	8	25	4	17
D61n	26	7	2	16
Average D	*16*	*18*	*4*	*18*
E68n	16	68	11	79
E71s	-	26	11	8
E75n	5	147	4	91
Average E	*12*	*73*	*10*	*48*
F84	3	4	20	6
F90	3	2	31	15
F96	4	4	36	15
Average F	*3.2*	*3.4*	*32*	*13*
Average of all beds	12	36	30	43
Average of all beds except F	20	57	29	57

NO_3-N (mg L^{-1})

Bed	First sampling		Second sampling	
	2 feet	4 feet	2 feet	4 feet
A4s	0.33	12	3.7	0.30
A8s	0.25	0.11	0.9	-
A12s	4.5	1.3	0.1	-
Average A	*1.9*	*5.2*	*1.6*	*0.30*
B21n	0.17	0.20	0.01	0.01
B25n	0.16	0.16	0.34	0.01
B29n	0.27	0.20	0.11	0.30
Average B	*0.20*	*0.19*	*0.19*	*0.08*
C38n	1.71	3.91	-	0.01
C42n	0.01	0.21	0.01	0.20
C46n	0.30	0.07	0.25	2.1
Average C	*0.80*	*1.1*	*0.13*	*1.0*
D54n	0.30	0.20	0.07	0.11
D57s	0.20	0.01	0.2	0.5
D61n	-	0.20	0.01	0.07
Average D	*0.28*	*0.14*	*0.10*	*0.24*
E68n	0.11	0.37	0.07	0.11
E71s	0.37	0.33	0.07	0.01
E75n	0.25	0.25	0.01	0.01
Average E	*0.26*	*0.33*	*0.06*	*0.04*
F84	28	0.30	0.16	0.11
F90	17	22	0.71	0.17
F96	78	24	0.97	0.35
Average F	*39*	*16*	*0.70*	*0.20*
Average of all beds	16	6.5	0.54	0.29
Average of all beds except F	0.73	1.4	0.45	0.33

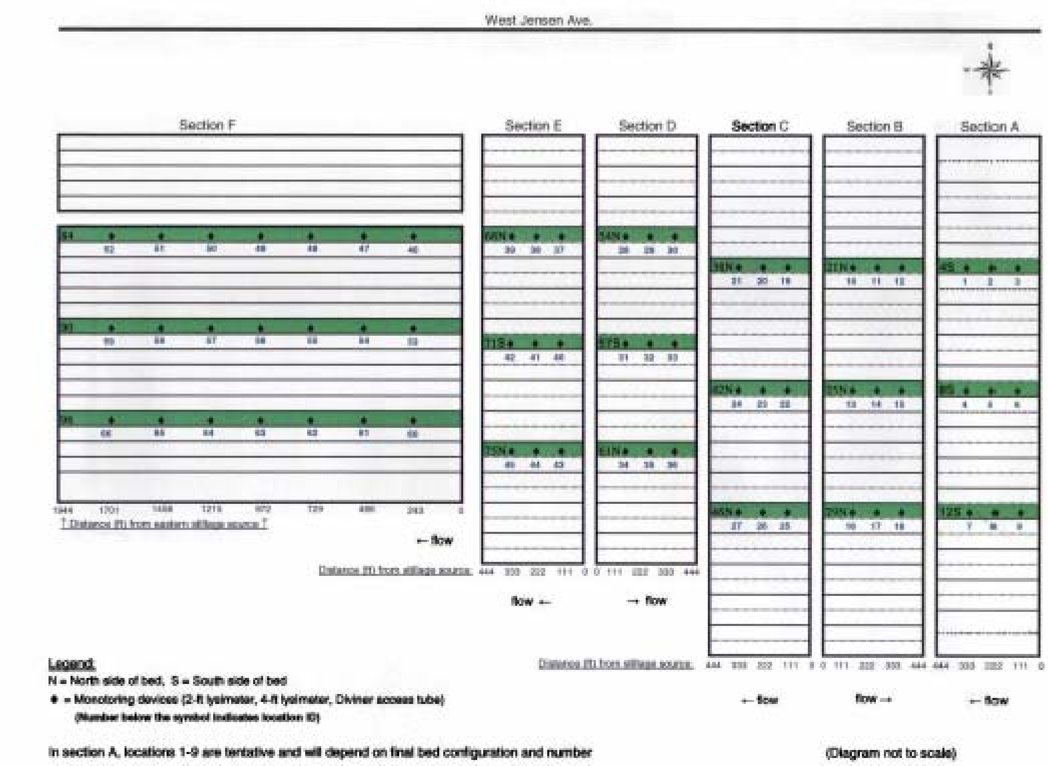

Figure 1: Layout of experimental plots at Stillage site showing location of lysimeters.

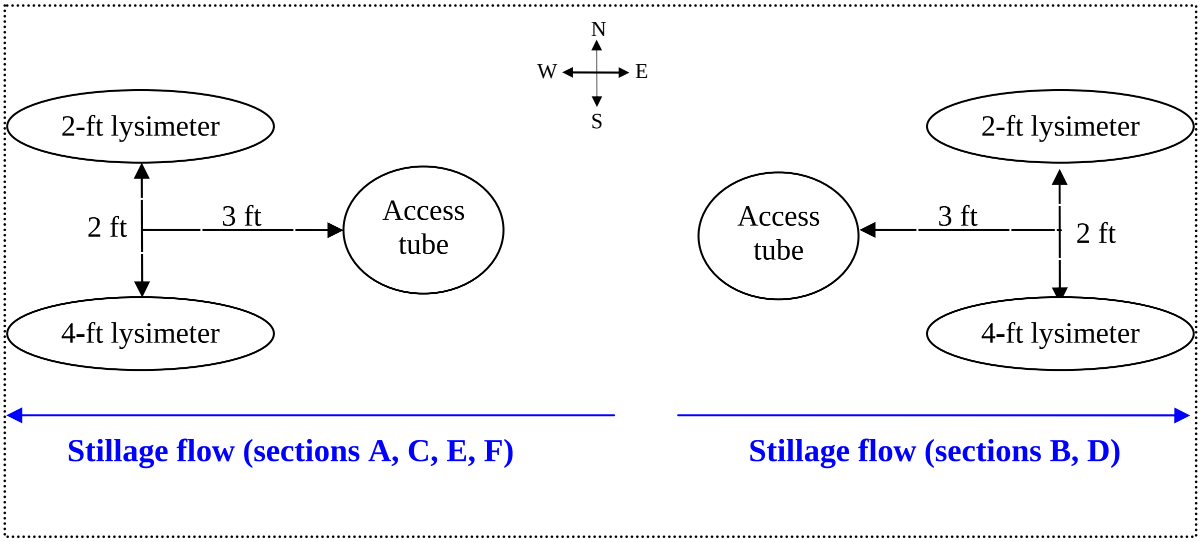

Figure 2: Relative position of the monitoring devices at each location

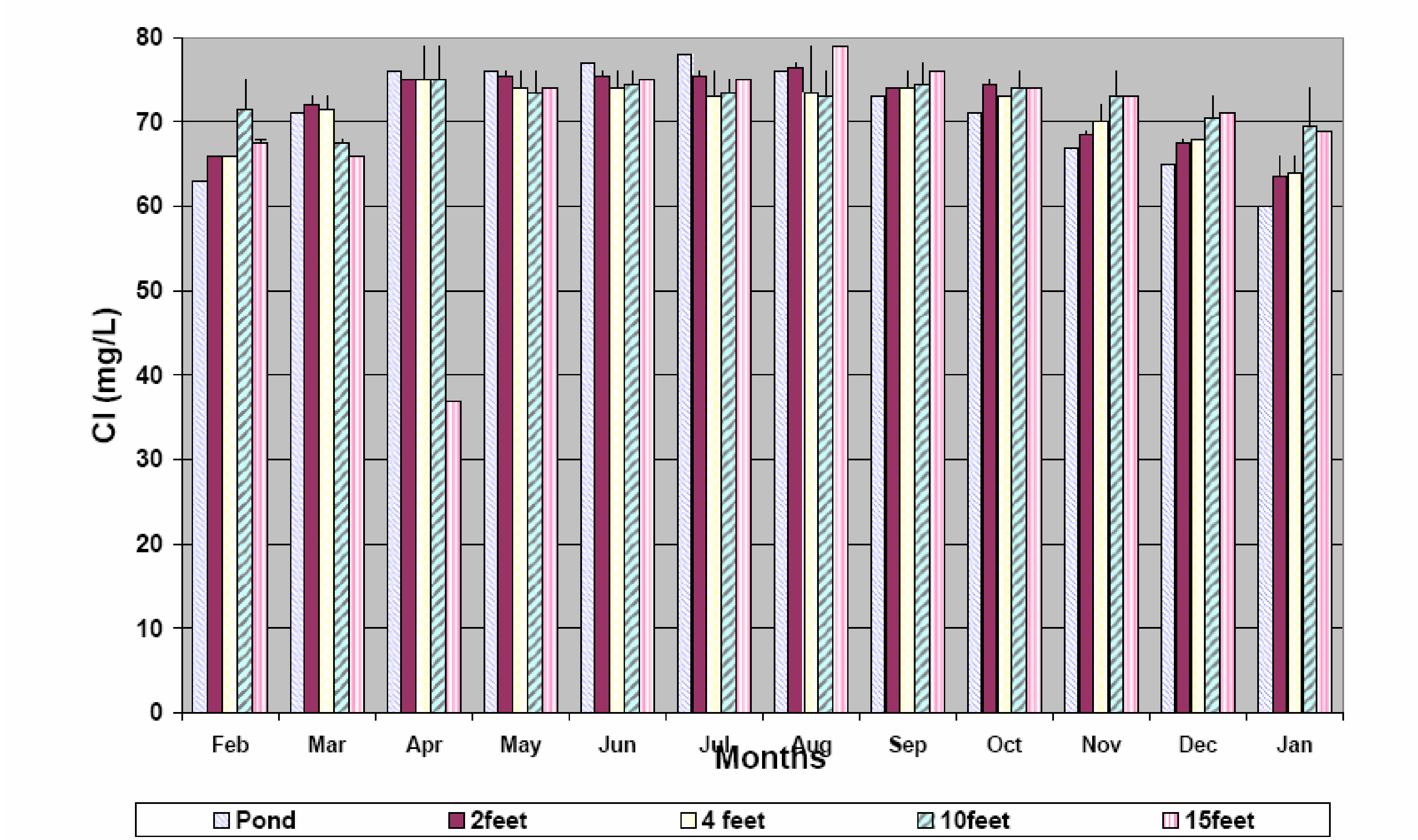

Figure 3: Average chloride concentrations detected at the municipal wastewater site.

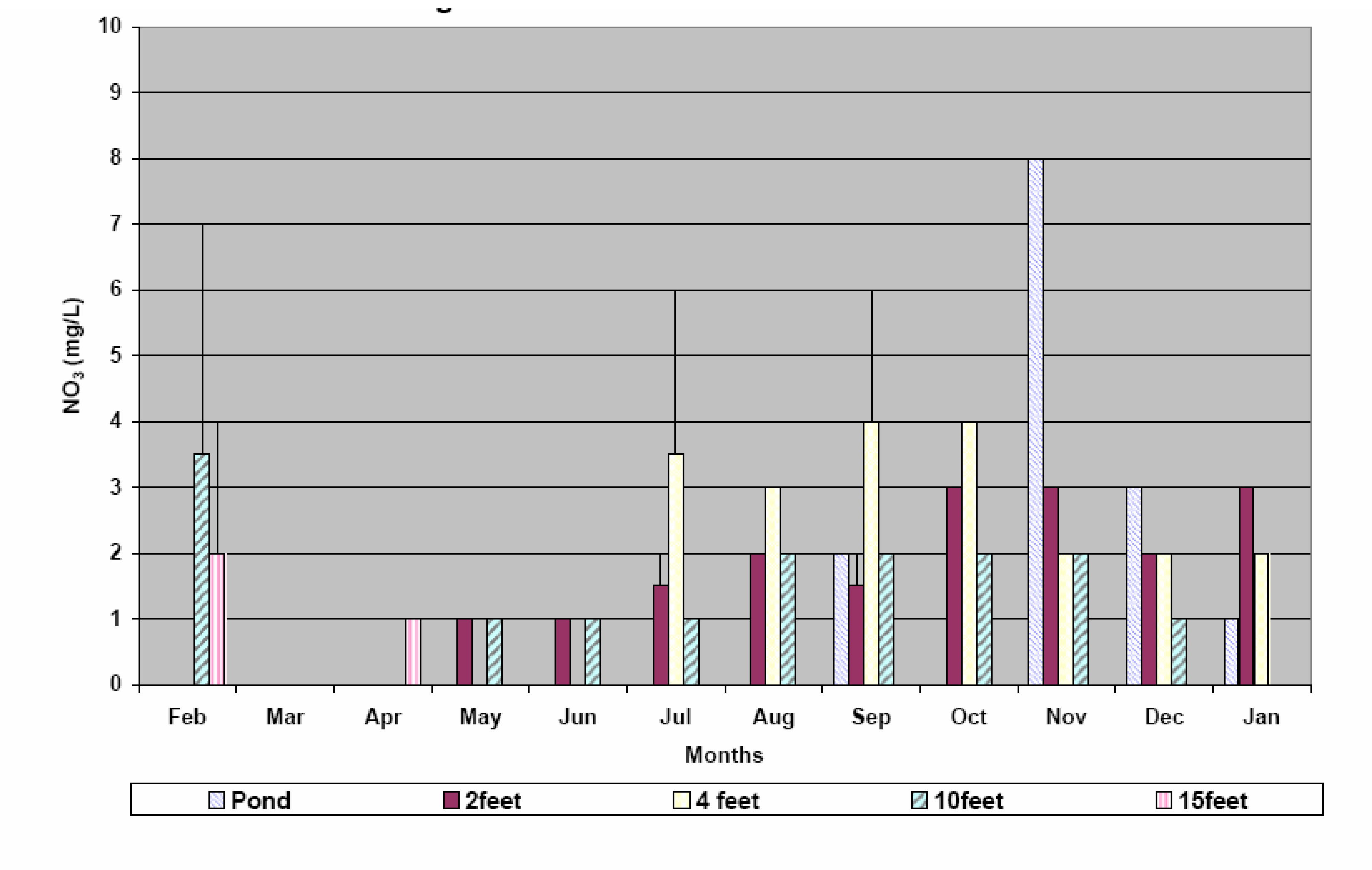

Figure 4: Average nitrate concentrations detected at the municipal wastewater site.

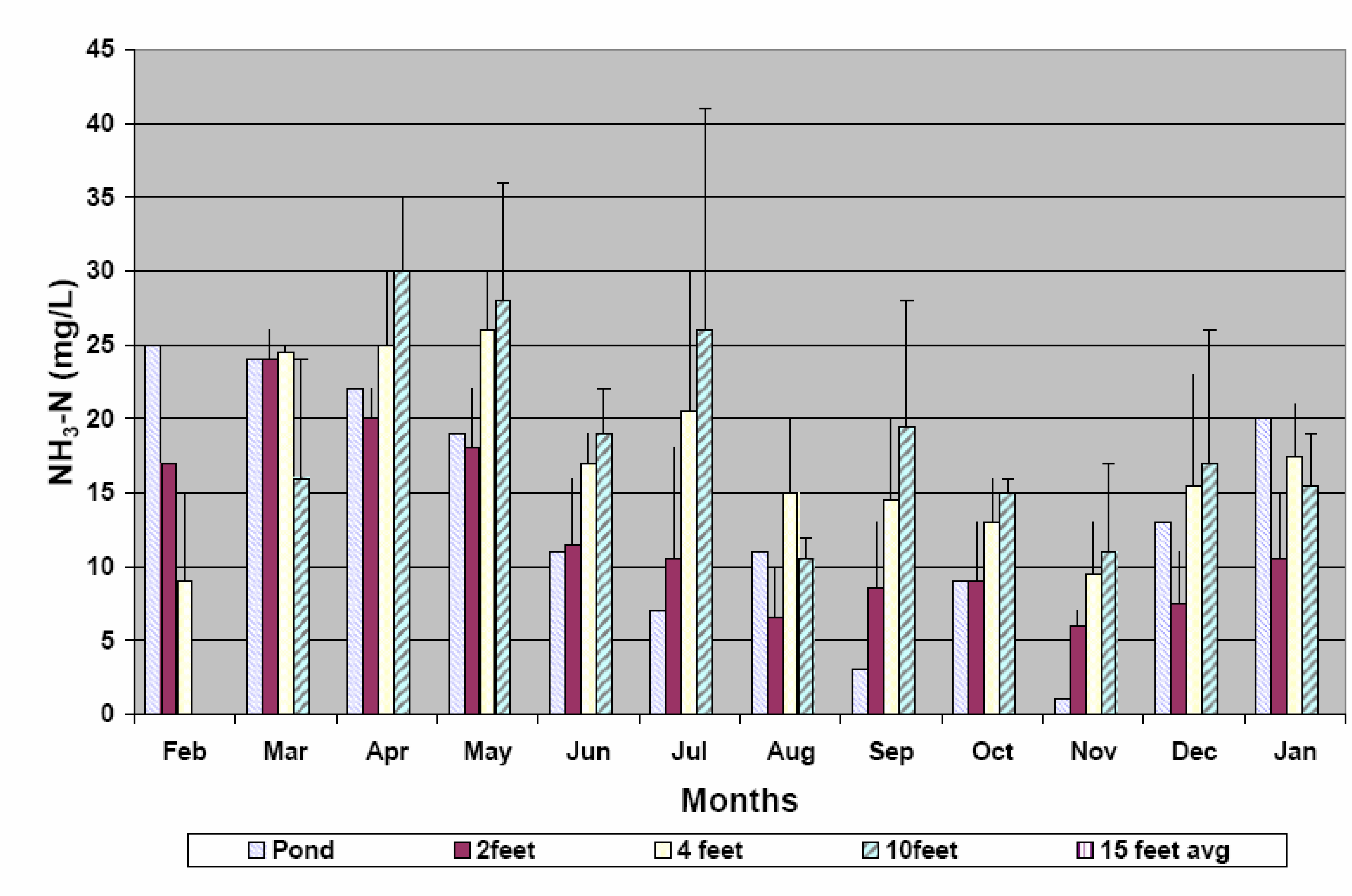

Figure 5: Average ammonia-N concentrations detected at the municipal wastewater site.

Salinity mapping of fields irrigated with winery effluents

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Abstract

Land application of food-processing effluent waters is a widely practiced treatment and disposal technique that allows for the beneficial reuse of nutrients and water. However, excessive application of these waters can lead to subsurface water degradation and increase in soil salinity. The objective of this research was to assess the spatial distribution of salinity in fields having received winery effluent waters and to evaluate the effectiveness of two forage grasses (Elephant grass and Sudan grass), in removing salts from the soil profile. Salinity mapping of the fields was conducted using the electromagnetic induction (EM) technique and soil sampling. The salinity maps indicated that both grasses were efficient in removing salt from the soils. However, the results suggested that the Elephant grass had a greater uptake capability. The study also showed that the use of the EM technique improved the knowledge of salinity variability across the fields and was a valuable tool for evaluating the beneficial effects of forage grasses in improving subsurface soil and water quality.

Introduction

Land application of food-processing effluent waters is a widely practiced treatment and disposal technique that allows for the beneficial reuse of nutrients and water. However, excessive application of these waters can lead to subsurface water degradation and increase in soil salinity. Such water contamination problems are encountered across the country, including in the Central Valley of California where intensive agriculture is practiced and numerous food-processing plants need to dispose of their excess waters. Researchers at the Center for Irrigation Technology (CIT) - California State University, Fresno have been working for several years with the City of Fresno's Public Utilities to monitor subsurface water quality at a disposal site that received winery effluents for thirty years. Such monitoring was mandated by the Regional Water Quality Control Board to determine the organic and nitrogen loadings that occurred on the site. In December 2003, the discharge of winery effluents to the site was ceased permanently. Since then, compliance with regulations requires the City of Fresno to plant and harvest forage grass on the site to uptake nitrogen and salts from the soil.

A research study is currently being conducted by CIT in one section of the site, where two forage grasses have been planted and lysimeters have been installed to determine the movement of nutrients and salts as the section is being irrigated with fresh water. The two grasses studied are Elephant grass and Sudan grass; each grass was planted in 2004 on 0.72 acre and 0.58 acre, respectively. Elephant grass is a perennial forage grass (*Pennisetum Sp*.) that grows throughout the tropical world and is one of the most widely used forage for animals. Elephant grass was introduced in California in 1994 and was patented by Morton Rothberg as "Promor A". This plant grows in clumps or stools with an upright growth habit and is very palatable to animals. Elephant grass is a fast growing C4 plant which can be harvested 3 times a year and can produce tremendous amount of high-nutrient animal feed. Past studies indicate this grass as capable of absorbing over 1000 lbs of total nitrogen per year (Goorahoo et al., 2004). Elephant grass can grow in soils with high salts and nitrogen content, and is the crop of choice for wastewater facilities and dairy farms because of its high nitrogen and salt removal capabilities. Details on the CIT study and results from the lysimeter data can be found in another paper presented at this Irrigation Show (Adhikari et al., 2005). In this paper, we present the spatial distribution of soil salinity in the areas planted with Elephant grass and Sudan grass, evaluate the changes in salinity that occurred over one year, and compare the efficiency of the two grasses.

Materials and Methods

The study was conducted at the stillage disposal site located at the Fresno/Clovis Regional Treatment Facility, CA. Soil salinity measurements were taken in the two fields planted with Elephant grass and Sudan grass. The electromagnetic instrument used in this study was the EM-38 dual dipole (Geonics Limited, Mississauga, ON, Canada) which provides measurement depths down to 6 feet without ground contact. The instrument includes a transmitter and a receiver spaced about 3.3 feet apart in a non conductive casing. Photograph of the EM38-DD meter is presented in Figure 1. The transmitter part of the instrument induces a primary magnetic field in the ground, which creates a current in the soil matrix and generates a secondary magnetic field recorded by the receiver. The electrical conductivity (EC) being measured is the ratio of these two magnetic fields. The EM technique has been used by several researchers for agricultural and environmental applications (McKenzie et al., 1989; Slavish, 1990).

Figure 1. EM-38 meter used in this study

In each field, the EM data were collected following a grid pattern of 15 feet X 18 feet. A total of 84 locations were surveyed in the Elephant grass field, and 90 locations for Sudan grass. The EM measurements were taken in July 2004 just before planting and then in April 2005 for both fields. After each survey, six locations were chosen in each field for ground truthing. This was required because the efficient use of the EM data required the conversion of apparent soil conductivity into soil salinity. The soil samples were collected down to 4 feet and were analyzed for EC, moisture content, and saturation percentage, following standard analytical methods (Klute, 1986; Miller et al., 1997). Then, the ESAP software was used to predict the soil salinity data based on the survey and sample information (Lesch and Rhoades, 1999). Contour maps showing the salinity distribution on both fields in 2004 and 2005 were generated with the Surfer software (Golden Software, 1999).

Results and Discussion

The electrical conductivity data of the soils collected after each survey are shown in Table 1. In 2004, the EC values were similar in both fields, ranging from 4.9 dS/m to 7.6 dS/m for Elephant grass, and from 4.9 dS/m to 9.6 dS/m for Sudan grass. Higher EC was found at 0-1 ft in the Sudan grass field and at 3-4 ft in the Elephant grass field. The EC values tended to decrease with depth for the Sudan grass field; no trend could be observed in the Elephant grass field. In 2005, the soil EC values considerably decreased in both fields, and particularly for the area planted with Elephant grass. The EC remained below 3.5 dS/m in the Elephant grass field with the lowest values found in the first two feet. In the Sudan grass field, the EC was not very variable across depth, ranging from 3.6 dS/m to 4.3 dS/m.

Table 1. Electrical conductivity of soil samples collected in both fields (average of 6 locations)

Depth	-------------------2004--------------------		-------------------2005--------------------	
	Elephant grass	Sudan grass	Elephant grass	Sudan grass
0 -1 ft	7.6	9.6	2.1	3.9
1 - 2 ft	5.9	5.3	2.3	4.3
2 – 3 ft	4.9	5.3	2.9	4.2
3 – 4 ft	7.0	4.9	3.5	3.6

Maps showing the spatial distribution of soil salinity in both fields are presented in Figures 2 and 3 for 2004 and 2005, respectively. The data represent the average soil salinity down to 4 ft. The 2004 maps represent the salinity levels just before planting and the 2005 maps show the salinity data about nine months after planting. Relatively high salt concentrations were observed for both fields in 2004. The average salinity levels ranged from about 4 to 8 dS/m in the Elephant grass field. The Sudan grass field exhibited a more heterogeneous spatial distribution with EC values ranging from 2 to 8 dS/m; the lowest EC was observed in the south-west part of the field. In 2005, the soil salinity levels decreased in both fields. The highest salinity values reached 4 dS/m and 5 dS/m in the Elephant grass and Sudan grass fields, respectively. However, in most parts of the Elephant grass field, the soil salinity levels remained below 3 dS/m. Soil salinity was higher in the Sudan grass field, ranging from about 4 to 5 dS/m. The study indicates that both grasses helped in removing salts from the soil profile. However, when comparing the two fields, the Elephant grass appeared more efficient in removing the salts from the soil profile.

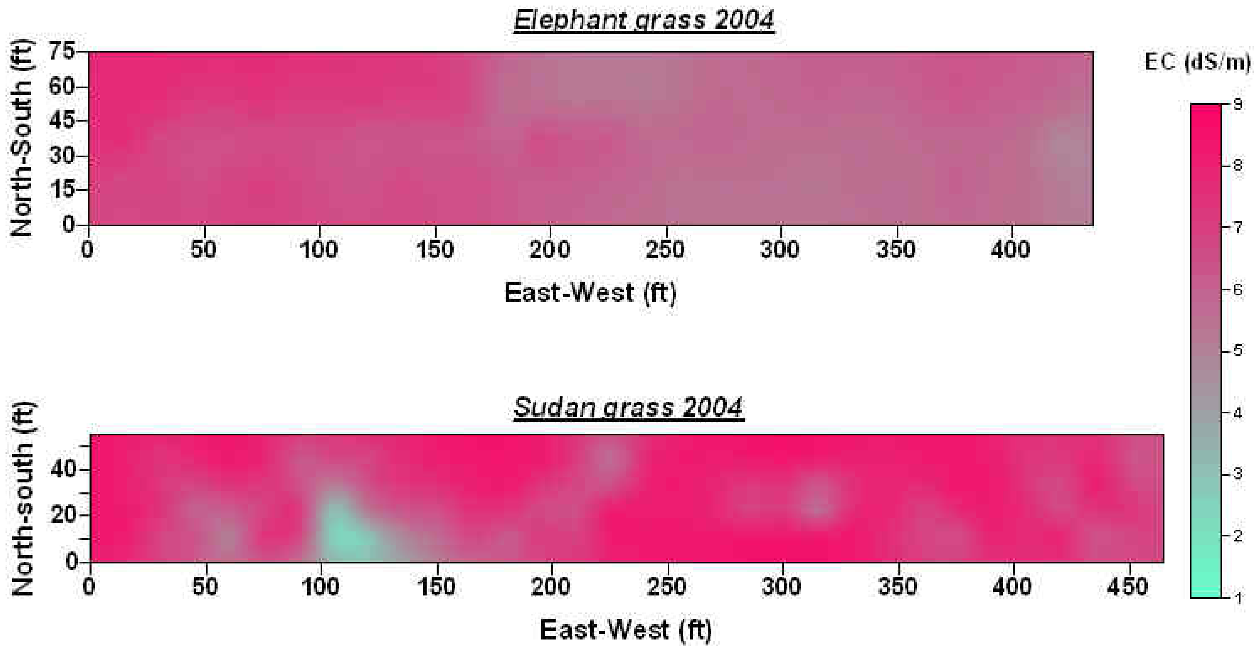

Figure 2. Soil salinity (dS/m) distribution observed in 2004 in both fields

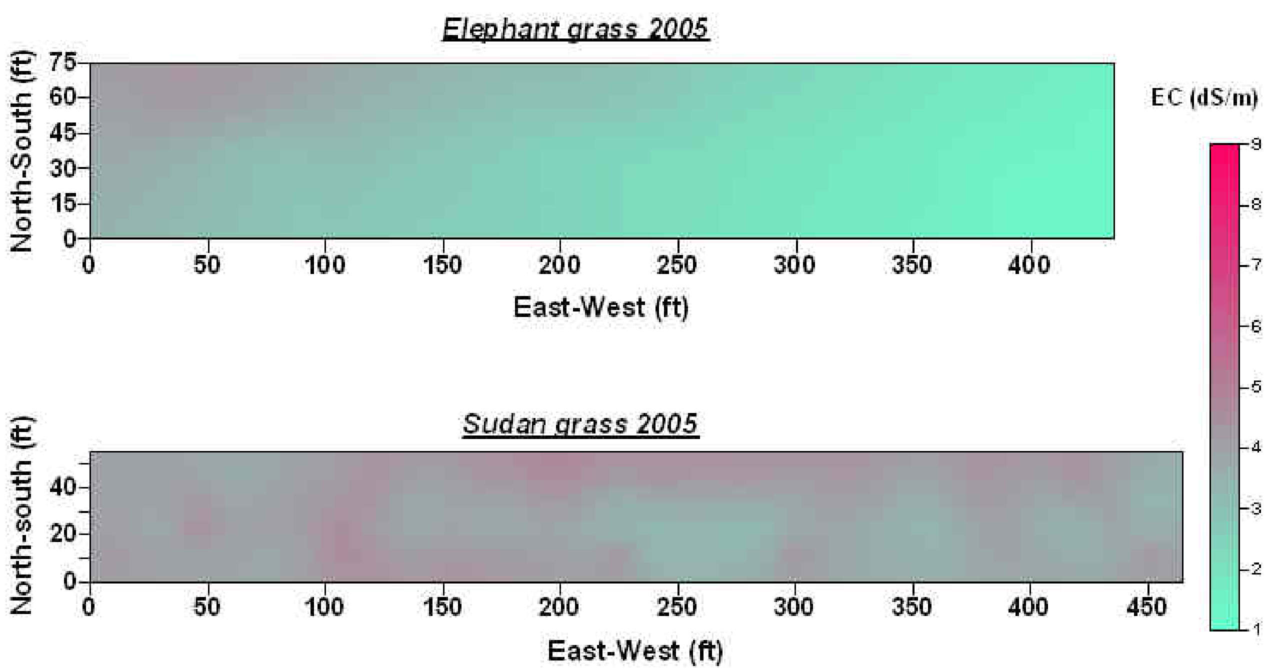

Figure 3. Soil salinity (dS/m) distribution observed in 2005 in both fields.

Conclusions

The purpose of the study was to assess the spatial distribution of salinity in fields having received winery effluent waters and to evaluate the effectiveness of two forage grasses, Elephant grass and Sudan grass, in removing salts from the soil profile. Results indicated that both grasses helped in salt removal; however, the Elephant grass appeared to have a better uptake capability. The study also showed that the use of the EM technique improved the knowledge of salinity variability across the fields and was a valuable tool for evaluating the benefits of using forage grasses for improving subsurface soil and water quality.

References

Adhikari, D., D. Goorahoo, and F. Cassel S. 2005. Vadose Zone Monitoring of Fields Irrigated with Recycled Processing and Municipal Wastewaters. Presentation at the technical session of the 26th Annual Irrigation Show, Phoenix, AZ.

Golden Software. 1999. SURFER. Version 7.00 ed. *Golden Software*. Golden, CO.

Goorahoo, D., F. Cassel S., M. Rothberg, D. Adhikari, D. Zoldoske, and E. Norum. 2004. Potential use of a new forage grass (*Pennisetum Sp.)* in best management practices involving irrigation with food processing and dairy wastewaters. Proceedings of the 25th Annual Irrigation Show, Tampa, FL.

Klute, A. 1986. Methods of soil analysis, Part 1 Physical and mineralogical methods. American Society of Agronomy, Madison, WI.

Lesch, S. and J. Rhoades. 1999. ESAP-95 Software Package Version 2.01R: User Manual *USDA-ARS, George E. Brown Jr. Salinity Laboratory*, Riverside, CA.

McKenzie R., R. George, S. Woods, M. Cannon, and D. Bennett. 1997. Use of the electromagnetic-induction meter (EM38) as a tool in managing salinisation. *Hydrogeology J*. 5:37-50.

Miller, R., J. Kotuby-Amacher, and J. Rodriguez. 1997. Western States Laboratory Proficiency Testing Program – Soil and Plant analytical Methods, Version 4.00.

Slavish, P.G. 1990. Determining EC_a-depth profiles from electromagnetic induction measurements. *Aust. J. Soil Res*. 28:443-452.

DIPAC- Drip Irrigation Water Distribution Pattern Calculator

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ABSTRACT

Emitter spacing and emitter flow rates should be matched with the soil's wetting characteristics to achieve precision and high irrigation efficiency. A method for determining surface wetted radius and depth of the wetted soil volume under drip irrigation was developed. The wetted soil volume was assumed to depend on the depth of saturated hydraulic conductivity, volume of water applied, average change of moisture content and the emitter application rate. Empirical equations relating the wetted depth and width to the other parameters were obtained. Many experiments were used to verify these equations. Very good agreement between the theoretical and experimental results improves the validity of these equations. The results show that the suggested equations can be used for a wider range of discharge rates and other soil types. DIPAC will ensure that water and fertilizer reach the crop root zone precisely and efficiently.

Keywords: trickle irrigation, wetting front, surface wetted radius, emitter spacing

INTRODUCTION

Drip irrigation method is a technique for control of irrigation water presently being employed at many locations around the world. With this method, water is conducted under low pressure to a network of closely spaced outlets which discharges the water slowly at virtually zero pressure. The objective in this system is to supply water to limited soil volume in which active root uptake can take place. If the shape of moisture distribution within the wetted volume is known, the emitter or emitters can be located at that moment so that the plant can consume water and nutrients efficiently. Many attempts have been created to determine water distribution and wetting pattern under drip irrigation using sophisticated mathematical and numerical models, required detailed information concerning soil physical properties and too complicated for routine use (Dasberg et al., 1999). Even with the availability of computers and models to simulate infiltration from a drip source, these are often not used by designer of irrigation systems (Zazueta et al., 1995). For many practical situations, detailed information on matric potential or water content distribution within the wetted volume is not necessary and prediction of the boundaries and shape of the wetted soil volume suffice. However, a simple empirical model is usually more convenient for system design than the dynamic models. The objective of this study was to develop simple approaches that can help to determine the wetting pattern geometry from surface point source drip irrigation.

THEORETICAL CONSIDERATION

In any soil, the functional relationship between all variables can be defined as follows:

$$r \propto f_1(K, n, q_w, V_w) \tag{1}$$

$$z \propto f_2(K, n, q_w, V_w) \tag{2}$$

where r is wetted radius, k is soil hydraulic conductivity, n is soil porosity, q_w is application rate, V_w is volume of water applied and z is the depth of wetted zone.

It appears that a simple procedure based on previous variables could be developed to predict the wetting pattern geometry. The accuracy of results depends on the following approximations:

i. A single surface point source irrigated a bare soil with a constant discharge rate (q_w).
ii. The soil is homogeneous and isotropic.
iii. There is not a water table present in the vicinity of root zone.
iv. The evaporation losses are negligible.
v. The effect of soil properties is represented just by its porosity and saturated hydraulic conductivity.
vi. The value of porosity equals the value of saturated moisture content. It could be obtained using an equation given by Hillel, (1982) which states:

$$n = \theta_s = (1 - \frac{\rho_b}{\rho_p}) \tag{3}$$

Where n is porosity of the soil θ_s is Moisture content at 0 bars ρ_b is bulk density of the soil (measured) ρ_p is particle density of the soil (assumed 2.67 gm/cm^3).

According to previous approximations, Eqs. 1 and 2 become:

$$r \propto f_1(K_s, \theta_s, q_w, V_w) \tag{4}$$

$$z \propto f_2(K_s, \theta_s, q_w, V_w) \tag{5}$$

Ben-Asher et al. (1986) investigated the infiltration from a point drip source in the presence of water extraction using an approximate hemispherical model. They suggested that the position of the wetting front is a function of the half value of saturation moisture content. For infiltration from a point source without water extraction they found that:

$$R(t) \propto (\Delta\theta)^{-\frac{1}{3}} \tag{6}$$

$$\Delta\theta \approx \frac{\theta_s}{2} \tag{7}$$

The new variable $\Delta\theta$ is called the average change of soil moisture content. This leads to:

$$r \propto f_2(K_s, \Delta\theta, q_w, V_w) \tag{8}$$

$$z \propto f_2(K_s, \Delta\theta, q_w, V_w) \tag{9}$$

Shwartzman and Zur (1986) proposed simple relationships of the following form between the wetted diameter and vertical distance to wetting front and emitter discharge rate, soil hydraulic conductivity, and the total volume of water in the soil:

$$w = K_1 (V_w)^{0.22} (\frac{k_s}{q_w})^{-0.17} \tag{10}$$

$$Z = K_2 (V_w)^{0.63} (\frac{k_s}{q_w})^{0.45} \tag{11}$$

where, W is wetted width or diameter (m), Z is vertical distance to wetting front (m), K_1 is 0.031 (empirical coefficient), K_2 is 29.2 (empirical coefficient), V_w is volume of water applied (L), k_s is saturated hydraulic conductivity of the soil (m/s), and q_w is point-source emitter discharge (L/hr).

Despite Eqs. 10 and 12 offering simple and useful means for predicting wetting pattern including the expected distortion in wetted volume, which is not predicted by the hemispherical approximation, it needs to be validated against experimental values. According to the approaches introduced by Shwartzman and Zur (1986) and Ben Asher et al., (1986), the nonlinear expressions describing wetting pattern may take the general forms as:

$$r = \Delta\theta^{\alpha} V_w^{\beta} q_w^{\gamma} k_s^{\lambda} \tag{12}$$

$$z = \Delta\theta^{\rho} V_w^{\sigma} q_w^{\delta} k_s^{\varsigma} \tag{13}$$

Where r is the surface wetted radius (L), z is the vertical advances of wetting front (L), $\Delta\theta$ is the average change in volumetric water content within the wetted zone (L^3/L^3), Vw is the total volume of water applied (L^3), qw is the application rate (L^3/T), Ks is the saturated hydraulic conductivity (L/T), and α, β, γ, λ, ρ, σ, δ and ς are the best fit coefficients.

Once the model structure and order have been identified, the coefficients that characterize this structure model need to be estimated in some manner. To determine the coefficients of Eqs. 12 and 13, four available published experimental data by Taghavi et al. (1984), Anglelakis et al. (1993), Hammami et al. (2002), and Li et al. (2003) were adopted. The choice of these experiments was essentially based on their convenient data. The procedures of these experiments are available in their original papers. Table 1 shows the input variables used in Eqs.12 and 13.

A nonlinear regression approach using *SSPS* statistical package version 11.5 and the adopted experimental measurements were used to find the best-fit parameters for the equations 12 and 13. The following equations are obtained:

$$r = \Delta\theta^{-0.5626} V_w^{0.2686} q_w^{-0.0028} k_s^{-0.0344} \quad (14)$$

$$z = \Delta\theta^{-0.383} V_w^{0.365} q_w^{-0.101} k_s^{0.195} \quad (15)$$

where consistent units are used; r and z [cm]; V_w [ml]; q [ml/h] and k_s in [cm/h].

Table 1. Numerical values of input variables used in the predicted models.

Input Parameters	Taghavi et al	Anglelakis et al	Hammami et al	Li. et al
Texture of soil	Clay loam	a. Yolo clay loam b. Yolo sand.	Silt	loam
Emitter application rate (lph)	2.1 and 3.3	a. 2.1 and 7.80 b. 9.0 and 12.3	1.0 2.0 4.0	0.6- 0.9 1.4-2.0 4.9-7.8
Saturated moisture content (vol)	0.53	a 0.513 b.0.453	0.58	0.47
Saturated hydraulic conductivity (cm/hr)	0.85	a.0.85 b.5.8	5.8	1.85

To test the models more thoroughly, a series of experiments selected from published data may support the proposed models for determining the wetting pattern (i.e., surface wetted radius and vertical advance of wetting front) under point source drip irrigation. The selected experiments were conducted by Li et al.(2004), Yitayew et al.(1998), Palomo et al.(2002) and Risse et al. (1989). The details of these experiments were discussed extensively in the literature.

RESULTS AND DISCUSSIONS

Equations 14 and 15 may provide a simple description of the boundary of the wetted soil volume under point source drip irrigation. If the results of comparisons between the observed and predicted data indicated high coincidence, it could then be reliably recommended in practice.

a) Data from Li et al. (2004)

Figure 1 shows the observed and predicted surface wetted radius as a function of elapsed time for different application rates 0.7, 1.0, 1.4 and 2.0 l/h. The input data used for this simulation were 0.42 and 2.1 cm/h for saturated moisture content and saturated hydraulic conductivity. As can be seen, the experimental and the predicted surface wetted radius agree in general. There are trends of slight over-estimation of the surface wetted radius with the predicted model simulation, as shown in the figure. The main reason for such discrepancies may be due to the variability of bulk density as a result of packing the soil in the container. Saturated hydraulic conductivity k_s and saturated moisture content θ_s are strongly related to the bulk density (Hill 1990).

The observed data of vertical advances of wetting front were used to evaluate the predictive ability of Equation 15. The results of the model evaluation for four application rates of 0.7, 1.0, 1.4, and 2.0 l/h, respectively, were plotted versus elapsed time as presented in Figure 2. As can be noted, the predicted model tracks the observed points and the path of the actual observations very closely. At larger times the simulated data are slightly lower than observed ones. This discrepancy can be due, as mentioned earlier, to the soil uniformity.

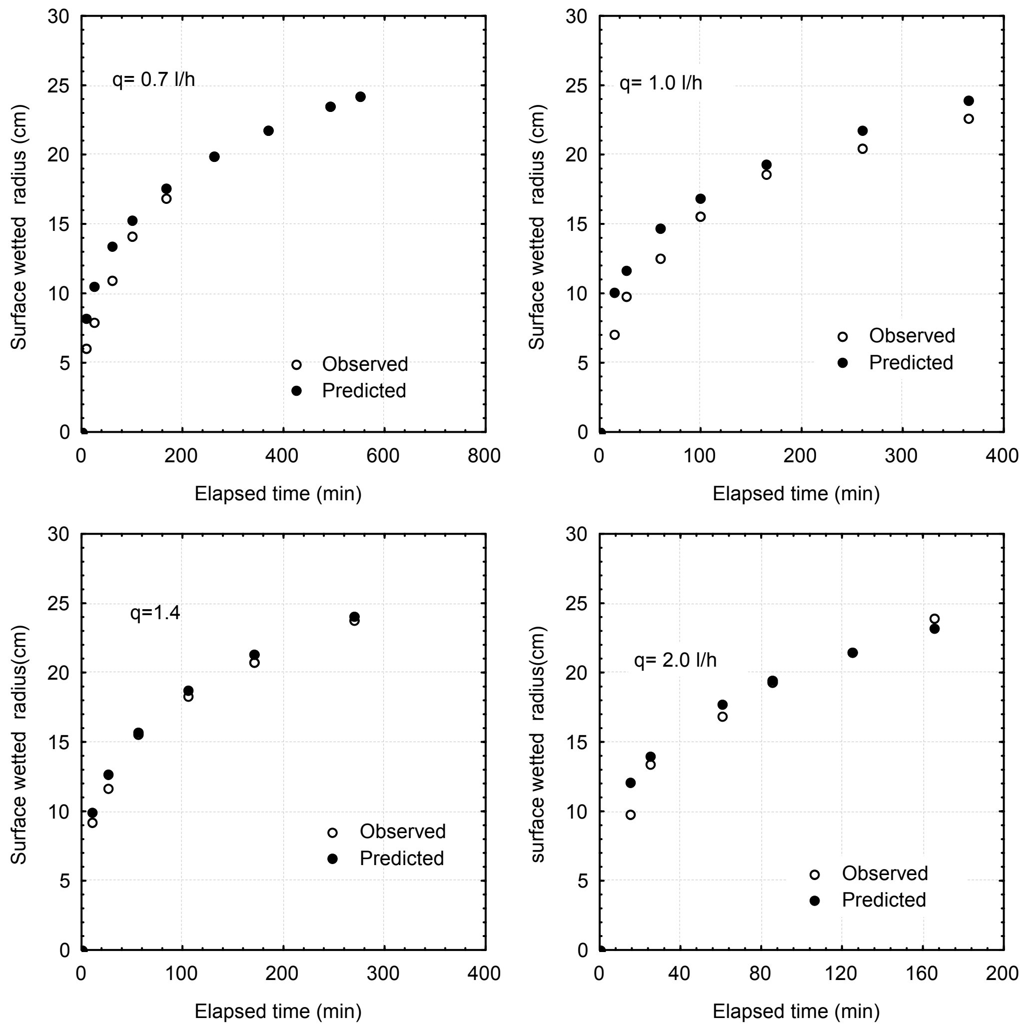


Figure 1: Observed and predicted surface wetted radius for sandy soil under application rate of 0.7, 1.0, 1.4 and 2 l/h.

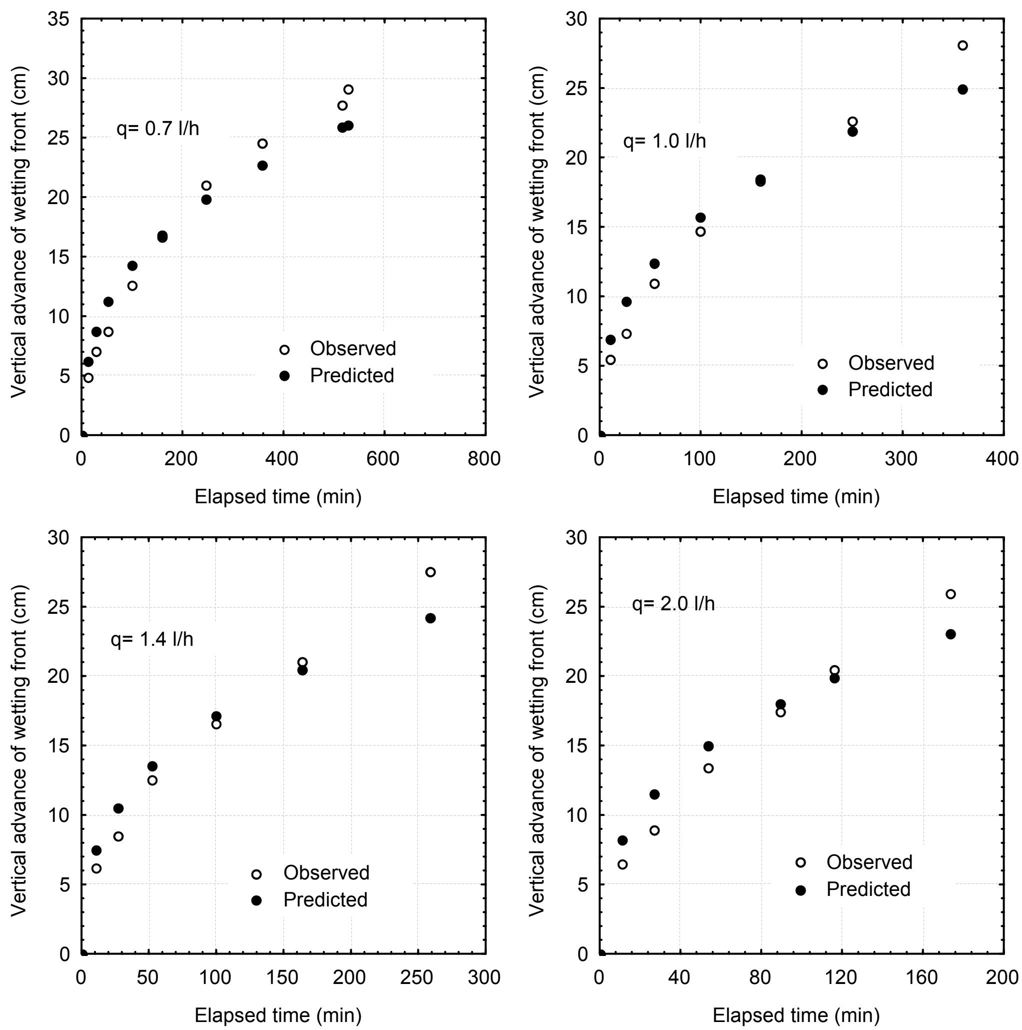


Figure 2: Observed and predicted vertical advance of wetting front for sandy soil under application rate of 0.7, 1.0, 1.4 and 2 l/h.

b) Data from Yitayew et al. (1998)

Running Equation 14 to determine the surface wetted radius required the hydraulic parameter of θ_s. However, θ_s for each soil were estimated using ROSETTA (Schaap et al., 2001), a pedotransfer function software package that uses a neural network model to predict hydraulic parameters from soil texture and related data. Inputting the data of particle size distribution for each soil to ROSETTA resulted in the following parameter estimates of θ_s, 0.3883, 0.3914 and 0.4008 for Loamy sand, Loam and Silty clay, respectively.

Figs. 3 through 4 show the extent of the experimental and simulated surface wetted radii at different time with 2.0 and 4 l/h application rates for loamy sand, loam and silty clay soils. As can be seen from the figures, the computed surface wetted radii agree well with the observed data especially for short duration. On the other hand, at longer duration the observed data show a faster movement of surface wetted radius compared with predicted data. The comparisons were found more favorably with loamy soil compared with the other soils.

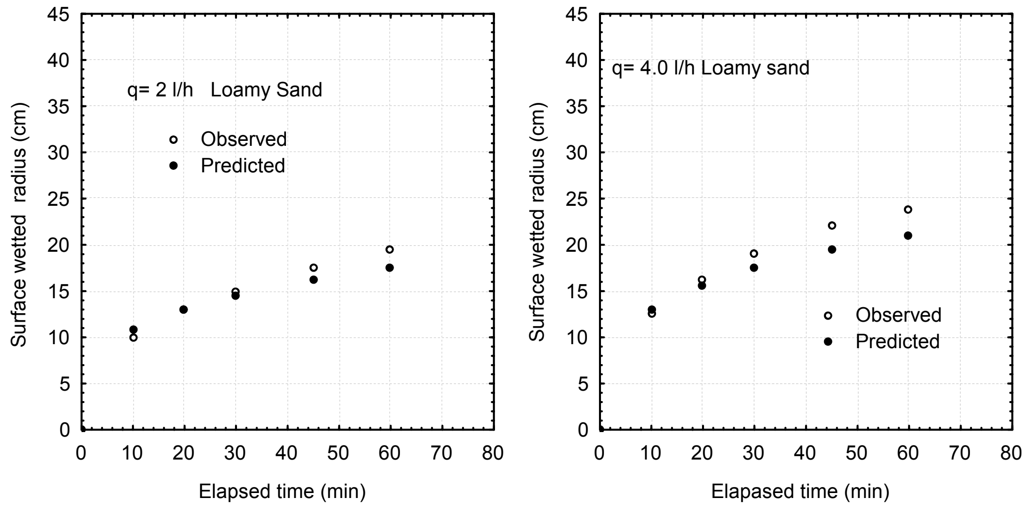
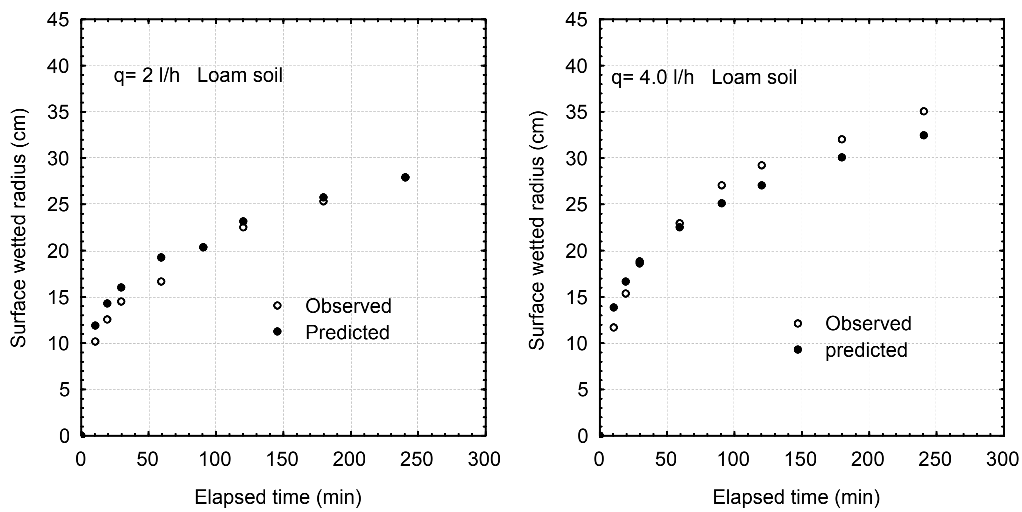


Figure 3: Observed and predicted surface wetted radius for loamy sand soil under application rates of 2.0 and 4.0 l/h



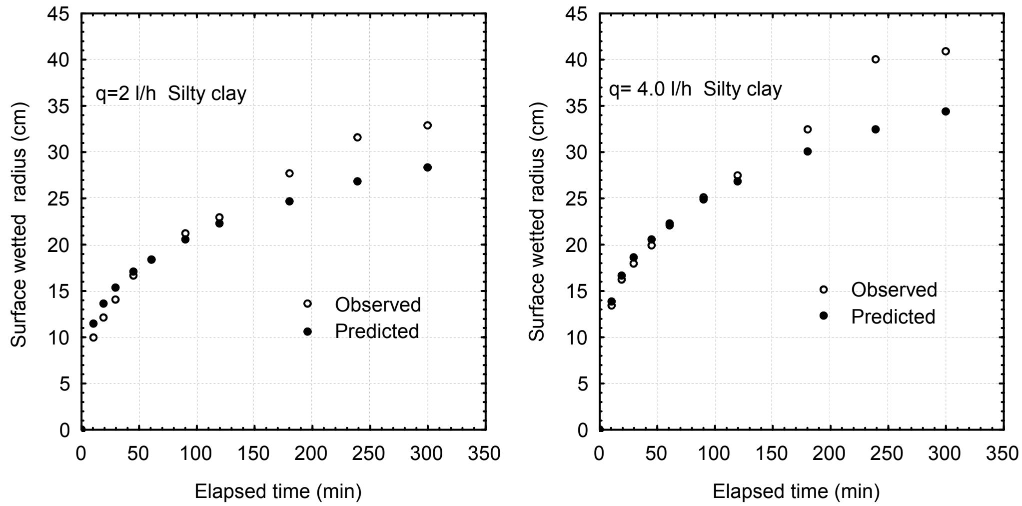


Figure 4: Observed and predicted surface wetted radius for loam and silty clay soil under application rates of 2.0 and 4.0 l/h

c) Data from Palomo et al. (2002)

Figure 5 shows the location of experimental and simulated surface wetted radius at different times. The values of k_s and θ_s used for simulation were 8.39 cm/h and 0.48. Excellent agreements between the simulated and experimental surface wetted radii are obtained for the whole time range. However, at longer duration the simulated data are slightly lower than observed ones.

The measured time for the wetting front to reach z is 30 cm was 156 min. At this time, the predicted maximum vertical advance of wetting front was 30.79 cm, which indicates excellent agreement between the measured and predicted value.

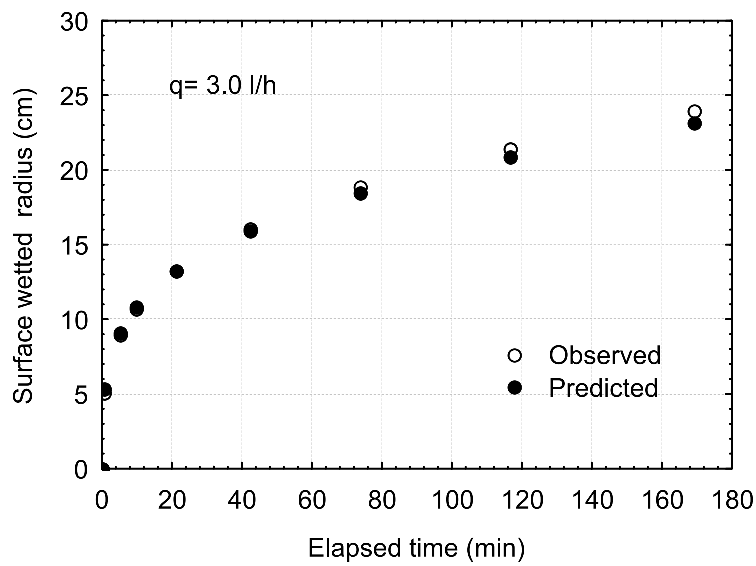


Figure 5: Observed and predicted surface wetted radius for coarser sandy soil under application rates of 3.0 l/h

D) Data from Risse et al. (1989)

Table 2 shows the inputs used in the prediction procedure and the predicted wetted radius for each trail. The saturated moisture content and saturated hydraulic conductivity were estimated by using ROSETTA. Table 2 also gives the percent error between the observed and predicted values. The average percent error for both treatments is only 8.7 %, but when broken down by treatments, the 3.78 l/h has an average difference of 6.37% while the 7.57 l/h treatment has an average error of 11% when compared to measured wetted radii. The discrepancies between predicted and observed data may be attributed to the variances within the observed data. For example, the wide range of observed wetted radius in case of treatments of 3.71 l/h and 3.56 l/h were 30.00 and 45.25 cm. This wide range cannot be explained using a texture variation of 3% and flow rate variation of less than 0.4 l/h.

Table 2: Comparison of the observed and predicted wetted radius for Cecil sandy loam soil

Flow rate (l/h)	Soil properties		Wetted radius (cm)		% Error**
	K_s (cm/h)	$\Delta\theta$	Observed *	Predicted	
3.71	2.68	0.199	30.00	39.65	24.30
3.97	2.68	0.199	33.75	39.65	14.80
7.91	2.68	0.199	31.00	39.57	21.66
8.29	2.68	0.199	36.50	39.57	7.76
4.09	2.58	0.200	37.25	39.68	6.13
3.94	2.58	0.200	36.75	39.68	7.40
7.46	2.58	0.200	36.00	39.61	9.13
7.57	2.58	0.200	32.25	39.61	18.59
7.95	2.40	0.201	37.75	39.59	4.67
8.10	2.40	0.201	37.75	39.59	4.66
3.56	2.40	0.201	45.25	39.68	-14.01
3.67	2.40	0.201	44.75	39.68	-12.76
8.21	2.83	0.202	34.50	39.24	12.08
7.91	2.83	0.202	35.50	39.24	9.54
3.44	2.83	0.202	38.25	39.33	2.76
3.94	2.83	0.202	30.50	39.32	22.40

* Average wetted radius as calculated from bromide tracer and water potential data

** Percent of error based on predicted data.

SUMMARY AND CONCLUSION

The soil type, the volume of water applied to the soil, and emitter discharge rate are the major factors affecting the wetted zone geometry. Equations 14 and 15, relating the surface wetted radius and vertical advances of wetting front to the saturated hydraulic conductivity and the average change of soil moisture content, the volume of water applied to the soil, and emitter discharge rate were developed using four published laboratory experiments results from Taghavi et al. (1984), Anglelakis et al.(1993), Hammami et al. (2002) and Li et al. (2003). The suggested equations were verified with other published experiments under different laboratory and field conditions. The results of these comparisons encourage the capability of using these equations in practice for a wider range of discharge rates and other soil types. DIPAC will ensure that water and fertilizer reach the crop root zone precisely and efficiently.

The quantitative discrepancies observed in some cases may be caused by any of the following:

1. Inadequacy of the adopted assumptions as it simplifies a very complex process.
2. Inability to create uniform initial conditions in the field.
3. Lack of precision in estimating the soil water parameters i.e., saturated hydraulic conductivity and saturated moisture content.
4. Different atmospheric conditions, where the predicted equations were developed based on experiments conducted under laboratory conditions.
5. The natural variability of the soil also could account for the observed differences.

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REFERENCES

Angelakis, , A. N, T. N. Kadir, and D.E. Rolston, 1993. Time-dependent soil-water distribution under a circular trickler source. Water Management 7:225-235.

Ben-Asher, J., CH.Charach, and A.Zeme, 1986. Infiltration and water extraction from Trickle Irrigation Source: The effective hemisphere model. Soil Sci. Soc. Am. J50: 882-887.

Dasberg. S, Or D, 1999. Drip irrigation. Springer-Verlag

Hammami, M., D Hedi. B., Jelloul and M.Mohamed. 2002, Approach for predicting the wetting front depth beneath a surface point source: Theory and numerical aspect. Irrig and Drain, 51:347-360.

Hillel, D. 1982, Introduction to Soil Physics. Chapters 1-7. pp 1-134.

Li, J, J.Zhang and L Ren, 2003. Water and nitrogen distribution as affected by fertigation of ammonium nitrate from a point source. Irrig. Sci 22:1:12-30.

Li, J., J. Zhang, M. Rao, 2004. Wetting patterns and nitrogen distributions as affected by fertigation strategies from a surface point source. Agri. Water Manag. 67: 89–104.

Palomo, M. J. F. Moreno, J. E. Fernández, A. Díaz-Espejo and I. F. Girón, 2002. Determining water consumption in olive orchards using the water balance approach. Agric. Water Manage. 1:15-35.

Risse, L. M., J. L. Chesness, 1989. A simplified design procedure to determine the wetted radius for a trickle emitter. Transactions of ASAE 32(6), 1909-1914.

Schaap, M.G., F.J. Leij, and M.Th. van Genuchten,2001. ROSETTA: A computer program for estimating soil hydraulic properties with hierarchical pedotransfer functions. J. of Hydrology, 251, 163–176.

Schwartzman, M, B. Zur,1986. Emitter spacing and geometry of wetted soil volume. J Irrig drainage Engr ASCE 112:242-253.

SPSS, 2003. Sigma Plot for Windows. Ver. 11.5. Chicago, Ill.: SPSS, Inc.

Taghavi, S. A., M. A. Marino and D. E. Rolston, 1984. Infiltration from trickle irrigation source. J. of Irrig. And Drainage Eng., ASCE 11094).

Yitayew M., A. A. Khan, A.W. Warrick, 1998. In situ measurements of soil hydraulic conductivity using point application of water. Applied Eng in Agriculture, 14(2):115-120.

Zazueta,F.S, G.A.Clark, A. G. Smajstrla and M. Carrillo, 1995. A simple equation to estimate soil-water movement from a drip irrigation source. Proc. of the fifth international microirrigation congress, ASAE. (581-856).

Survey of reclaimed water (wastewater) use in the Alabama turf industry

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Abstract: Grey water, which is reclaimed or directly discharged wastewater effluent, is used throughout the United States as an irrigation and nutrient source for pasture crops. In many municipalities reclaimed water application is required in golf course management, and plans for the safe storage and delivery of reclaimed water to golf course turf are mandatory. This study seeks to quantify the amount of reclaimed water currently applied to Alabama golf courses. The study covers two areas: 1) a survey of golf course superintendents to determine reclaimed water use, and to evaluate why they do or do not use reclaimed water, and, 2) an environmental survey with three cooperating golf course superintendents, including soil and water sampling to evaluate nutrient loading from areas to which reclaimed water has been applied. The goal of the study is to provide preliminary data for future research on the environmental impact of reclaimed water reuse.

Introduction: Nationally, the USDA has identified the green industry as one of the largest and fastest-growing segments of U.S. agriculture. According to a recent Auburn University study conducted by the Alabama Agricultural Experiment Station (2005), the green industry in Alabama has emerged as the largest cash crop in the stat,. This clearly illustrates the tremendous and far-reaching impact of the green industry in Alabama. Data ranks Alabama third in the nation in turfgrass and sod production and sixteenth in nursery and greenhouse production, confirming the state, regional, and national significance of Alabama's green industry. Alabama's green industry has been classified in four sectors, including 767 nurseries and commercial greenhouses, 69 turfgrass and sod operations, 1029 state-licensed lawn and landscape operators and 727 retail establishments. This paper focuses on an initial survey of golf course turf in the state.

The environmental impact of reclaimed water application to golf courses is largely unknown and unstudied. This is remarkable, given that such areas receive human foot-traffic, and that fairways are often located near environmentally sensitive areas such as water or wetlands. This survey seeks to quantify the amount of reclaimed water currently applied to Alabama golf courses. The work will include a survey of golf course superintendents and an environmental survey including soil and water sampling to evaluate nutrient flux and loading from areas to which reclaimed water has been applied. This combination of a background survey coupled with initial data collection will provide direction for follow-up research.

Reclaimed wastewater effluent, which is the liquid byproduct of sewage disposal, is a waste product requiring land or water disposal. Increasing concerns about direct water disposal of reclaimed water have led to land application; and reclaimed water has long been applied to agricultural land, where it provides both water and nutrients (Sumner, 2000). As supplies of potable water become more scarce, there is an increasing need to reuse waste water efficiently, especially as direct application of potable water to agricultural and recreational areas becomes less financially and environmental sustainable.

Golf courses are an excellent potential location for the disposal of wastewater effluent (Graves, 1982). Golf courses are a desirable location for waste water application because: 1) they are comprised of large areas of maintained turf (each course averages around 250 acres), 2) there are no crops to be harvested for food (nutrient uptake by food crops can pose secondary issues about health and safety), 3) warm-season turfgrasses are large users of nutrients and water, and, 4) there are no periods in which bare ground is exposed, which limits nutrient runoff concerns. However, there is little research that examines the effect of long-term effluent application on turfgrass quality, and its' impacts on the surrounding environment.

The limited research which has examined effluent use in turf systems has been regional in nature, relegated to the arid southwest United States. That research showed that three years of effluent irrigation increased soil salinity, phosphorus (P), and potassium (K) content (Mancino and Pepper, 1992). In another study effluent application reduced seed emergence of perennial ryegrass (*Lolium perenne*), and there were signs of overfertilization due to nutrients contained in the effluent (Hayes et al., 1990a). Last, there were increases in leachate salinity and leachate sodium due to effluent application, but the increases did not exceed current recommended limits for drinking water quality (Hayes et al., 1990b). However, the arid climate, regional nature of this research and other work (Harivandi, 1991) limits its applicability to the humid southeastern United States. In our region, soil salinity and sodium is less of a concern, while nitrate and P movement through soil and to water sources is a greater issue.

Objectives and significance of research: The objective of this research project is to: 1) assay the extent of current reclaimed water use on Alabama golf courses, 2) determine the limitations that prevent golf course superintendents from adopting reclaimed water use into their irrigation plans, and, 3) collect background soil and water nutrient data from three golf courses that are currently using reclaimed water in their management programs. This research is significant because there is currently no data available on the magnitude of reclaimed water use on Alabama golf courses. Such a survey is under way in Georgia, but Alabama needs this data as well. Such data will help the golf courses industry better manage its' waste water, and help the Alabama environment as a whole. Anecdotal information exists that several of Alabama's coastal courses use reclaimed water, and they have agreed to participate in the soil and water sampling part of this project. We need the complete statewide survey and additional cooperating golf courses to complete a statistically significant database, allowing us to complete for competitive grants.

Figure 1 shows the location of the 162 golf courses surveyed, ranging from the states' largest four cities, Montgomery, Huntsville, Birmingham, and Mobile, to a large number of rural towns and cities distributed across the state.

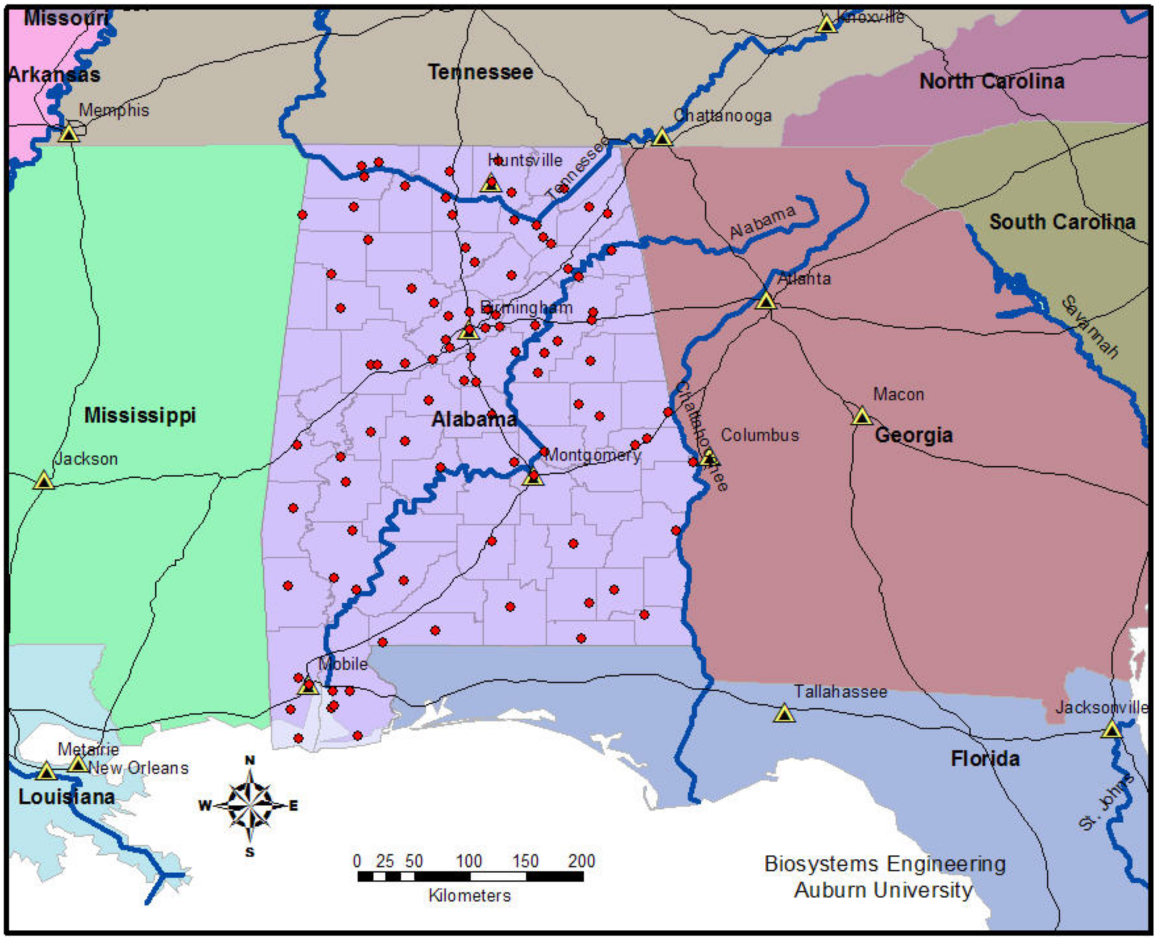


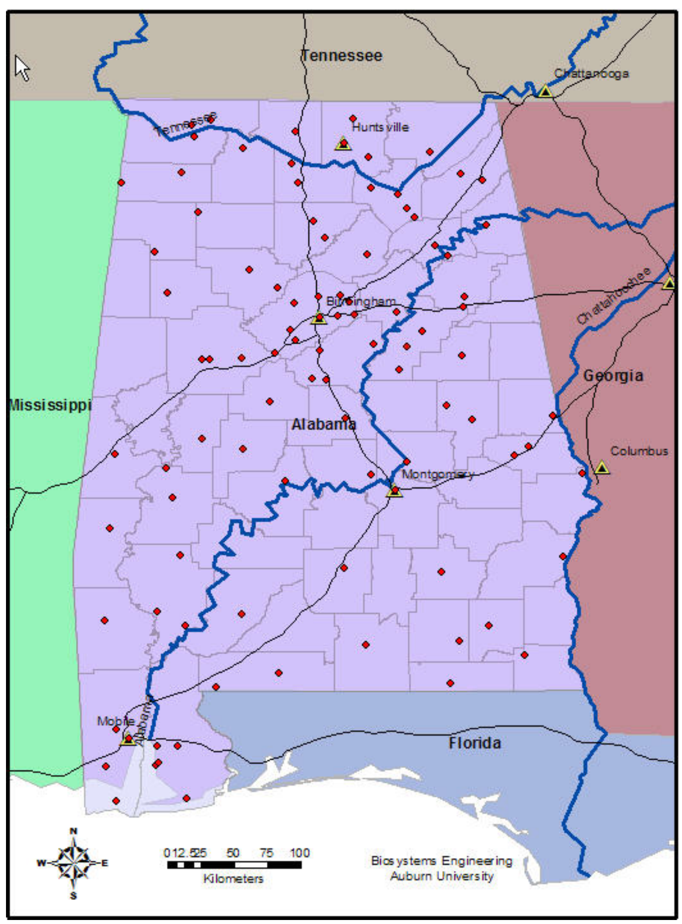
Figure 1. Location of 162 Alabama golf courses surveyed.

Methods: The survey is a short, one-page evaluation sent to every golf course in Alabama. The data base will ask if superintendents are using reclaimed water, and will follow-up with four to five related questions. The database of course names and addresses already exists, and previous experience in sampling this group has shown that superintendents are very willing to share agronomic information, and will do so without requiring anonymity. Thus, we can contact superintendents for follow-up discussion. These surveys are a success because: 1) they are short, and, 2) we offer a service. In this case the service is that we might use the course as a part of our monthly sampling study, and the superintendent will get detailed soil and water nutrient data as a byproduct.

Once participating courses have been identified, monthly soil and water sampling (for one year) will commence. At each course three replicate fairways that receive effluent will be used, and three replicate fairways that do not receive effluent will be studied. Fairways will be selected based on uniformity of soil type and other related factors (slope, etc.). Fairways will be sampled randomly in incremental depths (0-3, 3-6, and 6-12 inches) using a Giddings hydraulic soil probe, with approximately 10 samples removed from each fairway. Each soil sample will be analyzed separately, with all samples analyzed for pH, nitrate, ammonium, total N, P and K. Appropriate wet digestion techniques will be used for each analyte.

Bodies of water (ponds, streams or lakes) lying next to the selected fairways will also be sampled using a grab sample technique of 10 randomly collected samples. These samples will also be analyzed for nitrate, soluble phosphorus and dissolved oxygen. At minimum, over the 12 month sampling period approximately 6500 soil samples will be collected from participating courses (3 courses x 6 fairways x 10 samples x 3 depth increments x 12 months = 6,480). The number of water samples will likely be less.

Importance of findings to Alabama: Reclaimed water utilization by turfgrass in Alabama is both timely and environmentally responsible. This study is important to Alabama simply because there is currently no data available on the magnitude of reclaimed water use on Alabama golf courses. Such a survey is under way in Georgia, but there is no comparable effort underway in Alabama. This type of data will help the golf courses industry better manage its' waste water,



and help the Alabama environment as a whole. Additionally, a complete statewide survey incorporated into a statistically significant database, will allow us to compete for externally funded research grants promoting the wise reuse of this otherwise wasted resource. Surveys were sent out in mid-summer 2005. Results are currently being compiled

Acknowledgments: Authors gratefully acknowledge start-up funding from Auburn University's Office of the Associate Provost and Vice President for Research.

References:

Alabama Agricultural Experiment Station, 2005. "AU Study shows shift in agriculture" *In:* AU Report. Auburn University, Auburn, AL. May 23, 2005.

Graves, R.M. 1982. Grey water and green grass. *In:* Technical conference proceedings - Irrigation Association. Arlington, VA: The Association.

Harivandi, A. 1991. Effluent water for turfgrass irrigation. Univ. of California, Coop. Ext. Ser. Leaflet 215000.

Hayes, A.R., C.F. Mancino and I.L. Pepper. 1990a. Irrigation of turfgrass with secondary sewage effluent. II. Turf quality. Agron. J. 82:943-946.

Hayes, A.R., C.F. Mancino and I.L. Pepper. 1990b. Irrigation of turfgrass with secondary sewage effluent. I. Soil and leachate water quality. Agron. J. 82:939-943.

Mancino, C.F., and I.L. Pepper. 1992. Irrigation of turfgrass with secondary sewage effluent: soil quality. Agron. J. 84:650-654.

Sumner, M.E. Beneficial use of effluents, wastes and biosolids. 2000. Commun. Soil Sci. Plant Anal. 31:1701-1715.

OREGON WATER WISE LANDSCAPE CONTRACTOWATER WISE LANDSCAPE CONTRACTOR CERTIFICATION

OREGON LANDSCAPE CONTRACTORS ASSN. (OLCA)

ENVIRONMENTAL RESOURCES COMMITTEE

WHY DID WE DO THIS?

- INTERMITTENT DROUGHT
- POPULATION GROWTH
- PUBLIC AWARENESS

GREEN INDUSTRY CONFERENCES

- LANDSCAPE CONTRACTORS
- WATER PROVIDERS
- NURSERYMEN
- DISTRIBUTORS
- MANUFACTURERS

ENVIRONMENTAL RESOURCE COMMITTEE

- FORMED IN 2003
- OLCA REPRESENTATIVES FROM AROUND OREGON
- TASKED WITH FORMULATING A PLAN TO COUNTER WATER SHORTAGES AND RESTRICTIONS

WATER WISE PROGRAM

- BASED ON IA BMP'S

- QUALIFICATIONS BASED ON IA CERTIFICATIONS (CLIA, CID AND CIC)
- VOLUNTARY PARTICIPATION

WATER WISE GOALS

- RAISE STANDARDS AND AWARENESS IN INDUSTRY
- REALIZE WATER CONSERVATION THROUGH BMP'S
- AVOID RESTRICTION IN DROUGHT CONDITIONS

WATER PROVIDER PARTICIPATION

- ALL WATER PROVIDERS HAVE GREEN-LIGHTED THE PROGRAM
- LEVEL OF INVOLVEMENT VARIES THROUGHOUT OREGON
- ENDORSEMENT AND PROMOTION OF WATER WISE CONCEPT AND CONTRACTOR

OBSTACLES TO PROGRESS

- DROUGHT IS SPORADIC
- WATER COST RELATIVELY LOW
- WATER SUPPLY VS POPULATION GROWTH ISSUES
- VOLUNTARY AT THIS TIME

Water Smart Contractor Program: A Public-Private Partnership Ensuring Irrigation Efficiency in Southern Nevada

By Jason R. Eckberg

The average Southern Nevada home uses approximately 70% of its water for landscaping, and one-third of that water is wasted. This fact, along with the use of return-flow credits for indoor water use, has led to much of the focus of Southern Nevada Water Authority's (SNWA) conservation programs emphasizing outdoor (or consumptive) water use.

Major programs such as the *Water Smart Landscapes* program and the *Irrigation Clock Rebate* program were developed to provide a financial incentive to encourage water users to either change their landscape to reduce water consumption or change their irrigation controller to one that could water their landscape more efficiently. These, along with other programs, various educational outreach events, and publications focus on encouraging residents to enhance their landscape's irrigation efficiency.

One of the foremost struggles when asking residents or businesses to make changes to their landscapes or irrigation hardware is that many don't know what to do, and they are often intimidated by the process. As a result, SNWA responded by offering classes and workshops for do-it-yourselfers and those who were willing to learn how to make those changes on their own. Conversely, many people including businesses prefer to hire a contractor to perform the work although finding a qualified contractor can be an intimidating process.

Unfortunately, the process of identifying qualified contractors is even more difficult in Southern Nevada due to the large number of unlicensed contractors doing landscape work in this area. Regrettably, as SNWA is a public agency, it is prohibited from recommending specific contractors to its customers. Moreover, contractors who are licensed and knowledgeable about irrigation may not be adequately informed on local laws and codes, Southern Nevada's water situation, or programs offered by SNWA. For these reasons, SNWA developed the *Water Smart Contractor* (WSC) program.

Only contractor companies that have a C-10 license (landscaping) with the State of Nevada Contractors' Board can become a Water Smart Contractor. The Nevada State Contractors' Board will issue an annually renewable contractor's license upon finding that an applicant has sufficient experience, a general knowledge of building and construction laws, is knowledgeable in the classification applied for, and is financially responsible. This license ensures that the contractor is bonded, providing protection for our customers.

In addition to having a C-10 license, the owner and a minimum of 50% of the company's supervisory staff, must attend eight hours of classroom training and pass examinations on the material covered in order to participate in this program. To enroll, the interested contractor or individual would visit www.snwa.com, fill in an interest form, provide their license number, and download all the necessary forms. The eight-hour training is broken up into two, four-hour classes. The first session teaches contractors about regional water issues, local codes, laws and regulations, landscape planning, plant selection, maintenance, and SNWA programs. The second session deals exclusively with efficient irrigation techniques. An exam is given at the end of each class. (This training is available in English and Spanish.)

Once 50% of the supervisory staff has attended the classes and passed the exams, and SNWA has received and verified their C-10 license, the contractor signs an agreement to meet WSC equipment and performance standards. These standards include abiding by all laws, codes, covenants, and standards on installing spray, drip, or other irrigation types. The company then receives a certificate stating that it is a Water Smart Contractor, decals to use on its vehicles, and the rights to use the WSC logo on business cards and advertisements, etc. The contractor's name is then added to the list of Water Smart Contractors on www.snwa.com along with contact information and photos of past work submitted by the company. (In 2004, SNWA's website had over 200,000 visitors.)

The list of Water Smart Contractors is maintained on SNWA's website to help our customers locate landscapers who are knowledgeable in desert landscaping, SNWA's programs, and efficient irrigation. This program is a vital tool for SNWA as it educates local contractors on its programs, local codes, and regulations regarding landscaping, challenges specific to our region such as weather and soil, as well as proper irrigation techniques for both grass and desert landscaping.

SNWA also offers an annual refresher course to keep participants up to date on issues regarding water conservation and SNWA's related programs. Water Smart Contractors are required to attend this course to retain their Water Smart Contractor designation.

This education better ensures that the landscape work performed by a Water Smart Contractor is achieved in such a way that water is used efficiently while keeping landscapes healthy and attractive. As homeowners see attractively xeriscaped front lawns appearing in their neighborhood, they are inspired to convert their grass to water-saving desert landscaping.

Finally, the Water Smart Contractor program creates a partnership between people who create programs focused on increasing landscape water efficiency in the community and those who are in the field making a living, working with customers, and working on the landscapes that SNWA's conservation programs are focused on sustaining.

Slow the Flow Colorado

Sprinkler Irrigation Audits

Tiffany Graham, Horticulturist/Water Conservationist
Earthscape Design Associates
Paul Lander, Water Conservation Officer
City of Boulder Colorado

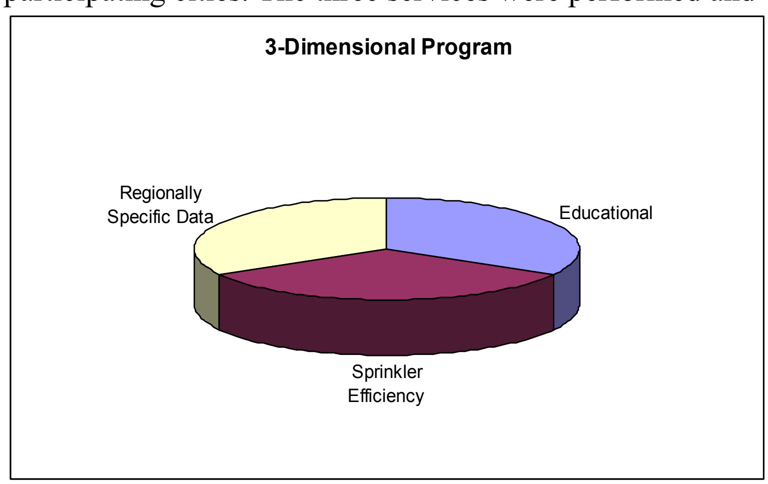
Abstract

After Colorado's severe drought in 2002, water conservation techniques and programs had reached the pinnacle demand generating Slow the Flow Colorado irrigation audit program. This program provides three dimensional services free to residential and commercial sites. It offers educational information to property owners, examines irrigation systems condition and efficiency, and provides water consumption data to the State of Colorado and cities within Boulder County. It was implemented in the city of Boulder during the summer of 2003 and the following summer extended to the county. Data collected includes precipitation rates that range from 0.22"/hr to 3.32"/hr for fixed spray heads and 0.09"/hr to 1.42"/hr for rotary sprinkler heads. Distribution uniformities data ranged from 14% to 92% for fixed spray heads and 16% to 92% for rotary sprinkler heads. These statistics coincide with other irrigation audit programs performed throughout the nation. Water records will be analyzed for water savings from audit in future.

Introduction:

The Slow the Flow Colorado program was implemented in Boulder Colorado during the summer of 2003 as an internship fulfilling the requirements for the Utah State University Water Efficient Landscaping Masters program. The irrigation audit program was patterned after the Slow the Flow, Save H_20, Utah's Water Check Program and the Irrigation Association's water auditing procedures.

The Slow the Flow Colorado program as stated in the abstract provides three dimensional services free to residential and commercial sites. It offers educational irrigation information to property owners from trained Colorado University interns, examines irrigation systems condition and efficiency by performing several tests, and provides water consumption data to the State of Colorado and participating cities. The three services were performed and documented for data collection.



FIRST DIMENSION

I. EDUCATIONAL:

The sprinkler irrigation audit provides a free one-hour consultation regarding the property owner's irrigation system. Residential owners and large commercial and industrial maintenance employees are involved in hands-on sprinkler education.

They learn the systems operating procedures, its current performance and if any, system malfunctions. They are given their own report card that allows them to evaluate how well their sprinkler system is performing and how to improve its operating capabilities.

IRRIGATION AUDIT INFORMATION

1. Recommendations
2. Precipitation Rate
3. Distribution Uniformity
4. Sprinkler Head Pressure
5. Irrigation Schedule

These actions and so called report card are important to reduce the deterioration of irrigation systems and reduce the usage of wasted water in the landscape. The sprinkler system operator and his/her behaviors are keystones in the amount of water used which also affect the water demand curve during the growing season.

II. BOULDER COUNTY IRRIGATION AUDIT RESULTS:

In the summer of 2003, the city of Boulder targeted sites that had dedicated water meters for the landscape. The following summer of 2004, landscapes included any type of meter from several cities within Boulder County. Data collected from these audits includes pressure taken at the sprinkler heads, precipitation rates that range from 0.22”/hr to 3.32”/hr for fixed spray heads and 0.09”/hr to 1.42”/hr for rotary sprinkler heads, distribution uniformity data ranged from 14% to 92% for fixed spray heads and 16% to 92% for rotary sprinkler heads. These statistics coincide with Slow the Flow Colorado’s sister program Slow the Flow, Save H_20 (*Jackson*) and also with nationwide irrigation audit programs.

Boulder County Pressure Rate Results

Table 1 demonstrates that 65% of the fixed spray zones exceeded 30 PSI and 9% of the rotary zones exceeded 70 PSI. Spray heads optimal operating pressure range from 20- 30 PSI and 50-70PSI (*Rainbird and Hunter)* for rotary type heads pending on manufacture design. Pressure that exceeds the manufacture details and specifications cause the distributed water droplets to decrease in size and drift away into the atmosphere or to other areas on the landscape that do not require water. During the summer of 2002, a catch cup test was performed on a Boulder residents spray zone that operated at 65 PSI. The distribution uniformity was a low 53%. The pressure was lowered to 30 PSI and a second catch cup test was performed identical to the first test. The distribution uniformity increased to an 85%. This outcome leads us to believe that pressure is an important element in water usage efficiency in the irrigation system.

Table 1. PRESSURE AT THE SPRINKLER HEAD	
Fixed Heads	65% over 30 PSI
Rotary Heads	9% over 70 PSI

The rotary type sprinkler head pressure varies on the manufacture, the model type, and the area the sprinkler head is designed to cover. Most of the industrial irrigation audit sites such as parks or soccer fields require 70 PSI or more. Residential sites that have rotary heads installed usually cover a smaller area in the landscape which requires a lower PSI, around 40-50. Table 1 suggests that rotary heads do not have high pressure problems as does the spray type heads.

Boulder County Precipitation Rate Results

Table 2 illustrates the precipitation rates among five different Boulder County cities. The Precipitation rate range from 0.22"/hr to 3.32"/hr for fixed spray heads and 0.09"/hr to 1.42"/hr for rotary sprinkler heads.

Precipitation rates have a dynamic range of results within the fixed spray type sprinkler head category but also with the rotary type. The average fixed sprinkler head applied 1.3"/hr which is a rate that most clay soils in Boulder County cannot absorb quickly enough. For this reason, clay soils irrigation schedules should be divided into intervals that will apply 0.5"/hr or less. Rotary sprinkler heads average application rate is 0.64"/hr which is half the amount of fixed sprinkler heads. With lower precipitation rates, rotary sprinkler heads application time should run longer than a fixed spray head to receive the mutual .5"/hr. Soil type and precipitation rate are two very valuable elements when calculating an irrigation schedule that does not over water or waste water.

Table 2. Boulder County's Precipitation Rates

		Fixed Sprays		Rotor	
	Audit #	Avg. PR (in/hr)	Range (in/hr)	Avg. PR (in/hr)	Range (in/hr)
Residential	416	1.3	0.22-3.0	0.64	0.1-1.5
		Fixed Sprays		Rotor	
Commercial	87	1.3	0.5-3.32	0.53	0.09-1.42

Catch Cup Tests and Efficiency Background

The distribution uniformity (DU) standards vary amongst irrigation, state, and city agencies allowing as low as 55% for fixed spray heads and 65% for rotary heads as acceptable operating conditions. Slow the Flow Colorado was patterned after the Slow the Flow, Save H_20, Utah's Water Check Program and the Irrigation Association certified water auditor training. Table 3 illustrates three different sprinkler head categories and what percentages are achievable, expected, and poor. Poor is the low DU category that advises not to recommend a water schedule due to the possibility of promoting water waste. Irrigation systems that operate at a 50% DU will apply two gallons of water to achieve the designed one gallon. Slow the Flow Colorado's minimum DU standards for their program are 70% for both the fixed spray type heads and the rotary type heads. The program also requires four catch cup tests per commercial site and two catch cup tests on residential sites.

Table 3. Estimated DU by Sprinkler Type and System Quality

SPRINKLER TYPE	EXCELLENT (achievable)	GOOD (Expected)	POOR (If lower than this, consider not scheduling)
Multiple Stream Rotors	85%	75%	60%
Single Stream Rotors	80%	70%	55%
Fixed Spray Heads	75%	65%	50%

(Irrigation Association Auditor Training Manual, 1996, p. *ix)*

Boulder County Distribution Uniformity Results

Table 4 illustrates the distribution uniformities among five different Boulder County Cities. The distribution uniformities range from 14% to 92% for fixed spray heads and 16% to 92% for rotary sprinkler heads.

Neither the rotary or fixed sprinkler heads are meeting the Slow the flow Colorado DU standard. There is clearly a dynamic range of poor and excellent performing irrigation systems. These inefficient sprinkler systems that are operating at 25% DU will use 4 gallons of water to receive 1 gallon on the landscape. Results like this are not only being compiled in Boulder County, but are being gathered in states such as Utah, Florida, and California. (Mecham, NCWCD). As a nation, our water industry needs to promote water efficient techniques and education to increase the efficiency and usage of our water resource. Statistics such as these are not acceptable performance in other natural resource industries and should not be accepted in the water industry.

Table 4. Boulder County's Distribution Uniformities

		Fixed Sprays		Rotor	
	Audit #	Avg. DU %	Range %	Avg. DU %	Range %
Residential	416	51	14-92	52	16-92
		Fixed Sprays		Rotor	
Commercial	87	55	21-81	54	19-78

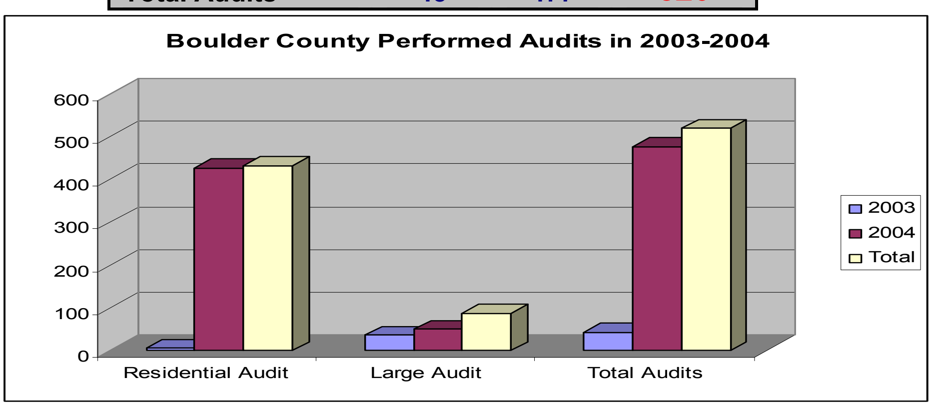
III. WATER CONSUMPTION DATA:

Slow the Flow Colorado performed 520 irrigation audits in Boulder County during the summers of 2003 and 2004. Out of the 520 audits, there are 433 residential sites, 32 home owners' association sites, 30 parks, and 25 commercial sites. A waiting list of 236 properties requesting an irrigation audit was compiled at the end of the 2004 season for the following season of 2005.

The 520 irrigation audits provide statistics from a variety of different landscape sites. In 2003, water records were requested from the water providers to reveal water usage on the landscape. One audited commercial property site from the summer of 2003 discovered that in the year 2001, 1,790,000 gallons or 144 inches were applied on 19,930 square feet. The actual water demand for

Table 5. **BOULDER COUNTY IRRIGATION AUDITS 2003-2004**

	2003	2004	Total
Residential Audit	6	427	433
Large Audit	37	50	87
Total Audits	43	477	520



236 Properties that are on a Waiting List for 2005 this turf site was 335,482 gallons or 27 inches. This converts into 433% water over use (*View Point*). The same year, a residential audited site of 2,755 square feet of landscape applied 192,800 gallons or 85 inches of water. The actual water turf need was 46,376 gallons or 27" (*Spotswood*). This converts to 316% over watering. Slow the Flow Colorado has the potential to decrease their water usage through the irrigation audit program. Slow the Flow save H_20 Utah residential irrigation audit properties have reduced their water usage by 10-15% and commercial irrigation audit properties reduced to 15-20% (*Jackson and Mohadjer, P, Saving Utah Water in the Fifth Year of Drought*). Boulder County's water savings has not yet been calculated.

STATE, CITY AND WATER PROVIDER DATA

- Water Consumption Behavior
- Water Use Overages
    - % Over Evapotranspiration
    - In inches
    - In Gallons
- Potential Water Savings

These above mentioned record generates the average water consumption in inches which help indicate trends of water usage behavior pending on rainfall. Table 6 provides data from the city of Boulder and illustrates the use of more than 27" (the average historical water use) of water was applied on the landscape between the years of 1997 - 2003. 1998, 2000, and 2001 were low rainfall years which reveals water usage increase above turf water requirement. In the growing season of 2002, the city of Boulder enforced water restrictions. The water restrictions and severe drought explain the small 3 inches of water used over the turf water requirement. The year 2003, water consumers remember the water restrictions and drought from the previous year, but are not enforced to conserve by city regulations. There is a 100% increase in water usage from 2002, but have not increased their usage to reach the level as in the years between 1997-2001. This water usage increase can be decreased or ceased by instigating continual water techniques and education programs that provide knowledge on how to properly irrigate vegetation as indicated in several different irrigation audit programs.

Table 6. The Average Property Water Use in Inches for Boulder County

	1997	1998	1999	2000	2001	2002	2003
# of Samples	76	138	145	189	250	263	261
Average "	40	39	33	43	43	30	33
Turf Requirement	27	27	27	27	27	27	27
Inches Over watered	**13**	**12**	**6**	**16**	**16**	**3**	**6**
Rainfall " (NCWCD B. Mecham)	13.37	7.92	14.93	5.96	8.92	5.91	9.05

IV. CONCLUSION:

The future for urban water consumption in Boulder and neighboring counties is unknown and can be dynamic pending on the behavior of humans and the weather. These issues force state, city, and water entities to obtain regionally specific data and numbers from water conservation programs. More irrigation audit programs will be implemented or enforced as water supplies begin to diminish or cities begin to grow. Pressure, precipitation rate, and distribution uniformity statistics have provided knowledge for improvement in the irrigation systems design, installation, components, and water use that have also helped refine the education process and the technical process of irrigation audit programs. The Slow the Flow Colorado program will have more catch cup results and water usage behavior data for future audited years and follow up data comparing the years to each other.

Appendix

Slow the Flow Colorado Participants an Procedures 2003-2004

Funding: The city of Boulder funded the irrigation audit program in 2003 and the Center for ReSource Conservation housed the irrigation audit program for the summer of 2004. The center received a grant from the Colorado Water Conservation Board and matching funds from each participating municipality. The city of Boulder Water Conservation Office provided the technical support and program procedures for both years.

IRRIGATION AUDITORS

1. Jeannine Shaw
2. Melanie Meyers
3. Zach Temple
4. Sam Johnson
5. Nate Brown
6. Tiffany Graham

PARTICIPATING CITIES

1. Boulder
2. Longmont
3. Erie
4. Louisville
5. Lafayette

PROGRAM ADMINISTRATORS

Kara Csbrik
Tiffany Graham

Water Audit Methods

Water audit methods determine the precipitation rate, distribution uniformity, water pressure, and the overall quality of the irrigation system which follow the Irrigation Association *(IA Handbook, 1996).*

#1. Visual inspection

- Observing each zone's sprinkler heads and pipes that may be performing in good or poor condition. Providing recommendations to improve the efficiency of the irrigation system.

#2. Catch cup test

- Precipitation Rate- Sprinkler systems amount of water that it applies in a given hour. Different for each sprinkler system due to variable of material, hydraulics, and maintenance.
- Distribution Uniformity- A percentage that reflects how evenly the water is being distributed in the designed turf area.

#3. Soil Sample

- A soil probe will sample the length of the turf roots for drought resistance and soil type for water infiltration rate and scheduling.

#4. Result Sheet

- A sheet for homeowners and a report for large irrigated sites will be given with the test results and recommendation for the sprinkler irrigation site.

#5. Landscape Measurement

- The measurement is calculated for water usage on the landscape per site.

BIBLIOGRAPHY

Jackson, E. K., and Mohadjer, P. 2003. Saving Utah Water in the Fifth Year of Drought. 2003 Proceedings, National Irrigation Association, 2003 Conference, San Diego, CA.

Mecham, B. 2004. Historical Reference ET for Northern Colorado Front Range. Northern Colorado Water Conservancy District, 2004.Berthoud, Colorado. http://www.ncwcd.org/ims/ims_info/HRET_NCFR.pdf

Mecham, B. 2004. Using Distribution Uniformity to Evaluate the Quality of a Sprinkler System. Proceedings, National Irrigation Association, 2004 Conference, Tampa, Florida.

The Irrigation Association, Certified Landscape Irrigation Auditor Training Manual, 1996. Falls Church, Virginia.

Rainbird Landscape Irrigation Product Catalog, 2005. www.rainbird.com.

Hunter Landscape Irrigation Product Catalog, 2005. www.hunterindustries.com.

Slow the Flow, Save H_20

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Utah State University Extension

Abstract

An extensive radio and television water conservation campaign was initiated in 1999 when a dry year turned into a six year drought. Irrigation system audits of commercial properties were made free to the public by the Central Utah Water Conservancy District and its partners. Upon examination of water use records over a three year period, 106 large water use properties were able to reduce their seasonal water use per landscape acre by 14.9%. After receiving an irrigation system audit, properties were able to save 10.1% the year of the audit and 4.8% the year following the audit. One elementary school was audited before and after installation of a new weather-station based system. Landscape water was reduced from 1,254,528 to 712,206 gallons per acre. This 56% reduction in culinary water use brought the school down to within 14% of the evapotranspiration rate for that year.

Introduction

Water conservation efforts in Utah came to a forefront in 1999 when a dry year turned into a six year drought. The drought situation along with a forecast of rapid population growth in the state was responded to by the Central Utah Water Conservancy District and its partnering agencies with the development of the *Slow the Flow, Save H_20* water conservation campaign.

Data from the Utah Division of Water Resources in 1999 indicated that about 50% of Utah's culinary, treated water was used outdoors, primarily in the landscape (*Utah Division of Water Resources, 2003*). Outdoor water waste was targeted by offering irrigation system audits or "water checks" free to the public under a grant provided to Utah State University Extension by the Central Utah Water Conservancy District and its partnering agencies. The water check program was initiated in 1999 as part of Utah's *Slow the Flow, Save H_20* water conservation program and has continued to grow through 2005 (*Jackson and Rosenkrantz, 2004*). The *Slow the Flow, Save H_20* water conservation program, including water checks was adopted and endorsed as the statewide water conservation program in 2003 by Utah's Governor, Mike Leavitt (*Jackson and Mohadjer, 2003*). Water audits that were performed for commercial, institutional, industrial, large private and public properties were coined "large water audits" for the purpose of differentiating the large water use properties from a residential water check program also serviced by Utah State University Extension. (*Jackson, 2000; Lopez and Jackson, 2004*).

As limited information is available about system performance of operational irrigation systems, data was collected for distribution uniformity (system efficiency), precipitation rate (system output), and operating head pressure for large water audits within this study. This information provided an indication of the types of irrigation systems being used in Utah, often despite their poor performance.

Data collected from large water audits was twofold in purpose. Not only was information gathered about existing sprinkler system performance; participant water use records were also evaluated to determine program effectiveness (*Jackson and Leigh, 2004*). Additionally, most water professionals recognized that the majority of water waste occurred in the landscape although the amount of water waste had not been documented (*Utah Division of Water Resources, 2003; Jackson and Leigh, 2004; Jackson, 2000*).

The overall objective of this study was to determine the practicality of reducing landscape water use through recommending irrigation scheduling for turf based on actual irrigation system precipitation rates and historical evapotranspiration data. Additionally, this study targeted water use through providing recommendations for proper irrigation system maintenance and repair in personalized written reports. An evaluation of water use records for 106 large water use properties determined that landscape water use could be reduced as participants followed the site specific recommendations provided to them through participation in the water check program (*Jackson and Leigh, 2004; Jackson and Leigh, 2004; Lopez and Jackson, 2004).*

Materials and Methods

Water audits were performed by trained college interns employed by Utah State University Extension and were funded through grants provided by the partnering agencies of the Central Utah Water Conservancy District. Interns were generally from Utah State University, Brigham Young University, or Utah Valley State College in the course of studying horticulture, biology, natural resources or engineering.

Each large water audit consisted of a comprehensive evaluation of the participant's landscape and irrigation system, sprinkler catch cup and pressure tests, as well as a simple analysis of turf root depth and soil texture. These methods were similar to the guidelines established by the Irrigation Association for conducting an irrigation system water audit (*IA Manual, 2002*). Participants in the program received a personalized written report including recommendations for irrigation system improvements and a site specific irrigation schedule based on catch cup results.

A typical large water audit would begin with a walk through of the irrigation system. Common irrigation system problems were targeted and often included tilted, clogged, broken or sunken sprinkler heads, mismatched sprinkler heads, lack of head to head coverage, rotor zones without matched precipitation rate, and various other design or maintenance flaws. The various sprinkler system problems were noted and included in the written reports provided for the participants along with recommendations for improvements.

Several catch cup tests were performed at the audit sites to determine sprinkler precipitation rate (PR) and distribution uniformity (DU). Catch cup tests were performed on zones or stations in the landscape that were deemed representative of the entire irrigation system. The number of tests performed varied by site and especially by the size of the landscape. For each zone or station being tested catch cups were placed at and in between each sprinkler head in a grid. The number of catch cups placed within a zone also varied by site and size of the area being tested with a minimum of 20 cups used per test. Catch cups used for this study were designed and manufactured by the U.S. Bureau of Reclamation and were calibrated to measure water depth in inches or centimeters.

Precipitation rate, or application rate of the sprinklers in inches per hour was determined by multiplying the average depth of catch cups used for one test by sixty, divided by the minutes that the test ran, [PR inches/hour = (average depth of catch cups in inches * 60) / X Minutes]. Distribution Uniformity, or evenness of water application represented as a percentage from 0-100% was determined by dividing the value of the average depth of the lowest 25% of catch cups used for one test by the average depth of the total number of catch cups used and multiplying that value by 100, [DU% = {(average depth of the lowest 25% catch cup values) / (average depth of the total number of catch cup values)}* 100]. Systems were considered "efficient" if they had a DU rating of 70% or above, as influenced by the standards set forth by the National Irrigation Association.

Operating sprinkler head pressure in pounds per square inch (PSI) was measured using pressure gauges attached to a pitot tube for rotor heads or adapters made to fit in place of the nozzle for fixed heads. Pressure was generally measured at stations where catch cup tests were performed and was compared to industry standards for proper operating sprinkler head pressure in the water audit reports.

Hollow steel core type soil probes were used to determine soil texture as well as turf root depth in inches for each site. A simple feel test was used to determine if the participant's soil was predominately sand, loam, or clay for irrigation scheduling purposes. Existing turf root depth was primarily measured to give an indication of pre-water audit irrigation habits. Although current irrigation schedules were noted during the site inspection stage for the large water audits, root depth gave additional insight to these habits as irrigation schedules are generally not constant.

Information gathered at each water audit was analyzed and combined to form customized, site-specific irrigation schedules. A standard irrigation schedule was developed based upon analysis of historical evapotranspiration (ET) rates along the Wasatch Front over a thirty-year period. Evapotranspiration, or water loss from soil evaporation combined with plant water use and transpiration is measured in inches. ET data combined from several weather stations in the area was used. Historically, ET for the Wasatch Front is around 25 inches of water for the total growing season, April through October. A standard of ½ inch of water applied for each irrigation throughout the growing season was set forth with the following intervals to apply 25 inches of water throughout the season. Intervals or irrigation frequency followed monthly ET rates as it was recommended that turf be watered every fourth day in May, every third day in June, July and August, every sixth day in September and every tenth day in October until system shutdown.

The standard irrigation schedule was adapted for the participants based upon the sprinkler precipitation rates and soil texture at the audit sites. Individual precipitation rates from catch cup tests were used to determine sprinkler system runtime to apply ½ inch of water.

Soil texture was also used for scheduling purposes to determine if a recommendation for cycling runtimes would be appropriate. Cycling runtimes was recommended as the practice of breaking up sprinkler runtimes to allow water to penetrate the soil without runoff. This recommendation was for sprinklers to be turned on and off multiple times with rest periods of about an hour between each cycle thus allowing the water to percolate deeper into the soil profile. Soil infiltration rates for clay, loam or sandy soil textures determined how long the sprinklers could run without runoff. The total number of minutes from each of the cycles would apply the recommended ½ inch of water.

Irrigation runtimes were not corrected with distribution uniformity values for water audits, unlike the methods of the National Irrigation Association (IA). Under IA methods, if an irrigation system was considered 70% efficient, runtimes throughout the season would be increased by 30% to compensate for uneven application of water. For the purposes of this study it was determined that the capillary properties of water could be exploited through lateral movement of water in the soil caused by soil texture horizons. This approach was used to compensate for uneven water application. A trail and error recommendation was used as participants were instructed to set their irrigation controllers to the suggested runtimes and then observe the landscapes. If dry spots occurred then additional watering time could be added only to those areas rather than for the entire landscape in an effort to conserve as much water as possible.

In order to track the success of the program water use records were obtained from the water providers of the audit participants and analyzed. For each year of records obtained water consumption values were totaled by year and converted into gallons. In order to estimate water applied to the landscape for properties with indoor and outdoor water use from the same meter, usage from winter months was averaged, multiplied by 12 and subtracted from the total gallons used. Water use was converted into inches applied to the landscape and compared to the yearly ET value through the following formula [(landscaped acres/outdoor gallons applied to landscape)*(1/27154)]. An irrigated landscape size was needed for the conversion of gallons into inches, thus properties were measured for irrigated landscape in square feet using measuring wheels and global positioning units. Water use records were evaluated for total gallons, outdoor gallons, gallons per acre, inches applied to the landscape and percent of ET with an irrigated landscape calculation. A sample of 58% of the water records from audited properties were obtained and evaluated representing 106 properties. Water usage of these 106 properties was evaluated comparing water use the year before the water audit, the year of the audit, and the year after the audit. Unfulfilled water record requests, changing landscape sizes, broken water meters, denial of access to water records and primarily the use of secondary un-metered water made it impossible to track every property audited (*Jackson and Lopez, 2005*).

Irrigation system information was collected, compiled and evaluated for large water audit participants from 2001 through 2004 and is included in this summary. Participant water use was collected and compiled for participants from 2001 through 2004 although an evaluation of water use records for 2004 participants is not yet available. Thus, the following will include irrigation system data for 2001 through 2004 participants while water use data is limited to 2001 through 2003 participants.

Results and Discussion

For the purposes of data summarization participants in the large water audit program were placed into categories. Number of audits completed within each category is listed in parenthesis: Apartments (19), Businesses (55), Churches (19), Golf Courses (6), Homeowners Associations (51), Public Facilities (48), Parks (67), and Schools (44), along with 2 properties deemed as "Other". This total of 311 large water audits was conducted from 2001 through 2004. Data was collected and compiled for 302 of these properties as 9 of the properties were considered visual inspections or had other extenuating circumstances such as excessive wind during testing, un-testable mixed sprinkler head types or properties where the irrigation system was undergoing drastic changes or replacement (*Jackson and Lopez, 2005*). The vast majority of the large water audits were conducted in Salt Lake and Utah Counties.

System performance of operational irrigation systems was determined from 302 properties. Catch cup tests from these properties revealed that the average precipitation rate for rotor heads (large, rotating heads) within this study was 0.6 inches per hour with an average distribution uniformity value of 58%. The average precipitation rate for fixed heads (small, non rotating popup heads) within this study was 1.6 inches per hour with an average distribution uniformity value of 54%. This data for rotor head PR and DU values represents 605 total catch cup tests as data for fixed head PR and DU values represent 456 total catch cup tests from the 302 properties tested.

Catch cup data from the large water audits shows the types of irrigation systems being used in Utah. The data for distribution uniformity in particular shows that poor irrigation systems are generally the norm. It wasn't uncommon to find newer irrigation systems that also fell below the standard of 70% distribution uniformity. Inexpensive water, lack of proper design and few installation regulations have promoted inefficient systems in Utah for many years. Average distribution uniformity values for each of the property categories audited are depicted in the following tables.

Table 1 Distribution Uniformity – Fixed Head Average and Range

Fixed Head Distribution Uniformity %				
Property Type	Average	High	Low	Standard Deviation
Apartments	57	75	33	11
Businesses	57	83	29	12
Churches	59	77	27	12
HOA'S	55	86	3	14
Public Facilities	55	83	21	12
Parks	44	75	2	20
Schools	54	90	5	16
Database AVG	**54**	**81**	**17**	**14**

Table 2 Distribution Uniformity – Rotor Head Average and Range

Rotor Head Distribution Uniformity %				
Property Type	Average	High	Low	Standard Deviation
Apartments	53	74	20	16
Businesses	56	84	20	13
Churches	61	80	26	14
Golf Courses	67	92	30	13
HOA'S	56	79	28	12
Public Facilities	60	80	30	12
Parks	54	85	6	16
Schools	57	82	16	14
Database AVG	**58**	**82**	**22**	**13**

Most sprinklers apply water faster than a heavy rainstorm, which weathermen classify as rainfall greater than 0.4 inches per hour. High precipitation rates cause runoff or puddling, create waste, and prevent the turf root system from receiving all the moisture and oxygen it requires. High precipitation rates and runoff can be a problem primarily with fixed heads. The following tables compare precipitation rate data averages by sprinkler head type for the various property categories (*Jackson and Lopez, 2005*).

Table 3 **Precipitation Rate – Fixed Head Average and Range**

Fixed Head Precipitation Rate (inches per hour)				
Property Type	**Average**	**High**	**Low**	**Standard Deviation**
Apartments	1.6	3.1	0.6	0.5
Businesses	1.6	3.3	0.4	0.6
Churches	1.8	3.4	0.9	0.5
HOA'S	1.6	4.0	0.3	0.6
Public Facilities	1.6	2.9	0.6	0.4
Parks	1.4	2.6	0.3	0.6
Schools	1.7	4.7	0.4	0.7
Database AVG	**1.6**	**3.4**	**0.5**	**0.6**

Table 4 **Precipitation Rate – Rotor Head Average and Range**

Rotor Head Precipitation Rate (inches per hour)				
Property Type	**Average**	**High**	**Low**	**Standard Deviation**
Apartments	0.5	1.1	0.3	0.2
Businesses	0.6	1.1	0.2	0.2
Churches	0.7	2.5	0.3	0.4
Golf Courses	0.6	1.1	0.4	0.2
HOA'S	0.7	1.9	0.2	0.3
Public Facilities	0.6	2.5	0.2	0.4
Parks	0.5	1.6	0.1	0.2
Schools	0.5	1.7	0.1	0.3
Database AVG	**0.6**	**1.7**	**0.2**	**0.3**

Pressure directly affects sprinkler head performance and was commonly found to be operating at higher or lower values than manufacturer recommendations. The proper pressure for fixed heads is between 15 and 30 pounds per square inch (psi) while rotor heads operate best at pressures greater than 50 psi (*Rainbird Product Catalog, 2005*). High pressure causes misting and increased evaporation, lowers the distribution uniformity, and creates undue stress and wear on the sprinkler system. Low pressure can be detrimental to an even sprinkler coverage pattern. The following tables depict operational sprinkler head pressures for the 302 properties tested by property type.

Table 5 Water Pressure – Fixed Head Averages and Range

Fixed Pressure (PSI)				
Property Type	Average	High	Low	Standard Deviation
Apartments	43	75	19	15
Businesses	51	112	18	24
Churches	70	104	30	24
HOA'S	54	110	18	22
Public Facilities	53	108	20	21
Parks	59	100	15	20
Schools	56	100	24	21
Database AVG	**55**	**101**	**21**	**21**

Table 6 Water Pressure – Rotor Head Averages and Range

Rotor Pressure (PSI)				
Property Type	Average	High	Low	Standard Deviation
Apartments	51	78	14	18
Businesses	58	117	22	22
Churches	55	85	24	19
Golf Courses	71	100	45	13
HOA'S	59	104	20	19
Public Facilities	55	80	20	16
Parks	68	100	20	17
Schools	55	90	28	15
Database AVG	**59**	**94**	**24**	**17**

It is worth mentioning that the average large water audit participant had a turf root depth of only 4.8 inches. With a uniform soil and proper irrigation, a bluegrass lawn should have a root system up to 12 inches deep. A short root system would make it necessary to water more frequently during the summer to keep the lawn from going dormant (*Jackson and Lopez, 2005*). Average turf root depth depicted by property type is included in the following table.

Table 7 Root Depth – Averages and Range

Root Depth (inches)				
Property Type	**Average**	**High**	**Low**	**Standard Deviation**
Apartments	4.7	11	2	1.7
Businesses	4.4	9	1	1.6
Churches	5.2	9	2	1.5
Golf Courses	3.4	4.5	2.6	0.7
HOA'S	4.8	11	1	1.7
Public Facilities	4.6	9	2	1.4
Parks	5.7	13	2	2.4
Schools	5.2	12	2	2
Database AVG	**4.8**	**9.8**	**1.8**	**1.6**

The 311 irrigation water audits covered in this report do not constitute a randomized sample of apartments, small businesses, churches, golf courses, homeowners associations, public facilities, parks and schools along the Wasatch Front. Each property requested assistance in evaluating their system and determining the correct watering schedule. For statistical evaluation, there is no randomized control group for comparison. Therefore, each property has been compared to its own water use record by year. The water used over the growing season was evaluated the year before the water audit compared to the water used during the audit year followed by the water used the year after the water audit where records were available. Three-year water records for 106 properties were evaluated in several ways as shown in the **Table 8**.

Total Gallons Used per Property: The first row in **Table 8** shows the evaluation using the total number of gallons used per property for each of the three years. This number includes both indoor and outdoor water use and varies by the size of the irrigated landscape which ranged from 0.2 of an acre for a small business up to 388 acres for a golf course. By this method, the 106 properties in the water record database saved an average of 11.8% the year of the audit and followed by another reduction of 8.2% the year following the audit. By this method of calculation, the large golf courses and parks had more influence on the average than the smaller businesses and apartment complexes.

Total Gallons Used per Acre: The second method of evaluation reduces the variation caused by property size through calculating the total gallons used per season per one acre of landscape. Results from line two of **Table 8** indicate a reduction in water use by 4.2% the year of the audit and by 8.5% the year following the audit and shows a somewhat smaller savings than total gallons alone.

Outdoor Gallons Used per Acre: As irrigation system audits concentrated on outdoor water conservation line three of the table is based only on outdoor water used during the growing season. With this method, the amount of water used outdoors required calculation. This was not always an easy task since some water purveyors did not read the water meters on a monthly basis. Often times, the water consumption values provided by the water districts for the winter months were estimated with corrections made in later months. This method of calculation (outdoor water use per season per acre) indicates a savings of 10.1% the year of the audit and 4.8% the year following the audit resulting in 14.9% reduction in water use over a two year period (*Jackson and Lopez, 2005*).

Inches of Water Used per Acre: The fourth set of calculations converted gallons of water used into inches for use in comparison to evapotranspiration values. The results of calculation through this method were very close to the outdoor gallons of water used.

Percent Reduction in Evapotranspiration (ET): Outdoor water use can be evaluated through comparing usage to the turfgrass water requirement (net ET_{turf}). This comparison is valuable because it accounts for variability in weather patterns which may influence irrigation schedules. For this study a comparison was made to the evapotranspiration value for each year of water use. Since evapotranspiration values change each week, month and year, this set of calculations has the most room for error due to the number of calculations and conversions required. By this method, the average property in the database saved 10.7% the year of the audit and only 1.9% the following year indicating a total savings of 12.6% over the two year period.

Table 8 Water Saved by Different Calculation Methods

2001-2003 Water Savings Summary			
Percent Water Saved by Different Calculation Methods			
Calculation Method	Percent Water Saved Audit Year	Percent Water Saved Year After Audit	Percent Saved Over 2 Years
Total Gallons Used per Property (indoor + outdoor)	11.8%	8.2%	20.0%
Total Gallons Used per acre (indoor + outdoor)	4.2%	8.5%	12.7%
Outdoor Gallons Used per acre	10.1%	4.8%	14.9%
Inches of Water Used per acre	10.3%	4.8%	15.1%
Percent Reduction in Evapotranspiration (ET)	10.7%	1.9%	12.6%
Database of 106 complete water use records with information before audit, year of the audit and the year following the audit			

Water usage by property type was also evaluated for this study. It is interesting to note the variability of savings when the large water audits are categorized by property type. The following table shows the various responses to the water audit recommendations per property type. The assumption could be made that most businesses have little or no desire to reduce landscape water use. This assumption has been backed by the problem that water bills for chain businesses in particular are often paid at a corporate office in a different state. Water pricing in Utah has yet to send a big enough message to the water users that water conservation is important.

Table 9 Water Saved by Category

2001-2003 Water Savings Summary				
by Category				
Category	Number of Audits	Percent Water Saved Audit Year	Percent Water Saved Year After Audit	Percent Saved Over 2 Years
Apartments	**12**	6.9%	3.8%	10.8%
Businesses	**19**	1.5%	-4.1%	-2.6%
Churches	**6**	29.4%	-5.2%	24.2%
Golf Courses	**5**	10.1%	4.3%	14.4%
Homeowners Associations	**22**	12.1%	10.7%	22.8%
Public Facilities	**13**	9.1%	19.4%	28.5%
Parks	**16**	20.4%	1.6%	22.0%
Schools	**13**	13.5%	7.0%	20.5%
Calculations based on outdoor gallons used per acre per season				

Although information is limited about water savings based on irrigation system improvements one elementary school in West Jordan, Utah has provided a great example. A new Rain Bird Maxicom central control irrigation system was installed at the school in West Jordan City along with a new automated irrigation system. The system had its own weather station with sensors for air temperature, solar radiation, relative humidity, wind speed, wind direction and rainfall. The information was calculated for Evapotranspiration for turf on a daily basis and supplied to the computer running the irrigation system. Each irrigation zone was then programmed for the correct minutes to water each week. A total of 54% of the 10.8 acre site was measured as irrigated landscape. During 1998, 1999 and 2000, the school used an average of 7,305,110 gallons of irrigation water during the growing season. This equated to a value of

28.8 gallons of culinary water per square foot per season. The school was being watered at 201% of the actual turf water requirement. After the Maxicom automated system was installed, the water use records indicated that the facility irrigated at 114% of the current year's water requirement. When an entire sprinkler system was replaced with an automated system based on a weather station, the total water used was brought down to about the same level as the standard (*Lopez and Jackson, 2004*).

Water Savings by an Elementary School

West Jordan City Elementary School
Total gallons per landscape area
7,305,110 gal/ 5.83 acres
28.8 gal/ft^2/season
Comparison to turf water requirement (ET)
ET = 14.3 gal/ft^2/season
201% of ET
Prior to automation with weather station
With automated system
16.35 gal/ft^2/season
114% of ET

Conclusion

The results of this study are unique as they reflect tangible, real-life situations where beneficial changes were made to watering habits and where data was collected for existing, functioning irrigation systems. Although the nature of this study made it impossible to control all aspects of the data collection process, adaptability as well as consistency and quality from all contributors to this project proved effective. The large water audit program has been a well received public relations campaign in enabling mangers of large landscapes to successfully cut back on water waste by an average of 15%. Modified irrigation water audits are now being conduced in several other states with similar results (*Mecham, 2004; Graham and Lander, 2005*). Through providing recommendations for irrigation scheduling based on ET and actual irrigation system precipitation rates as well as recommendations for proper irrigation system maintenance, the overall objective of this study was met with notable results. In addition to water savings data, information compiled for operational sprinkler system performance will increase in value as water conservation efforts in Utah continue throughout the future.

BIBLIOGRAPHY

Graham, T., and Lander, P. 2005. Slow the Flow Colorado Irrigation Audits. 2005 Proceedings, National Irrigation Association, 2005 Conference, Phoenix, Arizona.

Jackson, E. K. 2000. Culinary Water Waste Along the Wasatch Front. 2000 Proceedings, Utah Water Users Association, 2000 Conference, St. George, Utah.

Jackson, E. K., and Leigh, J.R. 2004. Irrigation Scheduling for Large Water Users. 2004 Proceedings, National Irrigation Association, 2004 Conference, Tampa, Florida.

Jackson, E. K., and Leigh, J.R. 2004. Irrigation Water Audits of Large Properties – 1999 through 2003. Utah State University Extension Publication AG/Irrigation/2004-01.

Jackson, E. K., Lopez, R. M., Leigh, J. R., and Hinton, A. C., 2005. Utah State University Extension Publication AG/Irrigation/2005-01.

Jackson, E. K., and Mohadjer, P. 2003. Saving Utah Water in the Fifth Year of Drought. 2003 Proceedings, National Irrigation Association, 2003 Conference, San Diego, CA.

Jackson, E. K., Rosenkrantz, S. G., Lopez, R. M., and Leigh, J. R. 2004. Utah "Water Checks" – A Personalized Conservation Program. Proceedings, The Association of Natural Resource Extension Professionals, 2004 Conference, Wheeling, West Virginia.

Lopez, R. M., and Jackson, E. K. 2004. Ten Schools Tune-up Irrigation Systems. Proceedings, Extension Western Region Professional Improvement Conference. 2004, Woodland, California.

Mecham, B. 2004. Using Distribution Uniformity to Evaluate the Quality of a Sprinkler System. Proceedings, National Irrigation Association, 2004 Conference, Tampa, Florida.

Rainbird Landscape Irrigation Product Catalog, 2005. www.rainbird.com.

The Irrigation Association, Certified Landscape Irrigation Auditor Training Manual, 2002. Falls Church, Virginia.

Utah Division of Water Resources, Utah's M&I Water Conservation Plan - Investing in the Future, Salt Lake City, Utah 2003.

Utah Division of Water Resources, Identifying Residential Water Use - Survey Results and Analysis of Residential Water Use for Thirteen Communities in Utah, Salt Lake City, Utah, 2003.

Utah Division of Water Resources, Personal communication from Eric Klotz. For currant Evapotranspiration values and water conservation information in Utah see their web site at: www.conservewater.utah.gov.

The Calgary Courts Centre - Case Study

Application of Advanced Irrigation Design & LEED Technologies to Utilize Irrigation Water Efficiently

Prepared for:

Irrigation Association
26th Annual International Irrigation Show

Prepared by:

Bruce Laing, CSLA, CID, CLIA, LEED® AP
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PREAMBLE

I am going to sound like a zealot today but I firmly believe that we are at a crossroads in terms of landscape design/development and how our work is perceived in terms of irrigation water consumption.

As the graphic illustrates global water consumption has increased substantially over the last 125 years, and …

We are uniquely positioned to provide direction to the entire industry in terms of moving away from resource depleting, maintenance intensive and increasingly expensive landscape development.

1.0 CLIMATE CONSIDERATIONS

In Canada we are blessed with 25% of the world's fresh water, but to support our industrial, commercial, agricultural, residential and recreational water consumption we withdraw, on average, 120 billion litres every day from our rivers, lakes and aquifers. *That is a volume equal to the area of an NHL ice surface…47 miles high.*

Calgary's water source is the watershed consisting of the Eastern Slopes snow pack and the Bow glacier which feeds the Bow and Elbow Rivers within the South Saskatchewan River basin.

Recent research indicates that our droughts, in geological terms, are more frequent and of longer duration than had been previously thought. Rather than lasting from one to ten years, our droughts may have a duration measured in decades. What makes this particularly alarming is that the last 100 years, in Western Canada, has been the wettest century in millennia and hence our perception of what is normal in terms of water availability is even further skewed.

2.0 HISTORY OF WATER USE / INFRASTRUCTURE COSTS

In Canada we currently use 340 litres of water / per day / per person – almost three times what some European Countries use.

As the graphic also illustrates, there appears to be an unfortunate correlation between the unit cost of water and consumption volumes.

Of this total amount of potable water that we use every day, less than 3% is actually consumed by humans.

In 2002, U.S. households spent $3.5 billion on irrigation equipment. Outdoor watering, or irrigation accounts for, on average, over 30% of residential water use. During the summer months this outdoor water use can go as high as 70%. Our landscape expectations, coupled with the rising cost of the delivery of potable water has put the irrigation industry squarely in the cross hairs of water conservation interests as well as municipal water purveyors who are just starting to come to grips with irrigation water consumption, the rising cost of water treatment, and the bigger issue of water conservation itself.

Since 1949 the Irrigation Association (IA) and its members worldwide, have been working towards the vision of water conservation through efficient irrigation based on better design and construction practices through education.

3.0 DESIGN

TRADITIONAL APPROACH TO DESIGN / SITE

Calgary, with a population of 950,000 has an area of 278 square miles with 2,000 irrigated parks and 19,000 acres of “park” land.

Historically, irrigation design has been based on the volume of water applied rather than how it was applied.

Good irrigation design is no different than landscape design in that you must have a thorough understanding of the site and design parameters. To that end the following is a checklist of essential irrigation considerations as applied to the Courts site:

Plant Species Selection: Calgary is in Zone 3A according to Agriculture Canada’s Plant Hardiness classification, but equally as important as this general criteria is Calgary’s proximity to the eastern slopes of the Rockies and the “Chinook” weather fronts, which directly impact our weather conditions. The most extreme Chinook, on record, in the Calgary area, was in January of 1992 when the temperature rose 41ºC, from -19ºC to +22ºC in 1 hour. These, periodically extreme, weather conditions simply highlight the need to maintain plant material at the highest reasonable levels of health and vigour possible.

Microclimate: For the purpose of irrigation design microclimate consists of the site and its immediate contextual conditions such as architecture, surface treatments, site aspect, shade, and topography. Under “normal” circumstances none of these factors would unduly affect growing conditions. High microclimates are where the site is affected by heat absorbing/reflecting surfaces or high wind scour. Conversely, low microclimates are primarily a function of shade.

Both of these conditions exaggerate plant water requirements and therefore the irrigation system design in terms of how much water must be delivered to the plant material.

The Plants Themselves: There are five general factors, which affect plant growth:

- Genetics;
- Light;
- Air and Soil Temperature;
- Nutrient Availability; and
- Soil Moisture or Water.

As well as being a factor in itself soil moisture has a direct impact on soil temperature and nutrient availability.

Plant Available Water: Plants use water to transport nutrients, to control the shape and direction of growth, for photosynthesis and as a means of controlling plant body temperature through transpiration. In warm climates transpiration is by far the major water use by plants.

The sum of plant water use and water which evaporates from the surface of the root soil mass is called the EVAPOTRANSPIRATION RATE or ET. The graphic illustrates the six major ET categories that we use in North America to calculate irrigation water requirements.

Irrigation design is always based on peak ET rates.

Soils: Soil texture is absolutely critical to how irrigation water is available for plant use and one of the prime determinants in terms of the rate at which irrigation water should be applied. The graphic illustrates the relationship of the three principal soil components: clay, silt, and sand. In short, sandy, or course textured soils, have high water intake rates and low storage capacity; clay soils have a low water intake and high storage capacity. Silty or organic soils have medium to low water intake rates and medium to high storage capacities. As you can see water movement in the three soil types is quite different.

As landscape architects and irrigation designers, we do not always have the opportunity to modify site soils, hence, we must tailor the irrigation water application rate to suit the soil type.

Type, Source and Size of Water Service: With a potable or treated water source designers have not been required to be as attentative to irrigation water consumption volumes, as we probably should be. On sites where non-potable water is utilized, irrigation water volume availability is typically lower.

A water source must have the ability to provide the total amount of flow rate (gpm) demanded by the irrigation system at any given time and provide sufficient water pressure to carry the flow, and energy to make the sprinklers function properly.

When possible, irrigation zones should be established based on combining plant species, which have similar water use characteristics.

Plant physiology, in combination with daily temperature cycles, indicate that irrigation water applied at night or early in the morning is used much more efficiently by the plants than water applied during the day.

Irrigation Product Considerations: Sprinkler heads or emission devices (ED’s) are the most visible and variable components of an irrigation system. ED selection criteria should consist of:

- Size and configuration of areas to be irrigated.
- Type and number of obstructions within areas to be irrigated.
- Available irrigation water volume and pressure.
- Type of vegetation.
- Physical activities within irrigated area.

4.0 LEED® CONSIDERATIONS

How do LEED initiatives relate to irrigation design?

The US Green Building Council, as the governing agency for LEED criteria in the United States, and its recent counterpart, the CaGBC in Canada, promote similar, but less specific, design criteria as the Irrigation Association in terms of irrigation water conservation.

As you may be aware LEED design considerations are divided into five key performance categories:

- Sustainable Sites (14 possible points);
- Water Efficiency (5 possible points);
- Energy and Atmosphere (17 possible points);
- Materials and Resources (14 possible points); and
- Indoor Environmental Quality (5 possible points).

A sixth category: Innovation and Design Process (5 possible points) rewards exceptional environmental and/or design performance.

The LEED program is directed primarily at commercial, institution, and highrise residential building projects, but can be applied to any type of architectural project. Obviously, for projects that are, for example, industrial in nature it is a bigger challenge to score points. The LEED point system is as follows:

Certified:	26 – 32 points
Silver:	33 – 38 points
Gold:	39 – 51 points
Platinum:	52 – 70 points

From an irrigation design standpoint, we focus on the Sustainable Sites, Water Efficiency and Innovation categories. In the Sustainable Sites category…

<u>SS Credit 6.1:</u>

The intent is to…

Limit disruption of natural water flows by managing stormwater runoff.

This point hinges on reducing the peak storm discharge rate.

AND / OR

Quality of stormwater runoff.

<u>SS Credit 6.2:</u>

The intent is to…

Limit disruption of natural water flows by eliminating stormwater runoff, increasing on-site infiltration and eliminating contaminants.

This point requires the removal of 80% of average annual post-development Total Suspended Solids (TSS) and 40% of average annual post development Total Phosphorus (TP).

<u>SS Credit 7.1:</u>

The intent is to…

Reduce heat island effect to minimize impact on microclimate through providing: shade for 30% of the site's non-roof surface within 5 years.

OR

Underground or covered parking stalls.

OR

Use open grid paving system (less than 50% imperviousness) for a minimum of 50% of the parking lot area.

In the Water Efficiency category…………..

WE Credit 1.1:

The intent is to…

Limit the use of potable water for landscape irrigation to 50%.

To achieve this point, potable water consumption for irrigation purposes must be reduced by 50% over conventional means by using captured rain or recycled site water.

WE Credit 1.2:

The intent is to…

Eliminating the use of potable water completely for landscape irrigation purposes.

This point is achieved by using only rainwater or captured site water as the source for irrigation water.

In the Innovation Design category…………..

ID Credits 1.1 to 1.4 Inclusive:

The intent is to…

These credits are awarded for exceptional performance, on a discretionary basis, for resource conserving efforts above LEED Rating System requirements.

ID Credit 2.0:

This credit is somewhat self-serving in that it encourages design integration of the project team to streamline the LEED application and certification process and hinges on at least one principal participant of the project team being LEED® Accredited. From a personal experience standpoint I would suggest that at least one person from each and every discipline on the project team be LEED Accredited to facilitate design development discussions that are as constructive as possible.

5.0 INTRODUCTION TO COURTS PROJECT

The Calgary Courts project entails the redevelopment of 1.5 blocks of downtown Calgary

Phase One of the Calgary Courts Centre is a $275 M, 8,000 m^{2} / 86,000 ft^{2} development. It will be one of the first buildings in Calgary to achieve LEED Silver status and be based on the advanced design practices promoted by the Irrigation Association. It consists of north and south towers which are 24 and 20 stories respectively with a 26 story central atrium separating the towers. Because Phase One represented development of an existing Government of Alberta site landscape development was limited to at grade and raised planters in combination with trees in at-grade boxes. The irrigation water source will be harvested rainwater.

When we combine the irrigation design criteria with the architectural design and the LEED parameters:

- All plant species selected are Zone 3 hardy.
- Because of the “High” microclimate, with Chinook complications, we also selected species that were low and medium water users.
- On Phase 1 of the project we had the opportunity to completely modify the planting medium, so that a sandy clay loam would be utilized.
- In terms of evapotranspiration rates, Calgary is classified as a Cool, Dry climate, so an ET rate of 0.20 inches / day was utilized for the calculations.
- Because the tree and shrubs species selected for the project were similar in their water use characteristics, we used root mass and depth as the criteria to separate the site into irrigation hydro zones.
- The deciduous canopy trees will be planted in at-grade, oversized tree boxes and the raised planters will contain a combination of deciduous flowering trees, shrubs and groundcovers. The configuration of the planting structures in combination with the creation of a planting trench will allow us to increase the planting medium mass and run the irrigation lines between the planting areas without hard surface conflicts.

Based on the species selected it was determined that, at maturity, each deciduous canopy tree would require 140 US gallons per week. The deciduous flowering trees would require 77 gallons and the shrub and ground cover material would require 4.0 gallons per m^{2}. Our total maximum irrigation water requirement per week would be approximately 4,000 US gallons per week.

Now that we know what we need, where does it come from: potable water, harvested at-grade stormwater or harvested roof stormwater?

The creation of a stormwater cistern between structural components in the basement of the building allowed us to address LEED SS Credit 6.1 (managing stormwater runoff).

By combining a primary storm cistern which would overflow into a secondary irrigation cistern, the storm cistern essentially becomes a settling tank and responds to SS Credit 6.2 (reducing TSS and TP).

In sizing the irrigation cistern we determined that a 2-week water supply would be our minimum capacity which means each cistern must hold 8,000 US gallons. This sounds like a lot but it is only 30 m^3…. the size of one parking stall and a depth equal to my height.

Because such a significant portion of the Phase One site would actually be building, we decided to use harvested rain from the roof as the non-potable irrigation water source. This satisfies WE Credit 1.2 (the elimination of potable water for irrigation) and partly satisfies WE Credit 1.1 (limiting irrigation water use by 50%).

Roof harvested rainwater is typically much cleaner that surface harvested rainwater and therefore requires far less treatment. Non-the-less we will incorporate self-flushing cyclonic filters in the rainwater conveyance system to remove debris before the water enters the storm cistern.

To irrigate the trees we will use a sequence of 4 low-flow bubblers for each tree. This particular model of bubbler is mounted in a 100 mm diameter tube and is available in lengths ranging from 300 – 900 mm. The intent is for the tubes to be filled with small diameter aggregate so that the irrigation water wets the root zone uniformly. To serve the immediate needs of the tree's 2 – 300 mm bubblers will be placed immediately adjacent to the root ball with 2 – 600 mm bubblers located further out form each root ball to accommodate future water needs as the trees grow. The 600 mm bubblers will be kept turned off for the first number of years after installation.

For the shrubs and groundcovers we will utilize a grid distribution pattern with in-line emitters. In this case we are using 600 mm O.C. spacing. This type of system is typically called drip, trickle, or micro-irrigation, and water supplied is measure in GPH rather than GPM. The O.C. spacing of the emitters must be matched to the soil type.

The use of deep watering bubblers and inline emitters reduces or eliminates water waste and promotes healthier plant growth because you can:

Match the water application to the specific needs of each plant.

More closely match the application rate to the soil's infiltration rate.

Apply water directly to the root zone to reduce overspray and evaporation.

Reduce or eliminate runoff.

These factors combine to complete the requirements for WE Credit 1.1 (reducing irrigation water consumption by 50%)

Traditionally, the irrigation water requirement is lower in the spring and fall, than in the summer, because of lower air temperatures and increased levels of plant available water through natural precipitation. We have incorporated spring and fall irrigation schedules as a percentage of peak summer demand, which represents a further reduction in irrigation water consumption.

In closing…

This presentation is structured as a case study on the Calgary Courts Centre but in my mind it is really a primer for the type advanced of irrigation design that we should all be practicing.

Factors Affecting the Results for Lower Quarter Distribution Uniformity from Catch Can Tests

Brent Q. Mecham[1]
September 4, 2005

Introduction

One of the current Turf and Landscape Irrigation Best Management Practices published by the Irrigation Association states that lower-quarter distribution uniformity (DU_{LQ}) should be a minimum of 55% for spray heads and 70% for rotor heads. As water purveyors begin to adopt the BMPs for use in their local jurisdictions and perhaps require catch-can field tests to verify compliance, there appears to be a need to provide guidelines for performing field evaluations. This paper will look at several factors that affect lower-quarter distribution uniformity from catch-can tests results including wind speed, operating pressure and placement of the catch-cans in the test area.

Currently the Irrigation Association has proposed guidelines for performing catch-can tests which are listed on their website at www.irrigation.org. Some of these guidelines include a minimum number of catch cans to be used for a "valid" test depending on the number and type of sprinkler heads, how far apart the catch-cans are spaced especially in large area rotor installations and the maximum wind speed.

The purpose of the guidelines is to help establish a more uniform procedure to evaluate sprinkler head performance in the field. Currently there are no standards for how the catch-cans tests are to be performed so the guidelines are offered as a way to provide consistency among auditors who perform the tests and may have to certify the compliance of a sprinkler system with the BMPs that have been adopted as standards in many locations.

Audit procedures

The sprinkler audits were performed on three different test areas established at the Outdoor Laboratory for Landscaping and Irrigation Education at the Northern Colorado Water Conservancy District headquarters in Berthoud, Colorado. The test areas are large turf plots of Kentucky bluegrass measuring 70 feet by 100 feet with slope measuring about 1.3%. The soil is a heavy silty clay loam. The sprinkler heads are of various manufacturers installed on square spacing 35' by 35' on center. Each plot requires 12 sprinkler heads to cover the area. Two of the heads utilize full circle arcs and are on their own valve and can be operated independently of the part-circle sprinkler heads. Each valve has a pressure regulator and water meter. A Windtronic

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hand-held anemometer was set up on a tripod to measure wind speed during the audit process. The anemometer could measure the maximum wind speed as well as average the wind speed every five seconds during the test. These values were recorded along with water meter readings and operating pressures.

Various types of catch cans were used to perform the audits. Typically the CalPoly style catch can was used with the metal stand. The throat of the catch- can is an area of 16.5 square inches. A few audits were done using a new style catch can made by the US Bureau of Reclamation, which has a throat area of 14.2 square inches. This particular catch can has self-contained legs and the third style of catch can are in expensive plastic cereal bowls which are low profile and lay on top of the grass or can be pushed down into the turf. They are approximately 5.5 inches in diameter and have a throat area of 23.76 square inches. Usually these bowls were used at the same time as the other catch cans to run two tests at the same time. All of the readings were done in milliliters.

The catch cans were laid out following two methods.

a) The traditional IA methodology as taught in the Certified Landscape Irrigation Auditor training class (and is likewise taught in other similar programs) that is “at or near the head and half-way in between”. This method required 35 catch cans and created a grid of cans @ 17.5 feet apart.
b) The “grid method” which uses a regular placement of catch cans spaced a certain distance apart irrespective of the sprinkler head location. The grid arrangement was 8 feet by 9 feet and utilized 99 catch cans. The perimeter catch devices were placed 2.5-3.0 feet from the edge.

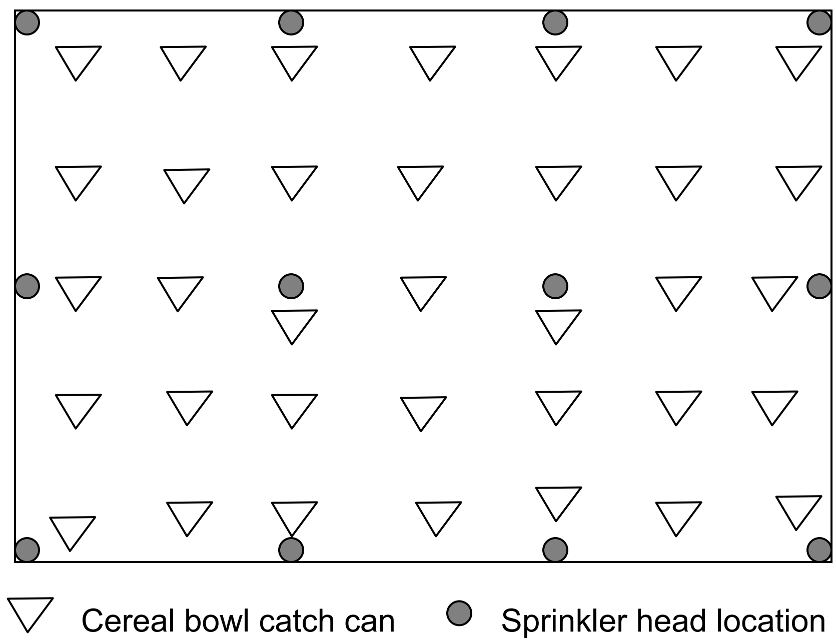
Any catch cans that were near a sprinkler head were recessed into the ground so that the water from the sprinkler heads could fall into the catch device without hitting the side of the device. Both methods were set up to perform the audit test simultaneously with the same water pressure and wind.

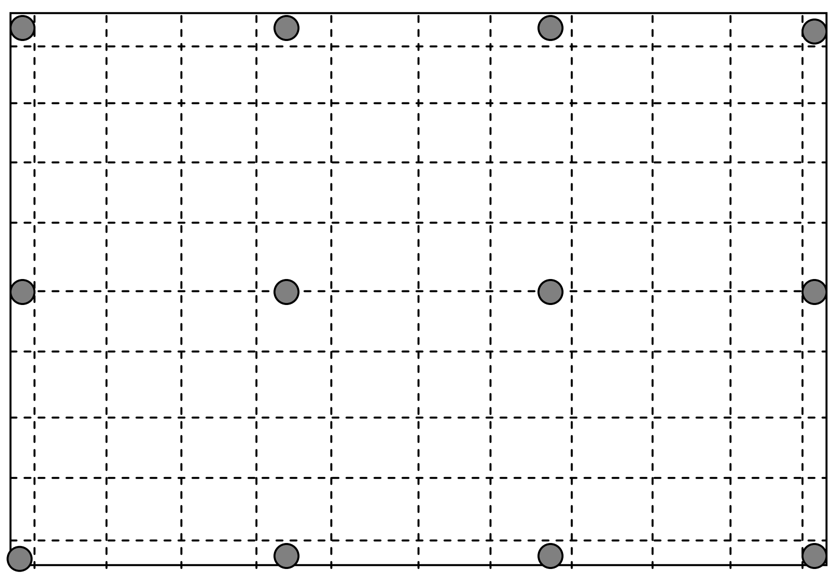
Results

Fifteen audits were conducted on the three demonstration areas over the period of several weeks. Adopting the IA guideline regarding wind speed, no audits were done when the wind speed averaged more than five miles per hour. The results are for three factors that can influence the outcome of an audit including placement and number of catch devices, wind speed, and operating pressures. The results displayed in the following tables came from the audits using the grid method for laying out catch devices.

Catch-can Placement

The quantity and placement of the catch cans in the field tests proved to be significant. Because the plots were identical in shape and size, a procedure was established using tape measures so that the catch-cans could be placed in approximately same spot for each audit. For the traditional IA method, the cereal bowl catch cans were used and placed near each head and halfway between the heads as shown in the following diagram.





The intersection of the dashed lines indicates a catch-can location.

The results from the fifteen audits performed comparing the “grid” audits to a traditional catch can placement of “at the head and half-way between” is shown on the following table. This includes all audits at different operating pressures and wind conditions.

Comparison of DU_{LQ} % between “grid” and “traditional” methods

Grid Method	Test Number	Traditional
60	1	65
39	2	42
75	3	67
61	4	48
69	5	55
66	6	54
63	7	61
65	8	68
68	9	60
66	10	55
63	11	54
55	12	51
68	13	60
59	14	48
67	15	61
62.9	Average	56.6

Thirteen of the fifteen tests showed a better DU_{LQ} for the gird method of auditing compared to the traditional audit method performed on the demonstration plots. Data presented are from a relatively few tests and the results are not conclusive, however the more catch-cans used the better the evaluation would be. The random low or high readings would have less impact on the overall results. The down side to using the grid method is the time it takes to perform such evaluations however if the sprinkler zone would pass the minimum requirement that is better than having to spend time to modify the sprinkler zone and re-test it.

<u>Wind</u>

To demonstrate the affects of wind upon the resulting lower-quarter distribution uniformity (DU_{LQ}) four tests could be used for comparison and is as follows:

	Pressure psi	Avg. Wind Mph	Max. Wind Mph	DULQ %
Plot A	**40**	**.8**	**4.9**	**61**
	40	**2.1**	**6.7**	**52**
Plot C	**50**	**2.1**	**6.1**	**66**
	50	**4.0**	**9.3**	**55**

As can be seen that even though the average wind speed was within the guidelines the impact upon the resulting DU_{LQ} shows about a 15-20% difference in the results for a specific sprinkler head.

Operating Water Pressure

For Plot A the recommended operating pressure for the nozzles selected for the sprinkler head is 50 psi. The results from 4 different audits where the water pressure was changed showed a significant impact on the DU_{LQ} for this particular head and nozzle combination. The full circle heads used the same nozzle as the half-circle heads and required twice the number of minutes of run time to achieve matched precipitation rate.

For Plots B & C the same sprinkler head was used but each had different nozzle combinations. Plot B the nozzles are matched precipitation rate and in this case the full circle heads can run at the same time as the part circle heads. In Plot C the matched precipitation rate is achieved using time, meaning that the full circle heads needed to run for twice as long as the part circle heads. The same nozzle was used for both the full circle and half circle sprinkler heads. The quarter circle nozzles had half the flow rate as the half-circle nozzles and would run on the same circuit or zone. For this particular head the pressure variation did not have as much effect on the Distribution Uniformity but there was definitely more impact upon the average precipitation rate.

Lower Quarter Distribution Uniformity at Various Pressures

	50 psi	45 psi	40 psi	30 psi
Plot A	75	69	61	39
Plot B		65		68
Plot C	66	67	68	63

While the results are not conclusive, it does illustrate the importance of proper operating pressure to get the desired results of optimal performance. A field observation of Plot B was that over an extended period of time while operating at 30 psi that the edges and corners of the plot showed severe signs of stress. After a period of time when the pressure was adjusted back to the preferred 45 psi the stressed areas improved.

While pressure has a definite impact upon the distribution of water from the sprinkler head nozzle there is a substantial change in the net precipitation rate. The results from the audits for the above mentioned plots and sprinkler zones and at the various operating pressures can be seen.

Average Net Precipitation Rate in Inches Per Hour

	50 psi	45 psi	40 psi	30 psi
Plot A	.55	.44	.45	.40
Plot B		.40		.34
Plot C	.62	.53	.56	.47

While the change in precipitation rate caused by changes in pressure and can be significant the bigger impact is the change that needs to be made to the run time on the controller to apply the correct amount of water. In the field observation mentioned before the pressure was reduced to 30 psi to perform the test and not re-established at the preferred operating pressure of 45 psi. Although the uniformity did not change substantially in this case, the resulting change in a lower precipitation rate was not compensated for with changes to the run time on the controller. Therefore, deficit irrigation was taking place over a fairly long and hot spell during the summer before the mistake was caught.

Conclusions

Obviously there are many factors that can affect the distribution uniformity of sprinkler heads working together to irrigate an area such as arc adjustment, height and tilt of the sprinkler head, hydraulics etc. The focus of this small study was to look at other factors besides maladjusted heads such as wind speed, operating pressure and the number and way catch devices are set out to perform a catch can test.

While the results of these few tests provide insight into how different factors influence the outcome of a catch-can test for lower-quarter distribution uniformity they are not conclusive. More such audits in different conditions need to be done. Common sense tells us that if the wind is blowing the results will be varied. What was surprising is how big a difference can be made in the audit results with only a minor change in wind speed even when the wind speed was within the proposed audit guidelines of less than five miles per hour. Obviously more audits documenting the results of changing the operating pressure needs to be done. Most likely the results will become product specific and may not necessarily be applied across the board to all sprinkler heads and nozzles. However, striving to operate the sprinkler head at the recommended pressure for the intended spacing of the sprinkler heads should yield the best results for uniformity. Usually the manufacturers will state that the preferred operating pressure is the middle values or the bolded values on their tables in their product catalogs.

Frequently the traditional methodology of placing a catch device “at or near the head and half-way in-between” is in reality the minimum number of catch devices that should be used and not the absolute number or placement of the catch cans. From the audits that were performed, the grid method using a closer spacing and more catch devices seemed to improve the overall results for measuring lower-quarter distribution uniformity. Since catch can audits represent a snap-shot of how the sprinkler system was performing at that moment, it is expected that a follow-up audit with the catch cans set up in a very similar pattern would produce results that would be within 10% of each other, either above or below the first audit. If the results fall within that parameter then the audit results should be fairly reliable. If the results are more than that, then it would cause concern about the validity of the catch-can tests and which was the most correct.

Water Retention and Evaporative Properties of Landscape Mulches

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INTRODUCTION

The use of mulches in landscape plantings is increasing. Mulches have been promoted by water conservation, green waste reduction, and other programs primarily to reduce evaporation from soil. In addition, many of the materials used for mulching provide an improved aesthetic appearance for the landscape and provide weed control. Many different materials are available from composted products such as manures, sludge, and greenwaste to non-composted products such as wood chips and yardwaste from landscape maintenance operations, bark products from lumber mills, and rock (CIWMB).

Mulches can benefit landscapes by reducing soil evaporation, cooling the soil, suppressing weed growth, and possibly providing nutrients for plant growth. Several studies have evaluated the moisture retention and cooling of soils under mulch (Bennett, Borland, and Groenevelt, et al.) An energy balance study evaluated (by measuring radiation, temperatures, and reflectivity) the changes in environment and growth of landscape plants resulting from mulch applications, (Montague and Kjeldren.). A number of trials have evaluated mulch for weed control (Lanini, et al.) and relationships between weed emergence and physical properties of mulches have been developed (Teasdale and Mohler). Additional studies have evaluated the effect of mulch on plant material performance (Litzow and Pellett). However, little information or standards have been developed on the water holding capacity or evaporation rate of mulch materials themselves. This information would be important in determining accurate and effective landscape irrigation management.

In the landscape, we observed that the use of mulch can affect the movement of water applied by sprinklers or rainfall. For example, investigation of a failing landscape that was heavily mulched revealed that sprinkler applied water was not penetrating through the mulch layer and the plant materials were suffering from lack of water. Although the irrigation manager was applying an adequate amount of water, frequent applications appeared to be absorbed and evaporated from the mulch, resulting in under-irrigation and plant death.

This study was designed to determine the water retention characteristics of mulches and evaporation of sprinkler irrigation water from them under field conditions independent of plant materials.

MATERIALS AND METHODS

Treatment Selection

The study was undertaken at two locations in San Diego County, CA: Cuyamaca College in El Cajon, CA and Quail Botanical Gardens in Encinitas, CA. The locations represented inland valley (El Cajon) and coastal (Encinitas) climatic conditions and were in full sun. Twelve mulch treatments were selected to represent an array of materials and application depths (Table 1). Reported recommendations on mulch depth are variable in the industry, but 2-4 inches of mulch is a common suggestion for landscaped areas (Bennett, Borland, CIWMB). Therefore, 8 of the mulch treatments in this study were applied 3 in. thick.

Landscape managers are encouraged to make use of ground yardwaste products available at little or no cost at municipal landfill sites. The yardwaste material used in the study came from the Miramar landfill in San Diego. It is produced by tub-grinding landscape greenwaste and was minimally composted. The yardwaste treatments were applied in 1-, 3-, and 5-in. depths. Composted yardwaste was also available at the landfill. Xerimulch and Gro-Mulch were obtained from Kellogg Supply, Inc. (Carson, CA). Xerimulch is a fine-screened bark product and Gro-Mulch contains very fine composted organic material and sewage sludge. A-1 Soils Co. (Hanson Aggregates, San Diego, CA) provided the medium-sized bark chunks, 1-in. rock, and their "Organic Ground Cover" (OGC), which is a blend of screened wood chips and bark. The landscape fabric was a 5-mil Tyvec® (Dupont) cloth commonly available at landscape supply dealers. Frequently, landscape personnel place fabric under one of the organic mulches, so fabric with OGC was also included in the study. The control treatment was un-mulched bare soil.

TABLE 1. Mulch materials and application depth of the 12 treatments studied at Quail Botanical Gardens and Cuyamaca College.

Treatment	Mulch	Depth
1.	Yardwaste	1"
2.	Yardwaste	3"
3.	Yardwaste	5"
4.	Composted Yardwaste	3"
5.	Xerimulch (Kellogg Supply, Inc)	3"
6.	Organic Ground Cover (OGC; A-1 Soils)	3"
7.	Gro-Mulch (Kellogg Supply, Inc)	3"
8.	Medium Bark (A-1 Soils)	3"
9.	Landscape Fabric (5-mil Tyvec®)	-
10.	Landscape Fabric + OGC	3"
11.	1" Rock (A-1 Soils)	3"
12.	Control (no mulch, bare soil)	-

Site Preparation and Experimental Design

At each site the soil was rototilled to a depth of approximately 8 inches and raked smooth. Temporary sprinkler irrigation systems were installed and the mulch treatments applied in 5 ft. by 5 ft. experimental plots. The 12 treatments were replicated three times for a total of 36 plots at each site in a Randomized Complete Block Design. To measure the evaporation from the treatments, a nursery flat was placed in the center of each experimental plot to allow for removal, weighing, and replacement of a sample from each plot. For the 3- and 5-in. deep treatments, the sides of the flats were extended by attaching the sides of one or two additional flats (bottom removed) to the initial flat.

Irrigation Systems

The temporary irrigation systems consisted of PVC pipe and fittings with sprinklers set above grade. Catch can tests were performed and analyzed to determine the system precipitation rates and uniformity. The irrigation system utilized four Hunter Industries PGP Series sprinklers located 5 ft. outside of the plot corners (40 ft. by 40 ft. spacing) at the Quail Gardens site. The precipitation rate was 0.86 in. per hour with a distribution uniformity of 79%. At the Cuyamaca College site, the irrigation system consisted of eight Hunter Industries PGM series sprinklers located approximately 18 inches outside of the plot perimeter. At this site the precipitation rate was 0.62 in. per hour with a distribution uniformity of 80%.

After the irrigation systems were installed and the mulch treatments were in place, the systems were operated twice at weekly intervals at each site to settle the mulch materials in the plots.

Testing Procedure

The irrigation systems were run long enough to apply approximately one inch of water to the plot area, thoroughly wetting the mulch treatments and underlying soil without ponding or runoff. The systems were run in the late afternoon of October 2 and 3, 1995 at the Cuyamaca College and Quail Gardens sites, respectively. On the following morning and on subsequent days, flats containing the mulch treatments were weighed to collect data on water retention and loss. The experiment was repeated again at the Quail Gardens site on October 12, 1995. This experiment was conducted similarly to the initial two experiments with the exception that flats of soil and soil covered with fabric were placed and weighed in the control and fabric treatments.

Water holding capacity for each mulch treatment was determined by collecting the mulch materials in each flat at the conclusion of the evaporation studies, placing the samples in paper bags, and drying in a forced air oven at 45 C. for 26 days. The dry weight was subtracted from wet weight data from the field experiment and converted to inches of water.

Reference evapotranspiration (ETo) data was obtained from California Irrigation Management Information System (CIMIS) automated weather stations at representative locations. These included data from in Escondido (CIMIS station 74) and Oceanside (CIMIS station 49), representative of El Cajon and Encinitas, respectively.

Data Analysis

Actual mulch weights were calculated by subtracting the tare weight of the sampling flat from the total sample weight. The weight of water lost since the previous sample was calculated by subtraction and converted to inches of water loss. Water loss data was then analyzed using analysis of variance and range programs in the MSTATC statistical computer program to determine statistical significance, means, and mean ranking and separation (LSD).

RESULTS

The experiments undertaken in this study show that many mulch materials can absorb, hold, and release significant amounts of water after overhead irrigation. The water holding capacities of the mulch treatments ranged from 0.0 in. for the control and fabric treatments to 1.1 in. for the 5-in. depth yardwaste treatment. (Table 2). Corresponding values in inches per foot depth of material ranged from 0.0 in./ft. for the control and fabric treatments to 0.09 in./ft. for 1-in. rock to 3.64 in./ft. for the Gro-Mulch treatments.

The different materials showed significantly different rates of water loss. Water losses from mulch treatments ranged from 0.0 to 0.18 inches per day (Tables 3, 4, and 5). Mulches with the highest water holding capacity lost the most water. Ranking of water lost from the mulch treatments was similar in the experiments at both sites.

Gro-Mulch 3 in. deep and yardwaste 3 and 5 in. deep had the highest amounts of water held and the highest rates of water lost (Tables 3 and 4). All mulch treatments lost the most amount of water on the first day after irrigation. The rock mulch held the least amount of water and lost the least amount in each experiment. Xerimulch, bark, Organic Ground Cover (OGC), and fabric covered with OGC had intermediate amounts of water lost (Tables 3, 4, and 5). Differences between the Gro-Mulch treatment, the un-mulched control and fabric covered soil were not significant in the second experiment at Quail Botanical Gardens (Table 5).

Table 2. Mean water holding capacity of mulch treatments in inches for treatment depth (with standard deviation) and in inches per foot depth of material.

TRT #	Treatment and Depth	Inches water	Std Dev	Inches/Foot
7	Gro-Mulch - 3"	0.91	0.11	3.64
3	Yardwaste - 5"	1.13	0.17	2.72
2	Yardwaste - 3"	0.63	0.11	2.51
1	Yardwaste - 1"	0.20	0.04	2.34
4	Composted Yardwaste - 3"	0.40	0.15	1.59
10	Fabric + OGC - 3"	0.35	0.04	1.42
6	OGC - 3"	0.31	0.01	1.25
8	Bark - 3"	0.28	0.03	1.11
5	Xerimulch - 3"	0.20	0.01	0.81
11	1” Rock - 3"	0.02	0.01	0.09
9	Fabric	-	-	-
12	Control	-	-	-

Table 3. Mean water lost between measurement days for each mulch treatment in inches, LSD @ 0.05 level of confidence, interval of days for the loss, and ETo in inches for the measurement period at the experiment performed at Cuyamaca College, El Cajon, CA.

TRT #	Treatment	10/4	10/5	10/6	10/7	10/8	10/9	10/17	Total
7	Gro-Mulch – 3"	0.177	0.080	0.042	0.045	0.030	0.030	0.156	0.560
3	Yardwaste – 5"	0.101	0.063	0.039	0.046	0.032	0.033	0.153	0.467
2	Yardwaste – 3"	0.094	0.054	0.032	0.038	0.023	0.027	0.110	0.378
4	Comp Ydwste - 3"	0.113	0.051	0.028	0.048	0.005	0.022	0.076	0.343
10	Fabric + OGC - 3"	0.086	0.044	0.025	0.028	0.024	0.023	0.100	0.330
6	Org Gr Cover - 3"	0.085	0.043	0.025	0.033	0.022	0.026	0.101	0.335
8	Bark - 3"	0.080	0.034	0.021	0.026	0.017	0.018	0.052	0.248
1	Yardwaste – 1"	0.074	0.040	0.015	0.019	0.004	0.004	-0.002	0.154
5	Xerimulch – 3"	0.061	0.027	0.013	0.018	0.015	0.011	0.029	0.174
11	Rock - 3"	0.043	0.011	0.004	0.011	0.004	0.008	-0.006	0.075
9	Fabric	-	-	-	-	-	-	-	-
12	Control	-	-	-	-	-	-	-	
	LSD @ 0.05	0.0128	0.009	0.004	0.013	0.014	0.003	0.023	-
	Interval (Days)	1	1	1	1	1	1	8	14
	ETo for Period	0.19	0.17	0.17	0.16	0.16	0.15	1.15	2.15

Table 4. Mean water lost between measurement days for each mulch treatment in inches, LSD @ 0.05 level of confidence, interval of days for the loss, and ETo in inches for the measurement period at the first experiment conducted at Quail Botanical Gardens, Encinitas, CA.

TRT #	Treatment & Depth	10/5	10/6	10/7	10/8	10/9	10/10	Total
7	Gro-Mulch - 3"	0.140	0.055	0.063	0.019	0.034	0.023	0.334
3	Yardwaste - 5"	0.075	0.045	0.067	0.017	0.035	0.025	0.264
2	Yardwaste - 3"	0.064	0.037	0.050	0.016	0.027	0.018	0.212
4	Comp Ydwste - 3"	0.059	0.026	0.043	0.001	0.017	0.010	0.156
10	Fabric + OGC - 3"	0.047	0.026	0.042	0.008	0.021	0.013	0.157
6	Org Gr Cover - 3"	0.049	0.027	0.033	0.019	0.020	0.012	0.160
8	Bark – 3"	0.042	0.021	0.033	0.012	0.017	0.008	0.133
1	Yardwaste - 1"	0.051	0.026	0.040	-0.001	0.011	0.005	0.132
5	Xerimulch - 3"	0.036	0.018	0.021	0.012	0.013	0.006	0.106
11	1" Rock - 3"	0.013	-0.003	0.020	-0.014	-0.002	0.001	0.015
9	Fabric	-	-	-	-	-	-	
12	Control	-	-	-	-	-	-	
	LSD @ 0.05	0.016	0.009	0.019	0.013	0.006	0.004	
	Interval (Days)	1	1	1	1	1	1	
	ETo for Period	0.13	0.14	0.13	0.13	0.13	0.12	0.78

Table 5. Mean water lost between measurement days for each mulch treatment in inches, LSD @ 0.05 level of confidence, interval of days for the loss, and ETo in inches for the measurement period at the second experiment conducted at Quail Botanical Gardens, Encinitas, CA.

TRT #	TREATMENT & DEPTH	10/12	10/16	10/18	TOTAL
12	Control	0.207	0.290	0.029	0.526
9	Fabric	0.173	0.302	0.045	0.520
7	Gro-Mulch - 3"	0.170	0.265	0.041	0.476
3	Yardwaste - 5"	0.108	0.181	0.048	0.337
2	Yardwaste - 3"	0.099	0.148	0.037	0.284
4	Comp Ydwste - 3"	0.103	0.097	0.022	0.222
1	Yardwaste - 1"	0.085	0.094	0.007	0.186
10	Fabric + OGC - 3"	0.072	0.093	0.018	0.183
6	Org Gr Cover - 3"	0.115	0.054	0.013	0.182
8	1” Bark - 3"	0.069	0.080	0.011	0.160
5	Xerimulch - 3"	0.058	0.054	0.005	0.125
11	1” Rock - 3"	0.023	0.004	-0.003	0.024
	LSD @ 0.05	0.044	0.051	0.008	
	Interval (Days)	1	4	2	7
	ETo for Period	0.07	0.46	0.22	0.75

DISCUSSION

These results are relevant to water conservation goals of landscape irrigation managers and water agency personnel. Many landscape plant materials can survive on water levels at or below 50 percent of ETo. Irrigation scheduling research suggests levels of 30 percent of ETo or less for drought tolerant plant materials used in the landscape (Shaw and Pittenger). Mulches are recommended to reduce evaporation losses from soil surfaces and thus further reduce irrigation needs of landscapes. However, until now there was no information on the water retention and evaporation rates of mulches used in the landscape.

In this study, the water lost from mulch treatments was as much as 100 percent of ETo on the first day following irrigation (Table 4). In the second experiment at Quail Gardens, water loss was not significantly different between soil, soil covered with fabric, and soil covered with Gro-Mulch for five days following irrigation (Table 5). This indicates that although the Gro-Mulch may be insulating soil from moisture loss, the water lost to the atmosphere is not different from bare soil or fabric covered soil. For these three treatments, the average evaporative loss exceeded 100 percent of ETo for the five days immediately following overhead irrigation. Hence, if irrigation managers are irrigating drought tolerant plant materials with overhead irrigation systems more frequently than every five days, the evaporation component exceeds the estimated plant water needs by 300 percent.

The water holding capacity and evaporation data from the bark, OGC, Xerimulch, and rock show that these materials had minimal water loss after two days. Rock and Xerimulch had the least evaporative loss of all treatments. However, the evaporation loss from bark, OGC, and yardwaste (1-inch deep) during the first two days after irrigation exceeded 40 percent of ETo (Table 3). In the first experiment at Quail Botanical Gardens, water loss from the mulch materials averaged less than 30 percent of ETo after six days. This information indicates that overhead irrigation should not be applied more frequently than every six or seven days in similar environmental conditions. Under this regime, the irrigation manager is taking advantage of the insulative properties of mulches while minimizing the evaporative loss from the mulch itself.

This study provides information on the water retention and evaporative loss rates for mulches commonly used in the landscape. Irrigation managers can utilize this information in deciding the mulch material to use, the type irrigation system, and frequency of irrigation. Under drip irrigation, evaporative loss would be minimized and any mulch material could be selected. With overhead irrigation, coarser mulches with lower water holding capacity or a thinner layer of mulch could be utilized. The irrigation manager should know the amount of water held by the mulch and apply additional water to compensate for this amount. Water savings can then be achieved by extending the interval between irrigations. Additional landscape variables affecting irrigation amounts include the type of plant material and its water needs, the uniformity of the irrigation system, and the percent of the irrigated landscape covered by mulch.

This study shows that mulch selection and irrigation frequency decisions can significantly impact the water needs of the landscape. Gross water and energy savings associated with informed selection of mulch materials and sound irrigation scheduling can be estimated using ETo estimates and a range of irrigation management situations. For example, ETo for San Diego is approximately 44.0 inches per year. If a drought tolerant landscape is irrigated with overhead sprinklers, the choice of mulch and irrigation frequency significantly affect water use. Table 6 provides a range of water and energy savings for several landscape scenarios using drought tolerant plant material and overhead irrigation in San Diego together with data from this study (Table 5). This example could be further refined by incorporating rainfall data, seasonal variation in ETo, percent cover of plant material, and estimates of irrigation uniformity and efficiency. However, the information provided gives an indication of the impact that mulch selection and irrigation frequency have on water use.

Table 6. Water use estimates per acre per year for drought tolerant landscape in San Diego utilizing overhead irrigation with different mulches and variable irrigation frequency.

ETo (Inches)	Mulch Treatment and Thickness	Irrigation Frequency (Days)	Estimated Percent of ETo	Water Use (Ac Ft/Ac/Yr)
44.0	None	7	70	2.6
44.0	None	<5	100	3.7
44.0	Yardwaste 3"	7	38	1.4
44.0	Yardwaste 3"	5	54	2.0
44.0	Bark 3"	5	32	1.2
44.0	Bark 3"	7	30	1.1

CONCLUSION

This study described the water holding capacities and evaporative losses occurring in 12 mulch treatments common to landscapes in California. Presentation of these data is not intended to discourage overall use of mulches, but to aid in providing best management practices for the wise use of mulch materials. Landscape management personnel can use this information in selecting mulch materials and determining irrigation schedules to maximize the performance of plant materials while conserving water and energy.

Further studies are necessary to determine the effects of mulch treatments in planted conditions under sprinkler and drip irrigation. This would provide information on overall effects of mulches in water conservation and growth of plant materials.

ACKNOWLEDGEMENTS

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REFERENCES

Bennett, J. 1982. Mulches to retain moisture and cool the soil. Horticulture. 60(7):55–56.

Borland, J. 1990. Mulch; examining the facts and fallacies behind the uses and benefits of mulch. Am. Nurseryman.172(4):132–143.

California Integrated Waste Management Board (CIWMB). 2002. A landscaper's guide to mulch. CIWMB Publication # 443-02-010.

Groenevelt, P.H., P. van Straaten, V. Rasiah, and J. Simpson. 1989. Modifications in evaporation parameters by rock mulches: Soil Tech. 2:279–285.

Lanini, W.T., J.M. Shribbs and C.E. Elmore. 1988. Orchard floor mulching trials in the USA. Le Fruit Belg. 56(3): 228-249.

Litzow, M and H. Pellett. 1983.Influence of mulch materials on growth of green ash. Journal of Arboriculture. 9(1):7-11.

Montague, T. and R. Kjeldren. 2004. Energy balance of six common landscape surfaces and the influence of surface properties on gas exchange of four containerized tree species. Scientia Horticulturae. 100(1):229-249.

Shaw, D.A., and D.R. Pittenger. 2004. Performance of landscape ornamentals given irrigation treatments based on reference evapotranspiration. International Irrigation Association 25th Annual Show Proceedings.

Smith, A.M., and D.A. Rakow. 1992. Strategies for reducing water input in woody landscape plantings: J. Arboric. 18:165–170.

Teasdale, J.R. and C.L. Mohler. 2000. The qualtitative relationship between weed emergence and the physical properties of mulches. Weed Sci. 48(3):385-392.

Water Conservation Diagrams Illustrate Benefits of Improved Irrigation[1]

Kenneth H. Solomon[2] and Joseph Kissinger[3]

Abstract: A water conservation diagram compares two water destination diagrams on the same chart, and is a wonderful educational tool for documenting, explaining and illustrating the benefits of irrigation improvements. Water destination diagrams are graphical depictions of the ultimate fate of all water applied by an irrigation system. Water destination diagrams show such features as the amount of water going to meet plant water requirements and the amount of water going to non-productive uses (runoff, overspray, deep percolation). The influence of distribution uniformity and of irrigation scheduling decisions on water application are easily shown. Comparing two water destination diagrams in a water conservation diagram clearly shows the benefit of irrigation improvements such as raising uniformity, reducing runoff, or eliminating overspray. This paper describes the construction, interpretation and use of water conservation diagrams for turf and landscape irrigation.

Introduction

Urban water use is an increasingly significant portion of total water use, particularly in the arid West. A major component of urban water use is for irrigation of the urban landscape. Improvements in the efficiency of landscape irrigation could offer considerable potential for water conservation in the urban sector. For example, the California Department of Water Resources (1998) has observed:

> *"The greatest potential reduction in urban water use would come from reducing outdoor water use for landscaping."*

Improvements in irrigation equipment, design and management all have roles to play in urban water conservation. Education also plays an important role. If water purveyors, irrigation professionals, and water users fail to understand the ways in which irrigation decisions affect water conservation, this lack of understanding poses a barrier to effective implementation of water conservation technologies.

Water destination and water conservation diagrams are useful tools, easily illustrating the fate of applied irrigation water. When used to compare the consequences of alternate irrigation decisions, they can illustrate as well the water conservation to be achieved, and/or the improvement in landscape moisture status to be obtained from making the superior decision.

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Water Destination Diagrams

As we will see, water conservation diagrams are constructed from two water destination diagrams representing competing irrigation decisions. So let's look first at how water destination diagrams are constructed.

As the name suggests, water destination diagrams show the destination or ultimate fate of water applied during an irrigation event. One of the key considerations is the uniformity with which water is applied to the irrigated area. Unfortunately, no irrigation system can apply water with perfect uniformity. Some parts of the irrigated area will receive relatively more water, while other parts receive relatively less.

The most direct way to observe and numerically evaluate this effect is through an irrigation audit. The Irrigation Association (2004) presents detailed procedures for conducting audits, but for our purposes, the key conceptual steps are these: (1) place catch-cans [think rain gages] throughout the area to be irrigated; (2) run the irrigation system as intended; (3) analyze and interpret the results. The first two steps in this process are illustrated in Figures 1a and 1b.

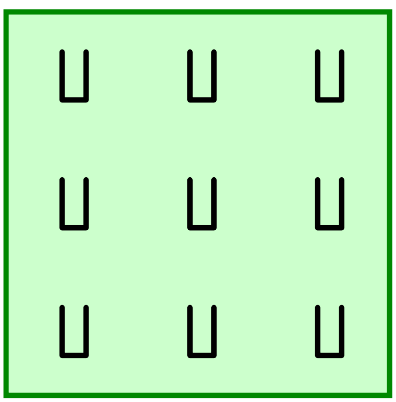


Figure 1a. To perform an audit, catch-cans must be placed throughout the irrigated area.

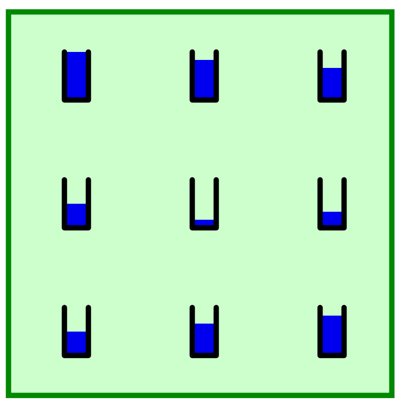


Figure 1b. After the irrigation system has been run, the catch-cans show the amount of water deposited in various locations.

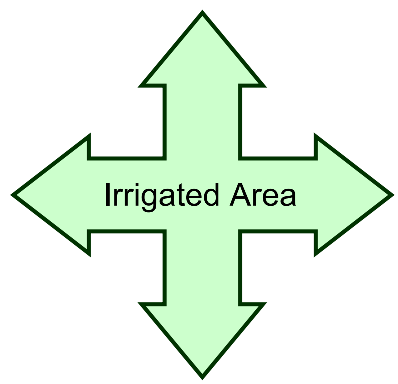


Figure 1c. Since the irrigated area is 2-dimensional (N-S and E-W), water amount represents a third dimension.

Figure 1c emphasizes the difficulty in trying to develop illustrations of audit results. The irrigated area is 2-dimensional (for example, North-South and East-West). So to develop a water diagram, the water amount would have to be graphed in a third dimension, which makes the whole situation difficult to present on a 2-dimensional piece of paper.

Water destination diagrams solve this problem by rearranging the catch-cans, as shown in Figure 2 (next page). The catch-cans are moved into a line, ordered according to the amount of water contained in each, with the larger amounts at the left.

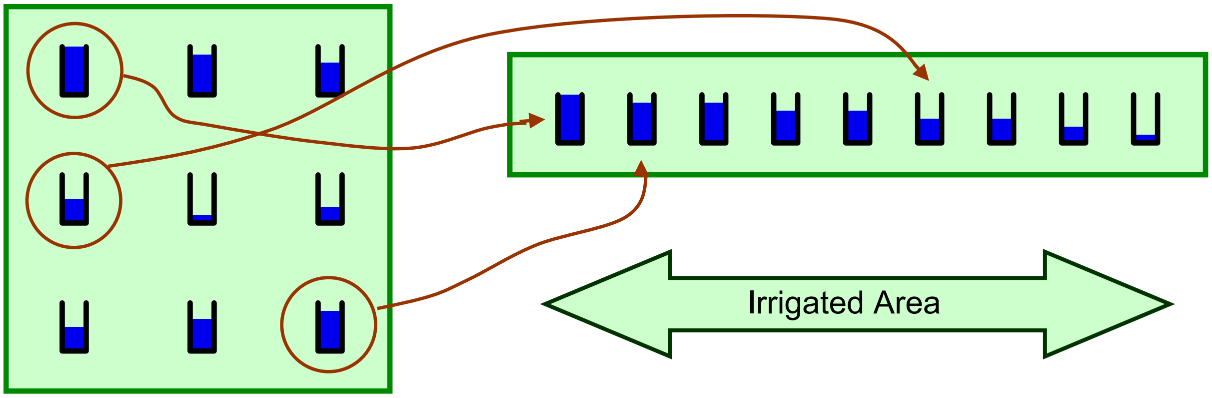


Figure 2. To enable the construction of the water destination diagram, catch-cans from the audit are repositioned into a 1-dimensional array, and sorted according to the amount of water caught in each can, with the larger amounts on the left. [The actual act of repositioning is shown here for only a few of the catch-cans.]

Adjacent catch-cans in the repositioned array don't necessarily come from adjacent locations in the originally audited area. However, each catch-can does represent a certain proportionate share (percentage) of the audited irrigated area. And, since the repositioned array is now a 1-dimensional representation, the amount of water can be illustrated in a normal 2-dimensional graph.

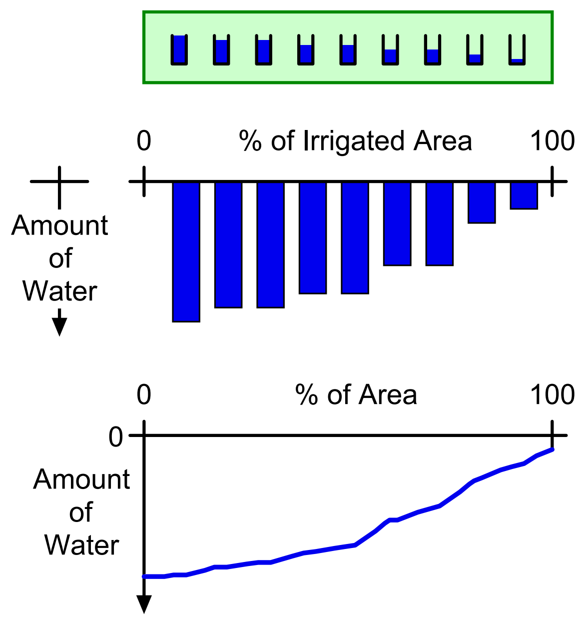


Figure 3. The uniformity part of the water destination diagram is constructed from the 1-dimensional array of repositioned catch-cans (top). The diagram may be shown as a bar graph (middle) or as is most commonly done, as a water application curve (bottom).

It is traditional to plot the amount of water in the downward direction, to represent water infiltrated into the ground (Figure 3). The horizontal axis represents the irrigated area. But since information about specific geographic location has been lost in the repositioning process, the horizontal axis is quantified only as the per cent of the area represented (see further on this point below).

The process of conceptually repositioning the catch-cans from an audit, as shown in Figure 2, is key to the construction and understanding of water destination diagrams. It has been our experience that individuals presented with a water destination diagram for the first time do not always grasp the significance of the horizontal axis. They do not easily make the jump between their mental image of an irrigation audit (as in Figure 1), and the "% of Area" axis in the bottom of Figure 3. However, with an explanation of the repositioning process, and with a demonstration or sketches such as Figures 2 and 3, the situation is usually clear. Most people comfortable with graphical presentations of numerical data in general will understand the water destination diagram, and be able to relate the diagrams to the consequences of irrigation decisions.

The uniformity portion of the water destination diagram from an actual irrigation audit is shown in Figure 4. [Note: The uniformity in this particular case is not very good. The Low Quarter Distribution Uniformity (DU_{LQ}) is only 58%.]

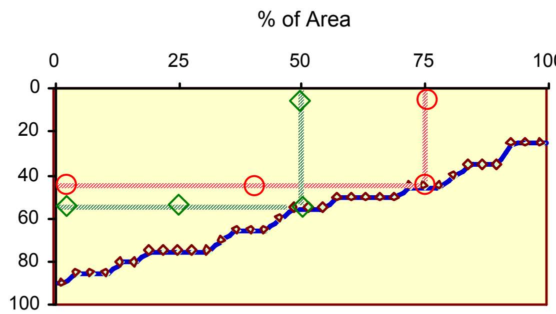


Figure 4. Water destination diagram from an actual irrigation audit.

The dashed lines illustrate how the graph is to be read. The dashed red lines (circle symbols) intersect at a point that indicates that 75% of the irrigated area received a catch-can value of 45 or more. An equivalent reading is that 25% (that is, 100% minus 75%) received a catch-can value of 45 or less. The dashed green lines (diamond symbols) intersect at a point that indicates that the catch-can value of 55 is the median value: about 50% of the area receives this much or more, while the other 50% of the area receives this much or less.

The minimum application amount occurs at the far right of the application curve, directly under the "100% of Area" position. The average application amount tends to occur approximately under the 50% position. The maximum application amount occurs at the far left of the application curve, directly under the 0% position.

Figure 5 shows how the water destination diagram shifts in response to improved uniformity. Water applications with low uniformity are represented by application curves that are relatively steep. They exhibit the widest difference between the minimum and maximum application amounts (red curve, circle symbols). Higher uniformity applications are represented by application curves that are less steep, with smaller differences between minimum and maximum application amounts (blue curve, triangle symbols). Perfect uniformity (an unattainable ideal, and therefore not shown here) would be represented by a perfectly level, horizontal application curve, with minimum, average and maximum application amounts all the same.

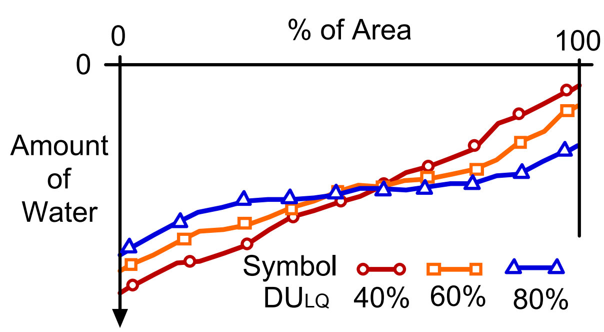


Figure 5. Steeper slopes on the application curve of the water destination diagram imply lower uniformity.

Factors Other than Uniformity

If the water destination diagram is to show the destination or ultimate fate of water applied during an irrigation event, more factors must be considered than just uniformity. Not all of the water applied may reach the irrigated area or infiltrate. The fate of some of the applied water may be overspray or runoff. Overspray is water sprayed outside the boundaries of the area to be irrigated, such as on adjacent sidewalks or roadways. Runoff is water that moves across the surface of the soil and leaves the irrigated area before it has the chance to infiltrate into the soil. How are these *destinations* shown on the destination diagram? The convention is to show these amounts above the zero line on the water amount scale (Figure 6).

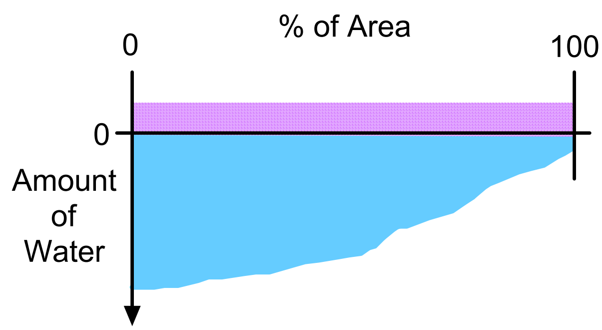


Figure 6. A complete water destination diagram. Infiltrated water is shown in solid blue. Overspray and runoff amounts are placed above the zero line, and are shown here in mottled purple.

Placing water destined for runoff or overspray *above* the water application zero line is consistent with the observation that water destined for these fates is not available to infiltrate into the soil, and therefore cannot contribute to meeting the goal of the irrigation, which is to deliver the required amount of water to the root zone of the landscape plant material.

Because the water lost in these ways never reaches the irrigated area, uniformity does not apply. In other words, it makes no sense to talk of the uniformity of runoff or overspray – they are extracted from the system before uniformity of application applies. Therefore, these losses are shown as a fixed amount across the entire irrigated area (see mottled purple bar in Figure 6).

Diagram Changes with Run Time

Figure 7 shows how water destination diagrams change with run time [actually, the net result of changes in both number of cycles and run time per cycle]. Increasing run time shifts the water application curve and the runoff/overspray line from the dashed to the solid curves.

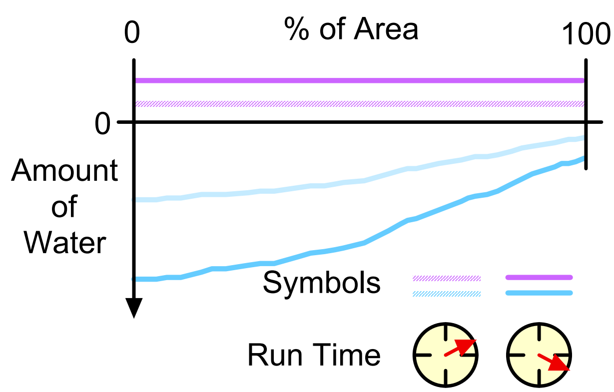


Figure 7. The effect of run time on water destination diagrams

Each application amount is scaled in direct proportion to the increase in run time (from 1x to 2x in Figure 7), so increasing run time shifts the application curve down. The numerical value of uniformity (DU_{LQ}), though, is not changed. Since each water amount is increased by the same proportion, both the average and the average of the low quarter application am ounts are also changed by that same proportion. Therefore the value of the ratio by which DU_{LQ} is calculated will not change.

Increasing the run time will also increase the amount of overspray in the same proportion. The runoff will increase as well, though perhaps not in the same proportion. Unless cycle numbers and soak time between cycles are adjusted, it is possible that runoff could increase by a factor greater than the increase in run time.

Irrigation Target

In order to determine whether or not an irrigation application has been effective, we must consider not only the application (uniformity, runoff, overspray), but the job that the irrigation is intended to do. A number of factors influence irrigation management and scheduling decisions, but ultimately, an irrigation event is intended to place a specific amount of water into the root zone of the landscape plant material being irrigated. The Irrigation Association (2005) presents an excellent review of all such factors, and procedures to determine irrigation intervals, run times, number of cycle starts, and soak time between cycles. For our purposes, we will assume that these considerations and procedures have been duly followed, and that the required water application amount is known. This amount is also known as the irrigation target.

The target amount can be plotted on the water destination diagram, and comparisons of water application amounts to this target can form the basis of judgments about the adequacy and effectiveness of the irrigation event.

Different management strategies can be used to set the position of the water application curve relative to the target. Figure 8 illustrates three possible strategies (in these water destination diagrams, it has been assumed that overspray and runoff are negligible).

On the water destination diagram in the top part of Figure 8, the crossing point of the water application curve (blue) and the target amount (horizontal green line) is nearly under the 0% position. Very little of the area receives more water than it needs, and the amount of over watering is very small.

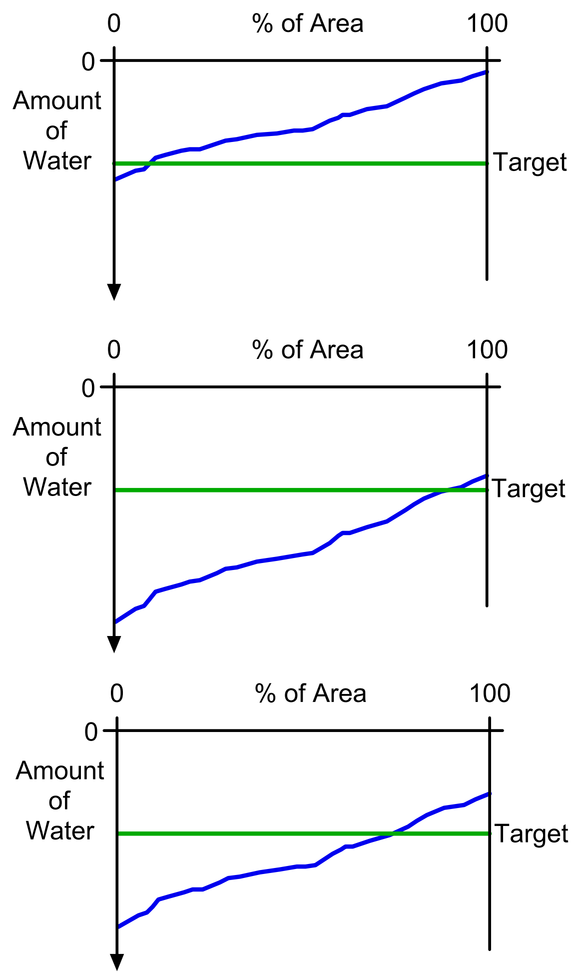


Figure 8. Different management strategies specify the positioning of the water destination diagram's application curve with respect to the target amount.

f th is management strategy is that almost all of the irrigated area receives less water than it needs, and for much of the area the deficit is quite large. This strategy minimizes water applied, but will probably produce landscape with very poor visual quality.

The management strategy shown in the middle of Figure 8 takes the opposite extreme. Virtually all of the irrigated area receives water at the target level or more, so there is very little deficit. However, most of the area receives more water than is necessary, and the amount of water applied in excess of the target amount is quite large.

Various management strategies in between these two extremes represent different trade offs between over- and under-irrigation, between water conservation and excess water application, and between landscape adequately irrigated and landscape suffering significant water deficit. Unless there is a drainage problem on the property, excess water application is usually less apparent than landscape with poor visual quality due to water deficit.

The bottom portion of Figure 8 illustrates the Irrigation Association's recommended management strategy. The IA (2005) suggests that irrigation run times be adjusted so that the low half average application is equal to the target irrigation amount (the amount required for local weather and plant conditions). In this case, the water application curve (blue) crosses the horizontal line indicating the target amount (green) approximately under the 75% position on the horizontal axis of the water destination diagram. The rationale for this recommendation (Mecham, 2001) is that since water may move horizontally through the thatch or the soil, the uniformity of soil moisture may be higher than indicated by catch-can tests. "An improved representation of soil moisture uniformity <u>for scheduling purposes</u> is the *lower-half* distribution uniformity [as computed from catch-can values]" (IA, 2005, page 1-22).

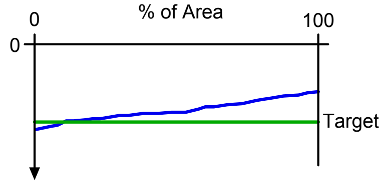
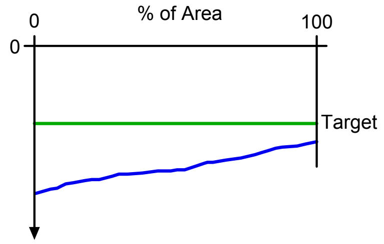
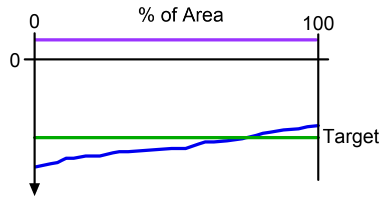
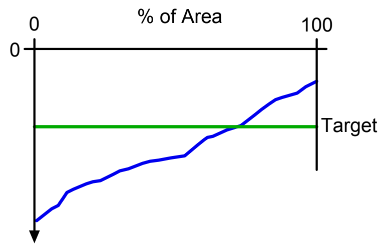
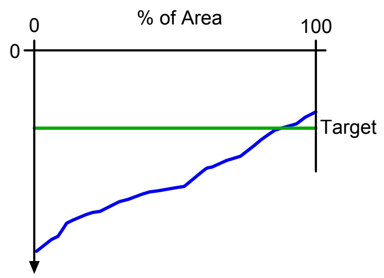
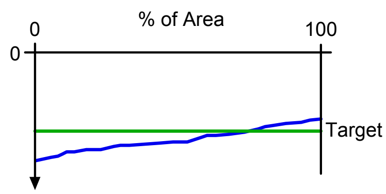
This approach to irrigation scheduling has proved reasonable for systems with adequate uniformity. However, for systems with low uniformities, this method of scheduling may result in some visual signs of stress in the turf or landscape (Allen, 2001). In such cases, it is recommended to correct those problems that cause the low uniformity, instead of just over-watering in an attempt to deliver adequate water to those areas receiving the least amount of water. From the water conservation standpoint, this is certainly the preferred approach.

Interpreting Water Destination Diagrams

Once the basic concepts of water destination diagrams are grasped, they can often be interpreted intuitively. Table 1 (next page) presents interpretations and recommendations based on characteristics easily discernable in water destination diagram sketches. It is relatively easy to make qualitative judgments about the uniformity, run time selection, and amount of overspray or runoff present just from the appearance of the water destination diagrams. Once these judgments have been made, recommended actions to improve or maintain the situation are obvious.

Overspray – Water lost because it is thrown outside the area to be irrigated may be reduced or eliminated by selecting sprinklers with coverage arc and radii appropriate to the area, or by adjusting sprinkler arc and radius settings if possible. Take care that arc or radius adjustments do

Table 1. Water Destination Diagram – Interpretations and Recommendations

Water Destination Diagram*	Interpretation	Recommendations
	• No overspray or runoff loss • Good uniformity • Poor run time selection: a significant portion of the area is in deficit	Increase run time so that the low half average application amount equals the target amount.
	• No overspray or runoff loss • Good uniformity • Poor run time selection: all of the area receives more water than the target amount; considerable water is wasted due to excess application	Reduce run time so that the low half average application amount equals the target amount.
	• Overspray or runoff losses are excessive • Good uniformity • Proper run time selection: application curve crosses target under 75% position (approx.)	Adjust arc and radius of sprinklers to eliminate overspray; reduce precipitation rate or adjust cycle starts and soak time between cycles to minimize runoff.
	• No overspray or runoff loss • Poor uniformity • Proper run time selection: application curve crosses target under 75% position (approx.)	Take steps to improve uniformity.
	• No overspray or runoff loss • Poor uniformity • Poor run time selection: excess water applied to try to eliminate deficit areas caused by poor uniformity	Take steps to improve uniformity; adjust run time so that the low half average application amount equals the target amount.
	• No overspray or runoff loss • Good uniformity • Proper run time selection: application curve crosses target under 75% position (approx.)	Monitor the system to maintain the current high level of performance.

* Water application curves in **blue**; Target application amount in **green**; Overspray/runoff loss in **purple**.

not affect the matched precipitation status of sprinklers on the same circuit – if the flow rate delivered to an adjusted arc or radius sector is not adjusted as well, the precipitation rate will change. Also, watch that adjustment of the radius doesn't adversely alter the water pattern for the sprinkler, resulting in lower distribution uniformity.

Runoff – Runoff may be reduced or eliminated by selecting or retrofitting to sprinklers with reduced precipitation rates, or by adjusting the number of cycles and soak time between cycles.

Run Time Selection – Proper run time selection results in the low half average application amount matching the target or required application amount (this according to IA recommendations). To achieve this result in practice requires:

- an understanding of plant characteristics and weather conditions to establish the target amount,
- an understanding of the sprinkler system's application rate and uniformity characteristics to calculate the necessary run time, and
- the ability to control the sprinkler system to achieve the desired run time.

With poor uniformity systems, proper run time selection as defined above may not result in adequate coverage for the entire area – portions of the landscape may receive insufficient water and have an unacceptable visual appearance. Inexperienced water managers observing this condition tend to increase irrigation run times in an attempt to eliminate deficits. Unfortunately, this may require a large increase in the amount of water applied (compare rows 4 and 5 in Table 1). It's just not efficient to fight a uniformity problem with water. Much better is to make changes to the system to improve the uniformity, and then select run times as recommended (so that the low half application amount matches the target).

Uniformity – As there are many factors that influence uniformity, there are many possible steps toward making improvements. Selecting the right sprinkler, nozzle, operating pressure and spacing *before* installation is the best course. However, even after the initial system has been installed, retrofitting to a more appropriate sprinkler selection can significantly improve uniformity.

Make sure that all sprinklers on the same circuit have the same precipitation rate, even after any arc and radius adjustments have been made to eliminate overspray. Selecting, or retrofitting, sprinklers with lower flow rates may improve uniformity in a couple of ways. First, the lower flow rates will reduce friction losses through meters and supply lines, resulting in an increase in the pressure entering the circuit. Second, the lower flow rates will also reduce friction losses in the piping within the circuit, resulting in a more uniform distribution of pressure among all sprinklers on the circuit.

Water Conservation Diagrams

When alternate irrigation decisions are contemplated, or when a change is proposed to a previous decision, water destination diagrams for the competing options will show the consequences of each choice. However, to emphasize the net effect of the differences between options, it is plot the water destination diagrams for both options on the same chart. This is called a *water conservation diagram* since it is such an effective way to illustrate the conservation benefits to be associated with the superior irrigation decision. Two examples are presented to demonstrate the concept.

Case 1 – An existing system has been audited and found to have excessive overspray and runoff losses, and poor uniformity. Due to low uniformity, portions of the landscape had poor visual quality. The irrigation manager has increased run times to try to apply sufficient water in these "dry spots." A system retrofit was performed to improve the situation. The existing spray heads were replaced with sprinklers that had lower flow rates and superior coverage on the existing spacings. The reduced precipitation rate eliminated runoff, and arc and radius settings were adjusted to eliminate overspray. The improved uniformity eliminated deficit areas, so run times were selected in accordance with the IA recommendations: so that the low half average matched the target application amount. Figure 9 shows the separate water destination diagrams for this system, both before and after the retrofit, and the combined water conservation diagram that highlights the net benefits of the improvement.

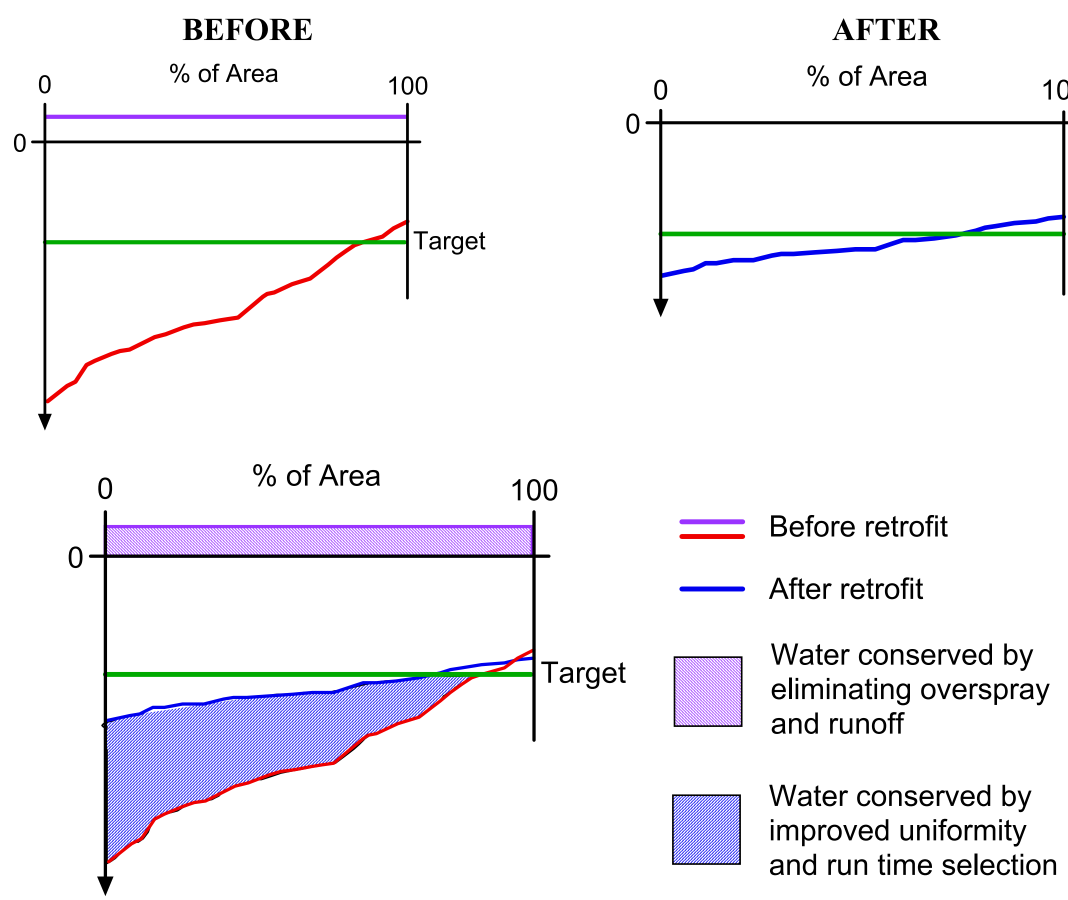


Figure 9. Diagrams for Case 1. Top left, water destination diagram for the existing system, before the retrofit. Top right, water destination diagram for the improved system, after the retrofit. Bottom, water conservation diagram highlighting the water conserved by the improvements.

efit of this retrofit was water conservation. Although poor uniform ity had initially resulted in deficits and landscape of poor visual quality, the irrigation manager had overcome this problem by increasing water application. This also increased the amount of water lost to overspray and runoff. Although deficits were negligible in both the *before* and *after* situations, considerably more water was required to eliminate the deficits before the retrofit. The water conservation diagram (Figure 9, at bottom) emphasizes the amount of water saved by the retrofit, and identifies the cause of each conservation component.

Case 2 – An existing system has been audited and found to have poor uniformity. No overspray or runoff were observed. Run times were selected according to IA recommendations. Due to low uniformity, portions of the landscape had poor visual quality. The irrigation manager recognized the cause as poor uniformity, and ordered a retrofit to improve the situation. The existing spray heads were replaced with sprinklers that had superior coverage on the existing spacings and better resisted pattern distortion under windy conditions. The improved uniformity greatly reduced deficit areas, so run times continued to be selected according to IA recommendations: so that the low half average matched the target application amount. Figure 10 shows the separate water destination diagrams for this system, both before and after the retrofit, and the combined water conservation diagram that highlights the net benefits of the improvement.

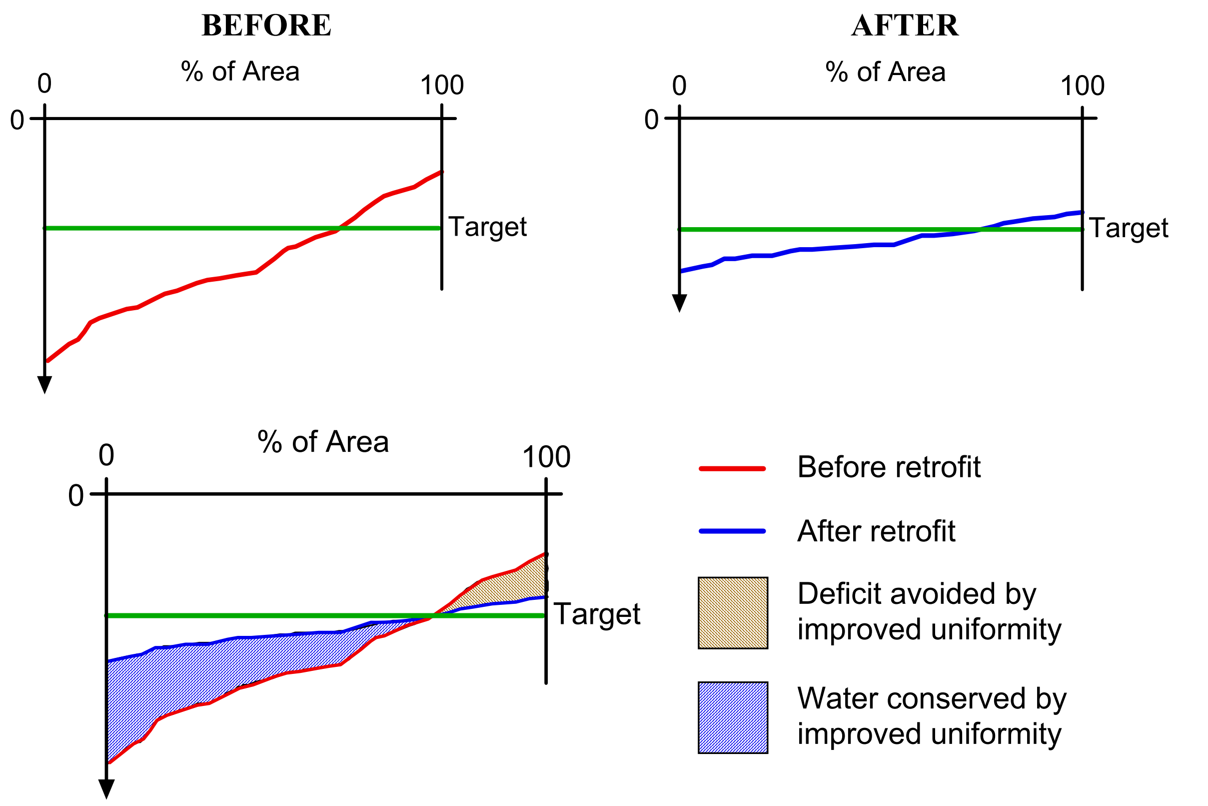


Figure 10. Diagrams for Case 2. Top left, water destination diagram for the existing system, before the retrofit. Top right, water destination diagram for the improved system, after the retrofit. Bottom, water conservation diagram highlighting both the water conservation and the deficit reduction achieved by the retrofit.

The benefits of the second retrofit were both water conservation and better looking landscape. The deficits and poor quality landscape evident in the existing system were corrected by the retrofit. The new system does a better job of caring for the landscape, since it greatly reduces the deficits previously experienced. Furthermore, it does so using less water than the old system! The water conservation diagram (Figure 10, at bottom) emphasizes both benefits of the retrofit – the amount of water saved and the reduction of deficits that had been causing poor quality landscape.

Summary and Conclusions

A *water destination diagram* shows the ultimate fates (destinations) of applied irrigation water. Techniques for explaining the construction of water destination diagrams to those unfamiliar with the concept are presented. When the target irrigation amount is also plotted on a water destination diagram, the adequacy and effectiveness of the irrigation can be judged. Intuitive interpretations of water destination diagrams are possible. Key characteristics of the irrigation system may be recognized in the water destination diagrams, and appropriate actions for correcting problems can be recommended. When water destination diagrams for two alternate irrigation situations are plotted on the same chart, the result is a *water conservation diagram*. A water conservation diagram emphasizes the net benefit of making the best decision or choosing the best system, and can be an effective tool in arguing for the superior alternative.

References

Allen, RG. 2001. Impact of Using DU Low Quarter or DU Low Half for Computing Gross Depth. November 2001, personal correspondence.

California Department of Water Resources. 1998. California Water Plan Update: Bulletin 160-98. California Department of Water Resources, Sacramento, CA. 570 pages.

Irrigation Association. 2004. Certified Landscape Irrigation Auditor Training Manual. Irrigation Association, Falls Church, VA. 278 pages.

Irrigation Association. 2005. Landscape Irrigation Scheduling and Water Management. Irrigation Association, Falls Church, VA. 190 pages.

Mecham, Brent. 2001. Distribution Uniformity Results Comparing Catch-Can Tests and Soil Moisture Sensor Measurements in Turfgrass Irrigation. Proceedings, Irrigation Association's 2001 International Irrigation Show, San Antonio, TX, November 2001, pages 133-139.

#1296 Evaluation of new retrofit technology for conversion of sprayheads to drip irrigation in municipal facilities

As in many other cities, a large portion of runoff in the City of Santa Monica originates from excessive or misdirected sprinkler irrigation. In 2004 the City's Environmental Programs Division (SMEPD) began a search for City-owned properties that could serve as demonstration sites for various water conservation and runoff reduction technologies for the City's property owners.

A good candidate was found in Santa Monica Fire Station #2 (Figure 1) which had been completely rebuilt in 2003 as a result of damage sustained in the 1994 Northridge earthquake. The rebuild included new landscaping consisting of three turf zones and five shrub zones totaling a little over 2000 square feet; and an irrigation system composed of an Irritrol MC+ controller, Rain Bird EFB-CP valves and Rain Bird 1800 sprayheads with Rain Bird MPR nozzles. Most of the zones in this landscape are adjacent to hardscape and prone to overspray and runoff from the sprinklers (Figure 2).

A plan was created in-house to convert the five shrub zones to line-source drip irrigation and to retrofit the sprayheads in the turf zones with rotor-type nozzles. (Figure 3)

Equipment Choices –

Since a goal of the project was easy replication by City residents on their own property, it was decided to use, as much as possible, simple, prefabricated assemblies. Devices chosen included the Rain Bird 1800-RETRO ("RETRO") (Figure 4) which provides a pressure regulator, filter and drip tubing connection point in a single assembly that can replace any existing sprayhead. Rain Bird Xericaps (Figure 5) were used to close off the remaining unconverted sprayheads in each zone. After a soil analysis, Agrifim 18mm Dura-Flo PC Dripperline with 0.5 gallon-per-hour (gph) emitters at 12" spacing was chosen as the line-source drip product (Figure 6). Agrifim ½" Swivel Tees and marlex street elbows were used to connect the tubing to the RETRO (Figure 7). Initially, It was planned to replace the existing valves with Weathermatic 21024E units; See VALVES below.

The Plan –

One sprayhead, located away from foot or vehicle traffic, was flagged in each zone for conversion with the RETRO (Figure 8). Remaining sprayheads were to be capped except for one or two chosen to be Tattletale / Flush units (described below). The tubing laterals were planned for layout in parallel rows bracketing the original planting rows that appeared to be approximately 30” on center (Figure 9). In long narrow plantings, such as the 32” wide parkway in zone 5, a single line of tubing was used snaking around alternate sides of the plants (Figure 10).

The existing Zone 7 (Figure 11) included both turf and shrubs in the same zone. To correct this it was planned to extend the drip tubing from Zone 1 to include the zone 7 shrubs and all the sprayheads in that area would be capped leaving the unconverted portion of Zone 7 as turf only.

Installation –

SPRAYHEADS – Because the original equipment was Rain Bird, the flagged sprayheads in each zone were converted with the RETRO device by simply removing the cap, nozzle, stem and spring from the existing unit and replacing it with the cap and internal portion of the RETRO. If other brands of sprinklers are being converted, the entire sprayhead body must be replaced with the complete RETRO unit (Figure 12). Rain Bird Xericaps (Figure 13) were used to close off the remaining unconverted sprayheads in each zone except for one or two chosen to be Tattletale / Flush units (described below).

TUBING -- First, the tubing was pulled into place below the canopy of the plants. When all lines were roughly in place, their location was adjusted at each plant and then fastened in place with galvanized steel, hairpin-shaped stakes at approximately three-foot intervals (Figure 14). When the laterals were in place, A feeder line of plain tubing without emitters was installed to connect the laterals to the RETRO (Figure 15) Rain Bird *Easy-Fit* connectors were used to make all tubing-to-tubing connections (Figure 16).

TATTLETALE / FLUSH ASSEMBLIES (TFA) – Maintenance personnel working with drip irrigation for the first time frequently are uneasy about shifting from observing water spray to observing plants in order to tell if the irrigation system is working properly. To assist in this transition we created the TFA (Figure 17) which is a 12” pop-up sprayhead with a Rain Bird PA-80 adapter and PVC cap in place of the nozzle. In drip systems designed from scratch, we specify a TFA to be placed at the extreme ends of the pipe manifold in each drip zone. In normal operation, these white-capped *tattletales* pop up to full height for a visual indication that the system is pressurized and that there are no serious breaks in the unseen drip tubing. These end-of-the-line caps are easily removed for flushing the manifold when needed.

In conversion of existing sprayhead systems, such as this project, there are built-in opportunities to create TFAs simply by capping the stem of the sprinkler rather than the body (Figure 18).

VALVES – Small-scale drip systems usually require a valve with a very low minimum flow rate ("MinFR"), frequently less than one gallon per minute (GPM). When converting sprayheads to drip, the existing valve frequently does not meet those specs, with a MinFR of 3-5 GPM more commonly found. This was the case at Fire Station #2 where the Rain Bird EFB-CPs have a MinFR of 5 GPM while some of the converted zones have flows of less than one GPM. Initially we purchased replacement valves for the five drip zones (Weathermatic 21024E) but decided, since the fire station is occupied at all times, to experiment with throttling down the flow controls on the existing valves before proceeding with replacement.

TURF ZONES – The standard nozzles in all turf zones were replaced with MP Rotator MP1000 nozzles.

CONTROLLER – A new program based on historical ET and actual zone precipitation rates was calculated and the controller was completely reprogrammed with the new data.

The installation was completed in February 2005.

MULCH – The system was observed in operation for two months to confirm correct placement of the tubing and check for leaks and then a 2-3 inch layer of shredded fir bark mulch was placed over all the shrub beds in April 2005.

Cost –

Total material cost including the mulch and the as-yet-unused valves was $1195 (77¢ per square foot) for the shrub zone conversions and $136 (30¢ per square foot) for the turf areas. The installation was done by one irrigation tech and two untrained volunteers and required 42 person-hours.

Results –

PLANTS – Plant growth was initially observed to be extraordinary. But the installation was completed as the wettest winter in Southern California history was ending, so it would be difficult to attribute the lush growth to the new drip system. However, as the garden moved through spring and a summer that was unusually hot, plant health continued to be very good. The one exception to this was a long line of shrubs against a south-facing wall in Zone 1 which became quite scorched. Ironically, the problem was found to be a malfunction in one of the sprayheads that had been converted to a TFA which created a leak that diverted water from the shrubs.

RUNOFF AND OVERSPRAY – Runoff has been completely eliminated from this site. Overspray still exists on hardscape adjacent to the turf zones. This is virtually unavoidable when turf is planted immediately adjacent to hardscape. However, the very low application rate of the rotor nozzles has reduced the problem to a level short of runoff.

WATER CONSUMPTION – Landscape water usage for Fire Station #2 increased 50% for the first six months after the conversion compared to the previous year. Since the new controller schedule was calculated based on ET using a K_c of 0.6 for the shrubs and 0.8 for the turf, it can be assumed that the previous operator of the system was deficit irrigating particularly since the previous system had significant runoff. The controller schedule has been recalculated using lower plant factors.

MAINTENANCE – There have been 5 incidents requiring maintenance in the first six months of project operation. Two of them involved failures of sprayheads left in place to act as TFAs. One involved tubing cut by maintenance personnel, one involved the failure of a tubing connector and the fifth resulted from a valve not shutting off properly. Total repair time for all five incidents was one hour and fifteen minutes.

Additional Efforts –

COLLATERAL MATERIAL

~ SMEPD has developed distinctive signage for use in landscape demonstration sites (Figure 19). A descriptive sign in this format is being created for the Fire Station #2 site.

~ A how-to booklet is being developed for residents and/or contractors to replicate this procedure on their own property.

~ Information about this project is being developed for posting on SMEPD's website at http://www.smepd.org.

COMMUNITY RESPONSE -- Thus far one workshop for residents has been held at the site. Response was very favorable with attendees feeling that they could do a similar conversion in their own landscapes.

FUTURE PLANS FOR THIS SITE – After one year of operation in the current configuration, the existing controller will be replaced with a weather-based device.

FUTURE SITES – Santa Monica has three additional neighborhood fire stations and two branch libraries which would be good candidates for additional landscape demonstration projects.

Water Conservation Is Good For Business

By Karen Guz, Conservation Planner, San Antonio Water System

Irrigation contractors and water utilities interested in water conservation should not be in conflict. A partnership between the San Antonio Irrigation Association and San Antonio Water System has pushed forward several conservation programs, improved irrigation standards that benefit the community, help meet water conservation goals and improve business for qualified irrigators.

It can be a challenge to compete with low-bid competitors who are not concerned with quality. It takes more supplies and time to put in efficient irrigation systems. Unfortunately, a bad system can be installed for about half the cost as a good one. The poor quality system will most likely not have head to head coverage, appropriate landscape zoning for water need, water may overspray to impervious surfaces and the customer will not be able to use sophisticated program tools. In the long-run the poor quality system clearly wastes water.

Convincing customers to spend a lot more on an efficient system can be a hard sell in the irrigation industry. Homeowners who have little or no background in irrigation may trust the low-bid contractor who convinces them that the higher value system is not necessary. Even more challenging is convincing a builder to put in a top-notch system. When a builder is offering irrigation systems as an “upgrade” to buyers or even requiring them on the property, their primary concern is not long-term efficiency. Their goal is to install an irrigation system that meets minimum requirements and then to make a profit by marking up the cost of the system for the home buyer.

Regulation helps resolve some of these problems. Rules should begin with standards for design, extend to plan review and then inspection after installation. Additional water waste rules that prohibit irrigation spray from hitting impervious surfaces or running off the landscape also help. When rules exist and are enforced, the low-bid contractor must improve or get out of the irrigation business. When builders and homeowners learn that they will have water waste violations resulting from bad systems, they are forced to upgrade them. Eventually this changes the marketplace standards.

Several years ago San Antonio irrigators took the lead in asking the City of San Antonio to upgrade standards above those already required by the State of Texas and to require plan reviews and inspections for systems. In order to accomplish this, they proposed that all irrigators register with the City of San Antonio and be required to pull a permit for each irrigation system they would put in place. The revenue from this permit process pays for the inspection staff necessary to review plans and on-site work.

It might sound as though irrigators in San Antonio have created extra work for themselves. However, what they have accomplished is making it very difficult for unprofessional irrigators to compete in the marketplace. “Fly by night” irrigators who put in poor quality systems do not pass the initial plan review phase or the inspection phase. The cost of having irrigation systems has increased, but the rate of new systems going in has not gone down. Business for the professional irrigator has improved and the non-qualified installer cannot compete. Systems quality is steadily improving.

Water waste rules also generate business for qualified irrigators. Badly designed systems cannot be run without having water run onto impervious surfaces. In San Antonio it is always against city rules to have water running down the street from watering activity. Homes or businesses with overspray problems are warned and then given water waste tickets if the problem persists. Systems must be changed to direct spray away from street and parking lot surfaces. This often requires extensive upgrades that can only be completed by experienced irrigators.

A new requirement that all large properties submit an "Irrigation Analysis" once per year to San Antonio Water System will also generate new business for irrigators. The analysis can be completed by non-irrigators. However, most property management companies are hiring irrigators to review their system for breaks, misaligned heads, overspray and other problems. Once they are presented with a detailed report on these problems, they usually ask the irrigator for a bid to correct them. The new requirement does not actually specify that repairs have to be done, but since the problems are documented on the report the site manager is well-advised to correct them to avoid water waste tickets. Completion of the "Irrigation Analysis" service is an excellent way to increase off-season winter revenue.

Streamlining customer complaint processes for poorly designed systems is another way to improve irrigation standards. When rules are in place at both the city level and the state level, consumers have more recourse when they discover their new home has a sub-par irrigation system. It is important that the consequences of the poor systems follow not just the irrigator, but also the builder. This provides an incentive for the builders to hire better irrigation companies in the future.

Another conservation effort that serves the expert irrigator well is new technology. Customers are more and more interested in knowing how to get the best value possible from their irrigation expenses. Irrigators who are familiar with the latest smart controllers, reclaim systems, and retrofits are in high demand. In communities where rebates are possible for system improvements, the irrigators are welcome to market their services by letting customers know about rebates they may earn by making improvements.

A WATER PURVEYORS VIEW OF SMART WATER APPLICATION TECHNOLOGY

By Jill Hoyenga, Water Management Specialist, Eugene Water & Electric Board

SILENT SERVER NO MORE

Water is necessary for life. In the 1800s North American communities pulled together to assure water supply, establish water management strategies and build infrastructure with an eye toward building to serve future generations. Their strategic planning and build-out has allowed water utilities to assume the roll of “silent server”. The business goal of most utilities is to be so reliable and serve such an excellent product that the customer could assume our product was pure and plentiful at the lowest price possible. North American water utilities have succeeded so well that many people take the water supply for granted. The average citizen has not had to think very much about water supply, water resource management and water utility infrastructure. In the past twenty or thirty years this comfortable situation has changed dramatically. Drought pressures, population pressures and the increasing cost of continued infrastructure build-out have conspired to make it everyone’s business to assure a reliable water supply. Municipal water management is especially important to businesses that rely on a ready supply of water, such as the landscape industry.

WATER USE PATTERNS

Municipal water use is generally divided into two sectors, residential and industrial/commercial/institutional (ICI). Water uses are generally divided into two categories, indoor and outdoor. ICI water use is characterized by a fairly consistent and large indoor water use year-round. Conditioned space cooling contributes a slight increase in ICI demand as weather warms. Parks are an exception to this pattern; they have very low domestic water use and large amount of outdoor water use for the landscaped park area. Residential water use is characterized by fairly low indoor water use and a large amount of outdoor water use. This huge increase in demand is a primary concern for water utility engineers and operators and is called “peak water use,” the “seasonal peak”, “peaking factor” or more often just “peak.” A secondary concern to water operators is daily peak water use. “Peak hourly use” refers to the hours of the day of greatest demand, typically morning and evening. Morning hourly peaks are much greater during the watering season due to the common recommendation to “water early in the morning” causing a predictable and considerable spike in water distribution pumping. Peak management is a challenge in the water business. The water infrastructure must be built to meet the demand of the peak season, more specifically the demand of the hourly peak during the peak season. The remainder of the year peak capacity infrastructure sits idle and does not generate revenue. For many western utilities peak capacity is only utilized for about three months of the year.

Statistically, in North America outdoor water use is an average of 60% of all residential water use. During the watering season the utility infrastructure must serve up more than double the amount of water used at other times of the year. Some utilities in the arid west experience a three to five fold increase in water demand in the summer watering season. When you consider that a fraction of the residential customers actually water outdoors, it becomes clear that the landscape watering of the few has a huge impact on how water utilities must build and manage the entire water distribution system on a seasonal basis.

WATER MANAGEMENT STRATEGIES

As populations grow and water supplies must be stretched to meet demand, water management becomes more important than ever. Assuming current demand trends, the looming funding gap for infrastructure build-out is expected to be $45 - $102 billion dollars in the United States alone by 2022 (EPA-816-R-02-0, September 2002). Many utilities have built oversized infrastructure to meet predicted summer peak demands and have come to view this oversized capacity as a resource, hence the phrase “conservation as a source of supply”. Effective use of current irrigation technology as well as introduction of new irrigation technology can manage irrigation demands such that capacity formerly allocated to meeting peak can reliably be allocated to new growth in the service area.

In the past, utilities noted demand trends then simply planned for future building based on those trends. Increasingly limited water sources, availability of land for reservoirs and other infrastructure have conspired to make this a prohibitively expensive way to do business, so many utilities are looking for demand management solutions that can assure capacity just as building new infrastructure had in the past. Several demand management solutions are available, including indoor hardware retrofits, landscape conversions from high water use turf to native plant materials, and innovative irrigation controller technology – all combined with aggressive customer educational programs.

While indoor hardware retrofit is well developed as an offset for demand trends for more than 20 years, outdoor technology solutions are just beginning to become a viable demand management strategy. Since irrigation is often the largest contributor to the peaking factor, it is the greatest opportunity for peak reduction.

In an attempt to offset the need for emergency drought response, many water utilities have enacted voluntary and mandatory watering restrictions, hoping to manage water treatment plant peaking. They have created water conservation educational programs, hoping to change the behavior of ratepayers. Some water utilities have offered irrigation audits, hoping that homeowners or commercial properties would repair or upgrade their irrigation systems to improve water use efficiency. Unfortunately, even if incentives are offered very few customers make the necessary repairs or upgrades and quantifying water savings from educational conservation programs is extremely difficult. All strategies outlined above have an expectation of changing human behavior rather than a reliable technology solution that provides sustained water savings.

A SENSE OF TIMING: CASE STUDY UPPER LEVEL PUMP SYSTEM

CASE STUDY: THE PROBLEM

In Eugene Water & Electric Board (EWEB), several upper level areas of the system are operated by continuous running pumps and are therefore particularly sensitive to large demands. One upper level area was experiencing peak demands and was nearing pump station capacity on Monday, Wednesday and Fridays between 5 a.m. and 7 a.m. This pumping pattern would require expensive upgrades much sooner than originally planned unless customers could manage water use to change demand patterns. When conservation staff took a closer look they determined that predicted building patterns had changed so that new homes had much more irrigated landscape than previously built homes in the area. Most of these irrigation controllers set on the same schedule were threatening to exceed pumping capacity about 10 years earlier than expected for pumping demands, totaling about 48 hours a year.

CASE STUDY: AVAILABLE OPTIONS

The available courses of action included expanding the pump station within two years and accelerate plans for building a future reservoir, or to somehow persuade customers to manage demand in this upper level pump system. EWEB engineers began drawing up plans for expansion while the conservation staff began the work of crafting a message for these customers.

CASE STUDY: SOLID RESEARCH

Emergency door hangers during the summer watering season had no affect. EWEB contacted local landscape contractors at association meetings. Contractors noticed that the water use peaks were on the same days that many of them set controllers throughout the city, however they let us know that most of their customers manage the controllers after spring start up. Further research was required on how to reach these customers. EWEB conservation staff conducted focus groups with customers from this neighborhood, explaining the problem and inviting them to help craft a cost-effective solution. The focus group participants told EWEB that they and their neighbors just needed solid information about the distribution system and their impact on it in order to make informed decisions about their water use patterns. These customers were adamant that they did not want prescriptive programs or water use restrictions. They were confident that given proper information they could manage the peaking problem and avoid costly emergency upgrades.

CASE STUDY: NEWSLETTER AND WEEKLY POSTCARD UPDATES

By mid-summer the next year, the same peak pumping pattern emerged and the pump station was again nearing capacity. Conservation staff had been hard at work crafting an information campaign called the “700-gallon per minute (GPM) Challenge”. At 700 GPM, only one of the pumps in the station would be needed. For this reason, the EWEB conservation staff targeted the 700 GPM benchmark as the goal for minimizing peaks that had begun to consistently exceed 1100 GPM and peak as high as 1350 GPM during the previous summer.

A newsletter explained the situation and the potential to avoid costs if customers changed behavior. This was followed by weekly pump station “GPM report cards”. The response was immediate and marked. After the first weekly report card the pump station GPM did not exceed the requested goal of 700 GPM for the rest of the summer. And after the second summer information campaign, only two pumping days exceeded the goal, 720GPM and 733GPM respectively.

The “700-gallon per minute Challenge” has enabled customers to help EWEB manage the distribution system, along with the associated operations and upgrade costs. Even as some new construction continues in this area, EWEB staff believes this reduced peak pumping pattern can be sustained and will decrease pump maintenance costs, possibly manage electric costs, as well as avoid emergency upgrades. As of now, the future reservoir will likely be built according to the original timetable.

CURRENT TECHNOLOGY VERSUS NEW TECHNOLOGY

It is important to note that the change in irrigation demand on this upper level pump system was achieved using current technology. Only timing of irrigation was changed while pumping volumes remained virtually the same. The new smart controllers will be able to continue to manage timing to minimize peaking impacts on the distribution system, and they will provide better tools for managing the total volume used as well.

New irrigation technologies available today have solid demand management potential, though they will not assure captured capacity alone. Technology must be used in combination with Best Management Practices (BMP) for the design, installation and management of irrigation systems. The Irrigation Association®, as well as other professional organizations, has developed BMP guidelines. Many water utility resource managers have realized that it is time to partner with the landscape and irrigation industries, to help manage our distribution systems with mutual benefits.

Over the last decade, utilities have scrambled to find technologies to reduce the impact of irrigation. Many products have come to the marketplace that shows promise. For example, there are more than 20 companies alone that offer climate-based irrigation controller technologies. Even more products are available in sensor technology, including soil, rain, solar radiation and more. However, many landscape professionals have been slow to accept these new products because they view them as unproven in the field. Given the high expense of some of the new technologies, landscape professionals are sticking with proven methods for keeping it green.

Many water agencies and universities have conducted testing of some of the new weather-based irrigation technologies. However, since different testing methodologies have been used in each of the studies, water agencies have voiced skepticism that similar water savings and quality landscape appearance could be duplicated in their service area.

SMART CONTROLLER TECHNOLOGY ATTRIBUTES

Current controller products on the market do not apply water efficiently; because they do not automatically adjust run times to changes in plant water need or create watering schedules based on industry standards. They require people to calculate and set irrigation schedules in minutes of run time. To keep up with weather changes, people must repeat the action of inputting the correct scheduling information over and over again.

Smart controllers on the market alleviate the guesswork that comes with traditional irrigation scheduling. Several have built-in irrigation scheduling engines that create baseline schedules for every zone on the system, with daily updates to the watering schedule as the weather changes. For those products with scheduling engines, the installer simply inputs specific site information (i.e. soil type, plant type, sprinkler type, solar exposure, precipitation rate, system efficiency and degree of slope). Depending on the manufacturer, weather updates are received through wireless pager technology, on-site sensors, Internet, phone lines or cellular service. Other smart controller products update watering schedules based upon historical weather information, using a temperature gauge and a rain sensor or soil moisture sensor to modify irrigation run times. For water utilities concerned about maintaining strict watering days, most of these clocks have features that allow for interval watering and odd/even watering day restrictions.

Although the irrigation industry uses smart controllers as a generic term, water managers should not assume the same water savings levels between products, across homes and commercial landscapes. Some products use real-time weather data, while others rely on historical weather information. Of those that use real-time weather data, some receive their data from on-site sensors, while others receive them from a comprehensive network of National Weather Service stations. Additionally, moisture sensor-based products rely on sensors installed in the ground to delay irrigation.

IS THE TECHNOLOGY SMART

In 2002 the Irrigation Association initiated a partnership with water utilities that has come to be known as Smart Water Application Technology (SWAT.) The Association recognized that irrigation manufacturers, designers, distributors, contractors, consumers – as well as water utility managers, conservation staff and operators – need to be informed about the water management potential for efficiency-tested technology. In the past, irrigation manufacturers have been required to safety test their products according to Underwriter Laboratories Inc., International Association of Plumbing and Mechanical Officials and American Society of Agricultural Engineering (ASAE) test protocols. Now they also have the opportunity to pursue third party testing to be tested against water efficiency criteria. When conservation performance is assured, water utilities and landscape professionals will have reliable technology to promote to their customers that will assure captured water resource.

SWAT testing protocol have been peer reviewed by all interested parties using an Internet comment tool, then updated by the Center for Irrigation Technology (CIT) staff. All comments were answered, but not all were incorporated into the protocol. The committee was lucky to have Ed Norum, from the Center for Irrigation Technology in Fresno, as lead for the protocol writing effort. His more than 50 years of experience have included lab and field testing of all types of irrigation products using ASAE and other protocol, as well as participation in development of the International Organization for Standardization (ISO) Irrigation Standards. Norum's balance of technical knowledge, field experience and a firm grounding in irrigation science has proven to be of great service in this effort. CIT is the only SWAT testing facility to date, though the testing protocol are available to any public or private institution.

Several generous donations from water utilities made it possible to purchase the necessary equipment for CIT to begin beta testing for weather-based controllers during spring 2004, with regular testing offered to manufacturers for a fee since August 2004. Manufacturers submitting a product for testing will receive confidential test results, and may choose to release results to the public or go back to further develop their product. While ET Water Systems is the only controller manufacturer to release results at this time, three other controller products are currently undergoing testing with results expected during fall 2005. The protocol for soil moisture sensors was published in November 2004. The SWAT website was launched in 2004 and has postings of SWAT protocol, test results and more information about weather-based and sensor adjusted irrigation controllers (www.irrigation.org).

In California, Assembly Bill 2717 requested that a stakeholder working group develop, evaluate and recommend proposals for improving the efficiency of water use in new and existing urban landscapes in the state (Chapter 682, Section 1.a). According to Marsha Prillwitz, Project Manager, the AB2717 Task Force has recommended that all irrigation controllers sold in California after 2010 should be performance tested according to IA SWAT protocol. These recommendations must go through a public comment period before presentation to the governor for approval in December 2005. However, the consensus of the task force indicates a keen interest in testing of products claiming to irrigate efficiently and confidence in the SWAT controller protocol in particular.

FOCUS ON THE CUSTOMER

For all parties concerned, homebuilders, irrigation product manufacturers, distributors, contractors, irrigation consultants, designers, architects and water utilities—the customer is the focus. While most of these parties collect their payment from the customer and then go on to the next customer, the maintenance contractor and the water utility have an ongoing relationship with the customer. The customer can initially pay for efficient design and installation to a vendor with short-term interests, or will pay later in higher irrigation maintenance and water bills than necessary to a vendor with long-term interests. Landscape professionals are encouraged to educate builders and consumers to motivate them to pay the extra initial cost so operation costs can be managed better for the life of the irrigation system. The hidden cost incurred by an inefficient irrigation system is the impact to the utility’s infrastructure. You are invited to partner with the water utility to manage infrastructure build-out costs that will ultimately impact ratepayers. As a partner you can be at the table when water management decisions are under consideration. You will be able to offer your expertise to the efforts to keep the water flowing in your municipality. You will have opportunities to understand the constraints of your local utility regarding water resource and water infrastructure management and offer irrigation efficiency recommendations and possibly services. Educating our mutual consumers and fostering a dynamic, innovative partnership with your local water utility are proactive ways to manage your customers' access to the water needed to keep it green and ultimately the health of your business.

REFERENCES

EPA-816-R-02-0, September 2002. The Clean Water and Drinking Water Infrastructure Gap Analysis, 43

California Assembly Bill 2771, Chapter 682, Section 1.a

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Cisar, J.L., K.E. Williams, H.E. Vivas, and J.J. Haydu. 2000. The occurrence and alleviation by surfactants of soil water repellency on sand-based turfgrass systems. J. Hydrol. 231-232:352-358.

Dekker L.W., K. Oostindie, A.K. Ziogas, and C.J. Ritsema. 2001. The impact of water repellency on soil moisture variability and preferential flow. Int. Turfgrass Soc. Res. J. 9:498-505.

Green, R.L. 2005. Trends in golf course water use and regulation in California. http://ucrturf.ucr.edu/topics/trends_in_golf_course_water_use.pdf.

Grigory, S.C. 2003. Golf course water use. http://hillcountrywater.org/GolfCourse.htm

Hallett, P.D., K. Ritz, and R.E. Wheatley. 2001. Microbial derived water repellency in golf course soil. Int. Turfgrass Soc. Res. J. 9:518-524.

Hallett, P.D., N. Nunan, J.T. Douglas, and I.M. Young. 2004. Millimetre-scale spatial variability in soil water sorptivity: scale, surface elevation, and subcritical repellency effects. Soil Sci. Soc. Am. J. 68:352-358.

Karnok, K.J. and K.A. Tucker. 2001. Wetting agent treated hydrophobic soil and its effect on color, quality and root growth of creeping bentgrass. Int. Turfgrass Soc. Res. J. 9:537-541.

Karnok, K.J. and K.A. Tucker. 2002a. Water repellent soils Part I. Where are we now? Golf Course Management 70(6):59-62.

Karnok, K.J. and K. A. Tucker. 2002b. Water repellent soils Part II. More questions and answers. Golf Course Management 70(7):49-52.

Kostka, S.J. 2000. Amelioration of water repellency in highly managed soils and the enhancement of turfgrass performance through the systematic application of surfactants. J. Hydrol. 231-232:359-368.

Kostka, S.J. and P.T. Bially. 2005a. The hydrophilicity of water repellent soil. U.S. Patent No. 6,851,219.

Kostka, S.J. and P.T. Bially. 2005b. Synergistic surfactant interactions for enhancement of hydrophilicity in water repellent soils. Intl. Turfgrass Soc. Res. J. 10:108-114.

Leinauer, B., P.E. Rieke, D. VanLeeuwen, R. Sallenave, J. Makk, and E. Johnson. 2001. Effects of soil surfactants on water retention in turfgrass rootzones. Int. Turfgrass Soc. Res. J. 9:542-547.

Miller C., and S.J. Kostka. 1998. The effect of Primer 604 nonionic surfactant on water repellency in sand-based soils. Proceedings of the Fifth International Symposium on Adjuvants for Agrochemicals. 1:291-297.

Mitra, S., S.J. Kostka, and M.A. Franklin. 2005. Managing soil moisture content by systematic injection of wetting agents. Geophys. Res. Abstr. 7:09477.

Mitra, S. 2005. Water conservation on fairways by systematic injection of wetting agents. http://www.greenmediaonline.com/uploads/cf/features/0507%5Fcf%5Fgs.asp.

Moore, R.A., S.J. Kostka, S. Mane, and C.M. Miller. 2004. Fully compatible water soluble fertilizer and use. U.S. Patent No. 6,826,866.

Park, D.M., J.L. Cisar, K.E. Williams, and G.H. Snyder. 2004. Alleviation of soil water repellency in sand based Bermudagrass in South Florida. Acta Horticulturae 661:111-115.

Park, D.M., J.L. Cisar, D.K. McDermitt, K.E. Williams, J.J. Haydu, and W.P. Miller. 2005. Using red and infrared reflectance and visual observation to monitor turf quality and water stress in surfactant-treated Bermudagrass under reduced irrigation. Intl. Turfgrass Soc. Res. J. 10:115-120.

Rottenberg, G. 2003. Green golf courses: A study of maintenance practices in Rhode Island. http://envstudies.brown.edu/thesis/2003/rebekah_rottenberg/index.htm.

Shimokusu, C. 2004. Future directions for golf course water use regulation: A regulators perspective. Green Section Record. 42(4):22-24

Snyder, G.H., B.J. Augustin, and J.M. Davidson. 1984. Moisture sensor-controlled irrigation for reducing N leaching in bermudagrass turf. Agron. J. 76:964-969.

Wallis, M.G., and D.J. Horne. 1992. Soil water repellency. Adv. Soil Sci. 20:91-146.

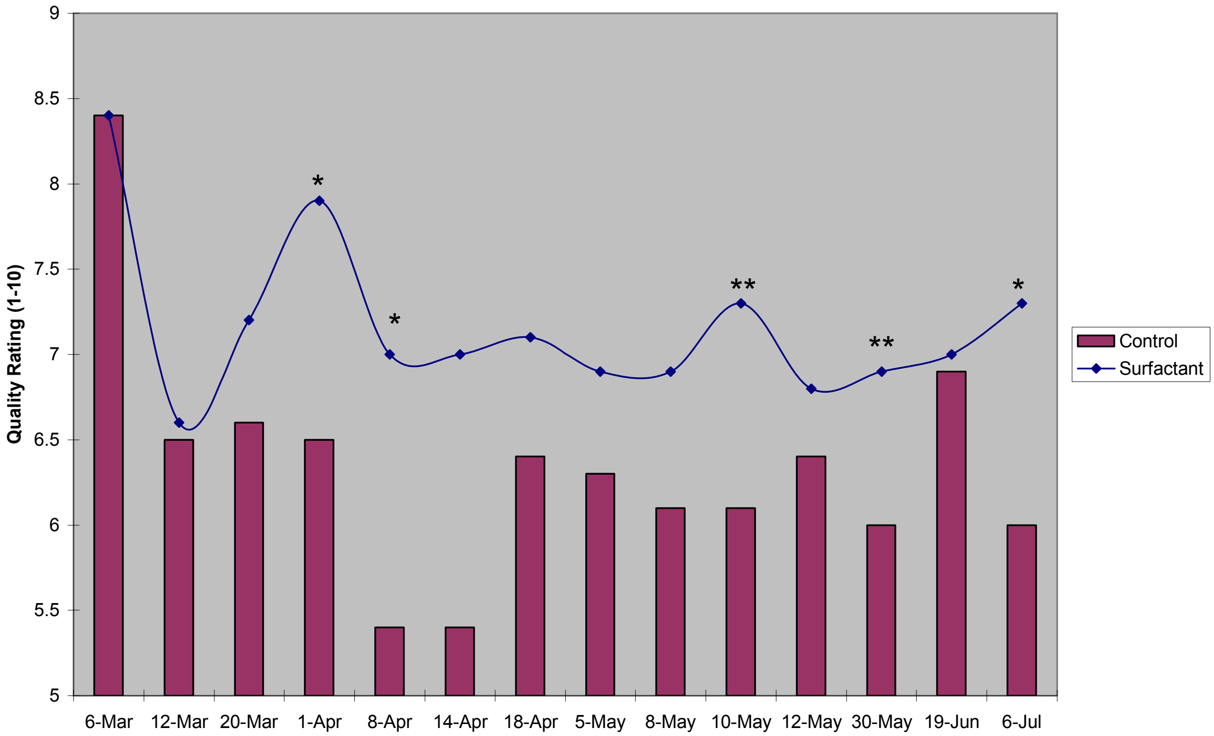

Figure 1. Effect of injected surfactant treatment on bermudagrass quality under Florida conditions (2003). The following indicate significant differences between means on an observation date: * and ** = P<0.05 and P<0.01 respectively.

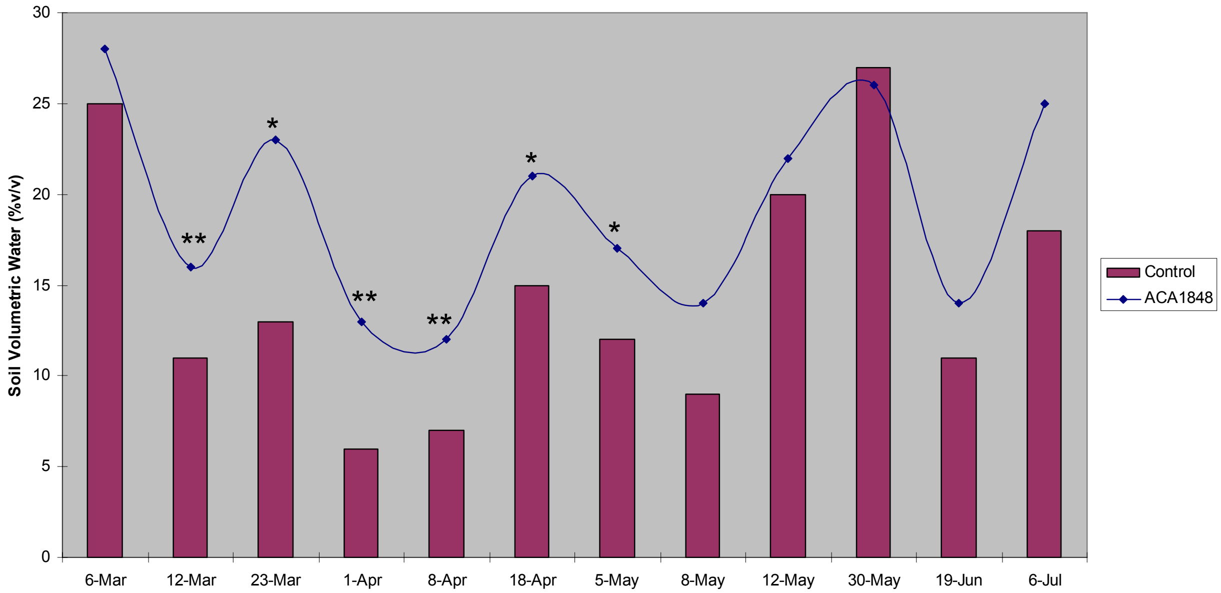

Figure 2. Effect of injected surfactant treatment on soil volumetric water content (vol:vol) in a fine sand soil under Florida conditions (2003). The following indicate significant differences between means on an observation date: * and ** = P<0.05 and P<0.01 respectively.

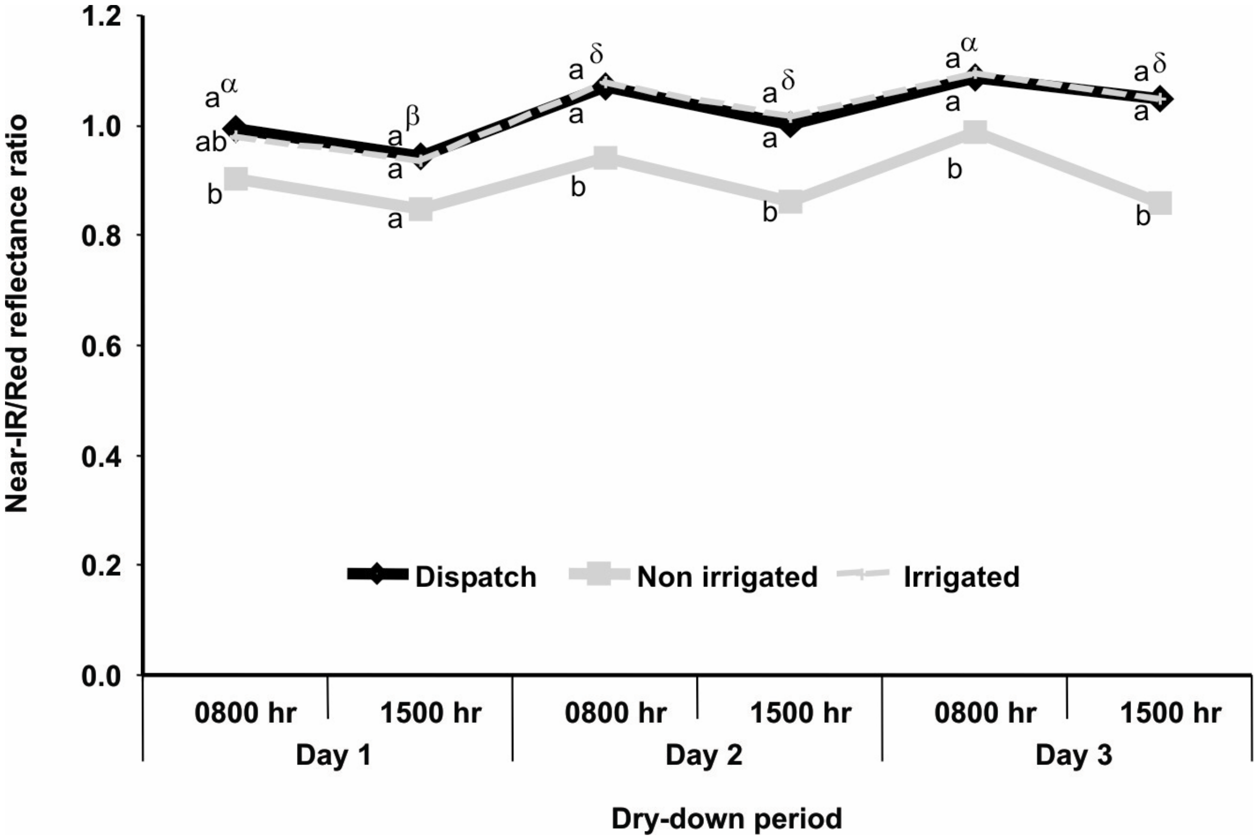

Figure 3. Mean morning and afternoon pooled trial near-IR/Red reflectance ratio (from Park et al, 2005). Means with the same letter within a column are not significantly different α, β, and δ = P<0.10, P<0.05, and P<0.01 respectively.

Surfactants and soil water repellency in golf course soils – water use and environmental implications.

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ABSTRACT

Golf courses are highly conspicuous consumers of surface and ground waters for irrigation purposes. As such, golf courses receive considerable public scrutiny on water use as well as on the impacts of management practices on surface and groundwater quality. Soil water repellency is a well established phenomenon in all soils supporting highly managed turfgrass stands. The objective of this presentation is to use recent findings from research conducted on irrigated, water repellent soils (with and without surfactant treatments) to illustrate the effects of soil water repellency on distribution uniformity and irrigation efficiency and its influence on maximization of irrigation inputs and minimization of losses from evaporation, runoff (overland flow), and leaching below the rootzone. Cost-benefit analyses will be presented for management of soil water repellency and the concomitant potential for water conservation.

INTRODUCTION

Water repellent soils are found worldwide under a range of crops and cropping systems (Wallis and Horne, 1992) and are common in sandy soils supporting turf or pasture grasses. The phenomenon is most pronounced in coarse sands and is attributed to the accumulation of hydrophobic organic compounds as coatings on soil particles and aggregates, as well as, physiochemical changes that occur in decomposing soil organic matter of plant or microbial origin (Miller and Williamson, 1977; Hallett, 2001). The environmental consequence is decreased infiltration of irrigation water and precipitation, non-uniform wetting of soil profiles, increased run-off and evaporation, and increased leaching due to preferential flow (Dekker et al., 2001).

Golf courses are highly conspicuous consumers of surface and ground waters for irrigation purposes. As such, they receive considerable public scrutiny on water use as well as on the impacts of management practices on surface and groundwater quality. Estimated annual water irrigation water consumption by U.S. golf courses is 1.8×10^9 m^3 (475 billion gallons). The amount of water consumed by individual golf courses ranges widely based on the region of the country. On a Rhode Island golf course, water consumption is estimated at approximately 7.5×10^4 m^3 $year^{-1}$ (20 million gal) (Rottenberg, 2003). In more arid states like Texas consumption rises further to 4.2×10^5 m^3 (110 million gal)(Grigory, 2003). In Arizona, that number reaches 6.8×10^5 m^3 (180 million gal) annually)(Shimokusa, 2004). In California, average golf course water consumption varies between 4.3×10^5 to 8.5×10^5 m^3 (110-220 million gal) depending on location within the state (Green, 2005).

Soil water repellency (SWR) is a well established phenomenon in all soils supporting highly managed turfgrass stands (Karnok and Tucker, 2002a, 2002b). On newly constructed golf courses, this phenomenon develops rapidly (usually within three years) with visible symptoms occurring seasonally under periods of high evaporative demand. Symptoms include turf wilting and development of dry areas, often impervious to water. These water repellent areas (referred to as localized dry spots or dry patch) are associated with degrading organic matter of plant or microbial origin (including basidiomycete fungi that cause fairy rings). Recently, Hallett et al. (2004) suggested that reduced water infiltration may be linked to small scale microbial and/or chemical processes that cause subcritical water repellency.

Management strategies have traditionally focused on alleviation of dry spot symptoms or control of fairy rings in order to improve localized turf quality and performance. With the worldwide realization of the fragility of water supplies and the occurrences of several prolonged regional droughts, the golf course industry has recognized that options must be developed to more effectively utilize available water resources. While SWR is a recognized problem in turfgrass culture, its hydrological impact and influence on irrigation efficiency is poorly understood.

Surfactants are well documented for the management of water repellency (hydrophobicity) in thatch and soils, and for the enhancement of soil hydration in managed turfgrass (Miller and Kostka, 1998; Cisar et al., 2000; Kostka, 2000; Karnok and Tucker, 2001). Leinauer et al. (2001) reported that different soil surfactants could influence the depth of water distribution in a sand rootzone mix, but not loamy soils under greenhouse conditions. The use of soil surfactants has been suggested as a tool to improve irrigation efficiency and water conservation, yet systematic studies to substantiate this hypothesis have not been published.

Maintenance of turf quality and simultaneous optimization of irrigation and conservation of water are goals of turfgrass managers, especially under drought conditions. Water may be conserved by maximizing input effectiveness (irrigation, precipitation) or minimizing output losses (transpiration, evaporation, runoff, and leaching or drainage below the rootzone). Irrigation practices also influence nitrogen leaching (Barton and Colmer, 2004) be that water does not move beyond the effective rootzone (Snyder et al., 1984) or that preferential flow is mitigated or not established (Bauters et al., 1998). Surfactants have been suggested as a strategy to remediate fingered flow (a form of preferential flow) associated with water repellent soils (Barton and Colmer, 2004).

The key to water conservation is maximizing the amount of water entering the turfgrass rootzone and its storage and availability once in the rootzone (Carrow et al., 2005). Management tactics include: reducing transpiration, reducing evaporation, increasing infiltration, reducing ponding, optimizing retention in the rootzone, and controlling water movement below the rootzone (leaching).

Preliminary studies demonstrated that blends of alkyl polyglycoside (APG) and ethylene oxide-propylene oxide (EO/PO) block copolymer surfactants improved the hydrophilization and infiltration of water into water repellent soils (Kostka and Bially, 2005a; Kostka and Bially, 2005b). The synergistic wetting interactions associated with APG-EO/PO block copolymer blends were produced by blends even when one or both components alone had limited effect on infiltration. When the APG-EO/PO block copolymer surfactant blend was mixed with urea ammonium nitrate (UAN 32) and applied via injection to *Cynodon sp.* growing in a clay soil, rootzone nitrogen and leaf nitrogen were increased in plots receiving the surfactant plus fertilizer treatment over that of the plots receiving the fertilizer alone (Moore et al., 2004) suggesting that application of the APG-EO/PO block copolymer surfactant blend also reduced N leaching.

It is the objective of this paper to review recently published research conducted on irrigated soils (with and without surfactant treatments) to illustrate the effects of soil water repellency on distribution uniformity and irrigation efficiency and its influence on maximization of irrigation inputs and minimization of losses from evaporation, runoff (overland flow), and leaching below the rootzone. Cost-benefit analyses will be presented for management of soil water repellency and the concomitant potential for water conservation.

CASE STUDIES

Case Study 1 - California

A two-year study was conducted at the Center for Turf Irrigation and Landscape Technology (C-TILT) at the California State Polytechnic University, Pomona (Mitra, 2005; Mitra et al., 2005). Twenty-four plots (each 9 m^3) of bermudagrass (*Cynodon sp.* 'GN-1'), growing in a clay loam soil and maintained under golf-course fairway management conditions, were laid out in a split-plot design. Irrigation-water quality (potable or recycled) was the primary factor with surfactant treatments as the secondary factor. Surfactants included, ACA1853, an EO/PO block copolymer formulation (20% ai), applied at 1.753 L ha^{-1} every two weeks and ACA 1848, an APG-EO/PO block copolymer blend (17% ai) applied weekly at 0.877 L ha^{-1}. Surfactant treatments were compared to an untreated control. Each treatment combination was replicated three times. The plots were irrigated at 100% of the reference cumulative monthly evapotranspiration (ETo) demand in May and were reduced to 70% ETo in June, followed by a further reduction to 30% ETo in July and finally 10% ETo in August. Soil volumetric water content was monitored through out the experiment using time domain reflectrometry (TDR) and time domain transmission (TDT) (Aquaflex Sensors, Streat Instruments, New Zealand).

Based on TDR, all the wetting agents treatments helped in retaining higher moisture levels in the soil compared to the control (Table 1). Similar results were obtained with TDT (data not shown). In a clay loam soil under high evaporative demand and irrigated at 100%, 70%, 30% or 10% ETo, ACA1848, the APG-EO/PO block copolymer, maintained higher soil moisture between irrigation cycles compared to plots treated with an EO/PO block copolymer alone (ACA1851) or the untreated control (Table 1). The treatment effect was more pronounced under moisture stress (30% and 10% of ETo). Similar results were obtained whether the plots were irrigated with potable or recycled water. On this fine textured soil, bermudagrass was maintained under optimum conditions with irrigation reduced by 50-70%

Table 1. Effect of surfactants on volumetric soil moisture (VMC) (%) content in soils. Data from the 15th of each month was used for the analysis. The means followed by the same letter do not significantly differ. (P = 0.05 Duncan's New Multiple Range Test).

Treatments	Volumetric Soil Water Content (%)							
	100% ET		70% ET		30% ET		10% ET	
	Potable	Recycled	Potable	Recycled	Potable	Recycled	Potable	Recycled
ACA1851	50 b	49 c	30 b	29 c	20 c	27 b	20 b	23 b
ACA1848	56 a	58 a	36 a	35 a	29 a	32 a	28 a	27 a
Untreated	46 c	40 c	28 c	28 c	18 d	22 c	16 c	17 c

Case Study #2 – Florida

A three-year study was conducted on replicated bermudagrass (*Cynodon dactylon* X *Cynodon transvaalensis* 'Tifdwarf") growing in a sand rootzone at the University of Florida, (Fort Lauderdale Research and Education Center, Fort Lauderdale). Each plot (4m x 4m) had a dedicated irrigation system with an injection system designed to deliver precise volumes of treatment solutions to each plot. Surfactant treatments (ACA1848 at 1.75 L ha^{-1}) were injected monthly in 2002. In 2003, ACA1848 was applied at 1.75 L ha^{-1} monthly or 0.89 L ha^{-1} weekly). In 2004, ACA1848 was applied at 0.89 L ha^{-1} weekly. Controls did not receive any surfactant treatment. Each treatment was replicated three times. Plots were exposed to a dry-down period after treatment applications, and allowed to recover between dry-down/declines with irrigation applied on a daily schedule until monthly surfactant treatments were re-applied. Turfgrass quality (scale of 1-10 with 10=dark green turf, 1=dead/brown turf and 6=minimally acceptable turf), volumetric water content (Theta Probe, Delta-T Devices, Cambridge, England, UK), and localized dry spot (percent), when evident, were taken for the duration of the experiment.

2003-2003 - Turfgrass quality and localized dry spot was significantly improved by addition of surfactant treatments during many rating dates as the dry season study period progressed in intensity from late winter through spring and early summer, with weekly applications producing more consistent quality (Park et al., 2004). Generally, surfactant treatments outperformed untreated controls. The weekly surfactant treatment maintained higher turf quality than the control throughout the test period (Fig. 1). Soil moisture content (VWC) in soils receiving weekly surfactant application was higher than in the controls (Fig. 2). These results suggest that improved turfgrass quality in the surfactant treated plots was a consequence of improved rootzone moisture status and availability.

During a dry six-week period of 2002, evapotranspiration replacement rates were evaluated. During this period, 198 mm of water were lost through evapotranspiration, with only 81 mm of water being replaced by rainfall and irrigation combined. Turf quality was maintained with a net water deficit of 117 mm; a 41% replacement of water lost through evapotranspiration. When this study was repeated in 2003 (March and April), combined irrigation and rainfall was approximately 143 mm, 86 mm less then the predicted ET of approximately 229 mm for that time period. Despite the water deficit, turfgrass quality was improved by surfactant treatment compared to the control. Even under such severe stress conditions, surfactant maintained acceptable turf quality ratings well above that of the control. This was achieved at 41% ET replacement in 2002 and 62% ET replacement in 2003.

2004 – In year three, turf performance was monitored in three separate trials conducted as drydown studies during periods of high evaporative demand (30 April – 02 May, 05 May – 06 May, 16 May – 18 May) (Park et al, 2005). Plots were arrange in a randomized complete block design with each plot receiving one of three treatments: irrigated daily to replace potential ET (irrigated control), no irrigation (non-irrigated control), and surfactant treated (0.89 L ha^{-1}) upon initiation of each drydown period (Table 2). Turfgrass quality and localized dry spot symptoms were monitored visually (as described above) and with an experimental active infrared/red sensor (LICOR, Lincoln, NE, USA).

Table 2. Total water applied to each test plot in each trial period (Fort Lauderdale, FL, 2004).

	Total irrigation applied (mm)		
Treatments	**Trial 1**	**Trial 2**	**Trial 3**
Non-irrigated	4.75	4.50	4.00
Irrigated	14.00	9.00	13.75
Surfactant treated	4.75	4.50	4.00

Surfactant treated plots, while receiving the same limited irrigation as the "non-irrigated" control, had significantly higher visual quality ratings in each trial (Table 3). Visual quality ratings in the surfactant treated plots (irrigated at 50% or less ET replacement) were statistically equal to the irrigated plots that received 100% ET replacement. Reductions in localized dry spots were observed in surfactant-treated and irrigated plots (Table 4). Improved turf physiological status was confirmed using the experimental active infrared/red sensor (Figure 3). The sensor also demonstrated small scale differences that developed between the non-irrigated control and the surfactant-treated and irrigated turfgrass. Surfactant treatment maintained turf quality in each of the three trials while reducing the irrigation requirement between 50% and 71%.

Table 3. Treatment effect on pooled trial mean daily visual quality ratings (1-10, 1 = dead, 6 = minimally acceptable, 10 = high quality) (from Park et al, 2005). Means in columns followed by the same letter are not significantly different according to Duncan's Multiple Range Test at P=0.05.

Treatments	**Day 1**	**Day 2**	**Day 3**
Non-irrigated	7.0 b	6.0 b	6.0 b
Irrigated	7.5 a	7.8 a	7.5 a
Surfactant-treated	7.4 a	7.3 a	7.4 a
Significance	**	***	***

** and *** = P<0.05 and P=<0.01 respectively.

Table 4. Treatment effect on pooled trial mean daily localized dry spot (%)(from Park et al, 2005). Means in columns followed by the same letter are not significantly different according to Duncan's Multiple Range Test at P=0.05.

Treatments	**Day 1**	**Day 2**	**Day 3**
Non-irrigated	10	36 a	58 a
Irrigated	3	9 b	13 b
Surfactant-treated	3	13 ab	14 b
Significance	Ns	*	***

ns, *, and *** = P>0.10, P<0.10, and P<0.01 respectively.

DISCUSSION

These results, based on multi-year evaluations in different environments and soils, provide science-based evidence that a specific group of surfactants, the APG-EO/PO block copolymer blends (Kostka and Bially, 2005a, 2005b) when incorporated systematically at low levels in irrigation water can improve infiltration into water repellent soils and increase soil rootzone moisture. This surfactant blend was more effective than the EO/PO block copolymer component alone. On a clay loam soil this surfactant blend maintained optimum turf quality when irrigation reduced by 50-70%. In a fine sand, bermudagrass performance was maintained under irrigation reductions of 38-71%. By delivering water more effectively, distribution uniformity was improved even under deficit irrigation conditions. Perhaps most striking is the ability of low level surfactant treatments to maintain turf quality and physiological status when irrigation was reduced by up to 71%.

What are the ramifications of this technology on water use and conservation on golf courses? As a basis for analysis, we use a fictitious California golf course using the minimum average consumption of 4.3×10^5 m^3 (110 million gal) $year^{-1}$ reported by Green (2005). Water cost estimates are based on pumping costs plus any fees to municipal providers. The two case studies reviewed substantiate that a 50% reduction in irrigation 2.15×10^5 m^3 (55 million) can be achieved realistically without reducing turfgrass performance. Based on the results from these studies and an estimate of surfactant cost reflecting application of the APG-EO/PO technology at 0.88 – 0.89 L ha^{-1}, the net annual savings, including the cost of surfactant, would range from \$23,500 - \$86,000, depending on water source and local cost structure.

	Water Cost (Estim.)	Surfactant Costs	Projected Savings
Ground or Surface Water	\$57,000[a]	\$5,000	\$23,500
Municipal Water	\$140,000[b]	\$5,000	\$65,000
Effluent Water	\$170,000[b]	\$5,000	\$80,000

[a] Estimate of energy costs
[b] Includes energy costs

Currently, "best management practices (BMPs)" recommend a diversity of options for conserving potable water (Carrow et al, 2005). The surfactant technology evaluated in this study, provides a low cost strategy, high return strategy to a) reduce water requirements, b) conserve available water, b) maintain golfer and management expectations for quality turfgrass, and c) manage resources effectively.

REFERENCES

Barton, L. and T. Colmer. 2004. Irrigation and fertilizer strategies for minimizing nitrogen leaching from turfgrass. In: New directions for a diverse planet. Proc. 4th Intl. Crop Sci. Congr. 26 Sept-1 Oct 2004, Brisbane, Australia. (http://www.regional.org.au/au/cs/2004/media-01.htm#P99_21335).

Bauters, T.W.J., D.A. DiCarlo, T.S. Steenhuis, and J.-I. Parlange. 1998. Preferential flow in water repellent sands. Soil Sci. Am. J. 62:1185-1190.

Carrow, R.N., D. Wienecke, M. Esoda, F. Siple, F.C. Waltz, and R.R. Duncan. 2005. Two case studies: State BMPs for water conservation on golf courses. Golf Course Management 73(9):84-86.

Water Conservation from Precise Irrigation Scheduling Using a Subsurface Electromagnetic Soil Moisture Sensor

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Abstract

Instrumented weather stations are often used for evapotranspiration (*ET*) prediction in order to estimate crop water use for irrigation scheduling. A direct estimate of crop water use by subsurface measurements of soil water content has been limited by the high cost of reliable soil moisture sensors. Recent advances in electromagnetic (EM) sensor technology have made automated irrigation scheduling based on state-of-the-art soil moisture sensing capability a reality. Our objectives were: i) to compare irrigation scheduling based on weather station *ET* estimates with those from a novel time domain transmission (TDT) soil moisture sensor, and ii) to apply a computer-based numerical model to simulate any drainage occurring below the plant rooting depth. The TDT sensor was designed to schedule irrigation based on a threshold θ value (θ_{Thresh}). The sensor circuitry controlled the irrigation schedule by allowing a preprogrammed schedule to operate whenever the sensor-estimated θ (θ_{Sensor}) dropped below θ_{Thresh}. The TDT sensor was installed under Kentucky bluegrass with a nearby weather station providing estimates of *ET* for comparison over a period of approximately seven weeks. The HYDRUS-2D numerical simulation model was used for predicting drainage in the soil profile. The model input requirements include the flow domain geometry and boundary conditions, along with estimates of evaporation, transpiration, precipitation, irrigation and root water uptake data. Relative to *ET*-based irrigation recommendations, the TDT system applied approximately 16% less water when irrigating with a sprinkler having an efficiency of 0.80, and relative to a fixed irrigation rate of 5 cm week^{-1}, the TDT system applied approximately 53% less water. Modeling results of the TDT sensor control indicated that no detectable water drained below the estimated 30 cm rooting depth of turf grass when uncontrolled application events (e.g. rainfall) were ignored. Performance of the TDT system is dependent on the sensor burial depth and θ_{Thresh}. The θ_{Thresh} value is soil-type dependent and should be established via consideration of θ at field capacity and permanent wilting point. The potential water savings with the TDT system is not only important to water conservation, but can save irrigators an estimated \$5.00-\$100.00 per month based on average water prices in the US and a 1000 m^2 irrigated turf grass plot.

Introduction

Water conservation in relation to crop and turf grass irrigation has recently received much attention, especially in the Western United States, where extensive growth coupled with drought conditions in recent years has reduced the amount of water available for irrigation use (Ervin and Koski, 1998; Kjelgren et al., 2000). Environmental measurements such as evapotranspiration (Allen et al., 1998) and soil water content (Topp and Ferre, 2002) are gaining more utility as a means to infer plant water use and to properly schedule agricultural, municipal and residential irrigation. Such measurements not only conserve water, but also save growers and irrigators money by ensuring that plants are not excessively irrigated.

In situ soil water content estimates are accomplished using a variety of methods and sensors (Or and Wraith, 2002). Measurements and estimates of water content for use in irrigation scheduling have in the past been performed via gravimetric, neutron scattering, gypsum block and tensiometer methods. In recent years, water content estimates have advanced to include electromagnetic (EM) techniques such as time domain reflectometry (TDR) (Topp et al., 1980; Topp and Ferre, 2002; Robinson et al., 2003), time domain transmissometry (TDT) (Topp et al., 2001; Harlow et al., 2003; Hook et al., 2004; Blonquist et al., 2005a), transmission line oscillators (Campbell and Anderson, 1998; Seyfried and Murdock, 2001; Kelleners et al., in review), impedance- (Hilhorst et al., 1993; Gaskin and Miller, 1996; Hilhorst, 2000; Seyfried and Murdock, 2004) and capacitance-based approaches (Dean et al., 1987; Paltineanu and Starr, 1997; Kelleners et al., 2004; McMichael and Lascano, 2004).

Estimates of water content based on EM measurements provide real time, in situ measurements at a relatively affordable cost. Estimation of water content using EM sensors is based on the ability of sensors to measure the real part of the dielectric permittivity (ε), or an EM signal property directly relating to ε, which directly relates to volumetric soil water content (θ) owing to the ε contrast of soil constituents; $\varepsilon_a \approx 1$, $\varepsilon_s \approx$ 2-9 and $\varepsilon_w \approx$

80; where the subscripts *a*, *s* and *w* represent air, solids and water, respectively. The potential of EM θ sensors in irrigation scheduling has been demonstrated (Qualls et al., 2001; Paul, 2002; Leib et al., 2003).

The objectives of this research were: i) to compare cumulative water applications with irrigation scheduling based on evapotranspiration estimates from a weather station to scheduling based on soil moisture estimates from a time domain transmission (TDT) sensor, and ii) to apply a computer-based numerical model to simulate the water balance in the soil profile and estimate any drainage occurring below the plant rooting depth.

Materials and Methods

The Acclima® Digital TDT Sensor is a transmission line sensor that estimates θ based on bulk soil ε measurements, and has been shown to provide exceptional ε measurement accuracy when compared to research grade instrumentation (Blonquist et al., 2005a; Blonquist et al., 2005b). In order to make θ estimations and control irrigation, the Acclima Digital TDT Sensor must be connected to a custom controller; the Acclima CS3500 or Acclima RS500; in which is programmed a threshold soil water content value (θ_{Thresh}). The sensor makes continuous θ estimates, which are retrieved by the controller, and when the sensor estimates θ below θ_{Thresh}, the controller operates a preprogrammed irrigation schedule within the controller.

An Acclima Digital TDT Sensor was installed in an approximately 280 m^2 field plot of Kentucky bluegrass on the Utah State University Greenville Research Farm located in North Logan, Utah, USA. The sensor was installed in the soil horizontally with respect to the ground surface, approximately in the middle of the plot. The placement depth of the sensor was approximately 10 cm (Figure 1). The cross-section (Figure 1) displays the sensitivity of the sensor, or the soil cross-section in which 90% of the electromagnetic energy contributing to the θ estimation is contained. The sensor head measures approximately 9.0 cm in the horizontal direction and 2.0 cm in the vertical direction (Figure 1), which gives indication of the volume of soil contributing to the measurement, but the sensor is much more sensitive to the soil immediately surrounding the probe where the darker shaded area represents a greater concentration of electromagnetic energy (Figure 1). The θ_{Thresh} value was estimated using field capacity θ and permanent wilting point θ values for the soil type in the field plot and Kentucky Bluegrass. The θ values at field capacity and permanent wilting point for the soil were estimated to be 0.24 and 0.08, respectively, and the θ_{Thresh} value was estimated as 0.16, halfway between field capacity and permanent wilting point.

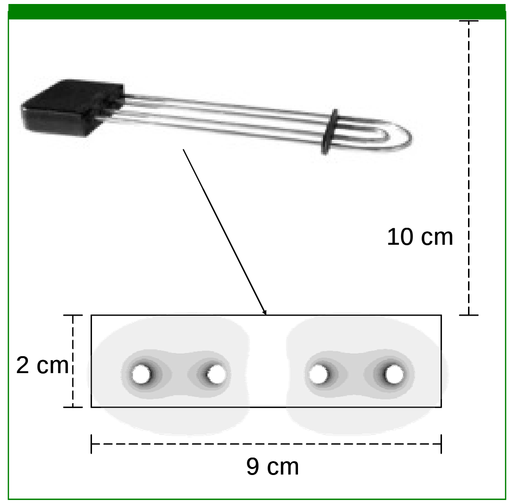


Figure 1. Cross-section of the TDT sensor oriented horizontally in relation to the ground surface. The cross-section shows the four rods and the area containing 90% of the electromagnetic energy that contributes to the measurement (gray-scale). The solid line surrounding the rods represents the sensor head and the approximate outer dimensions are outlined in black and labeled. The soil contributes less to the measurement further from the rods as indicated by the gray intensity scale, thus the water content estimation is largely dependent on soil properties adjacent to the rods.

Initially, irrigation was accomplished using a single impact sprinkler head (Rainbird® 30IBH with a 3/16" nozzle) outputting approximately 480 cm^3 s^{-1} (7.6 gpm), but midway through the experiment the sprinkler was changed to a lower flow rate gear-driven sprinkler head (Hunter® PGP with #9 nozzle) outputting approximately 375 cm^3 s^{-1} (5.9 gpm). The change was made in order to improve application efficiency. The application efficiencies of the impact and gear-driven sprinkler heads at the position of the TDT sensor, approximately 5.5 m from the sprinkler, were estimated at 0.50 and 0.80, respectively, by dividing the flow rate at the sprinkler head by the application rate measured at the position of the TDT sensor.

The experiment was conducted over a period of forty-nine days from July 30 through September 16, during which θ_{Sensor} and irrigation event data were estimated and logged with the CS3500 Controller. Evapotranspiration and precipitation were estimated and logged with a Campbell Scientific ET106 Evapotranspiration Station operated by Utah State

University and used by the State of Utah's Division of Water Resources to determine irrigation recommendations. The CS106 calculates *ET* via inputs from meteorological sensors onboard the station. The weather station is located approximately 200 m from the experimental plot under similar conditions over a large Kentucky bluegrass plot, thus the data supplied by the weather station are considered representative of the experimental plot.

We compared recommended irrigation amounts (including precipitation) based on *ET* estimates from the weather station to the actual amount of water applied to the plot using the θ estimates made with the TDT sensor, where the impact sprinkler head was used from July 31 to August 15 and the gear-driven sprinkler head was used from August 16 to September 16. We also compared irrigation amounts when applying water at a fixed rate of 5 cm week^{-1} over the duration of the experiment to the water applied using the TDT system. In addition to comparing irrigation amounts, we applied a computer program, HYDRUS-2D Model (Šimůnek et al., 1999), to simulate and compare drainage below the plant rooting depth under the three described irrigation strategies (recommendations based on weather station, TDT sensor θ estimates and 5 cm week^{-1}).

Results and Discussion

The ability of the TDT system to maintain θ above the established θ_{Thresh} is indicated by the field data presented in Figure 2 where changes in θ, irrigation events with the TDT system (water amount that the plot actually received) and recommended irrigation events (water amount the plot would have received had the recommendations been used) based on *ET* estimates from the weather station are plotted versus time (July 30-September 16).

The only time the sensor-estimated θ value did not increase following an irrigation event,

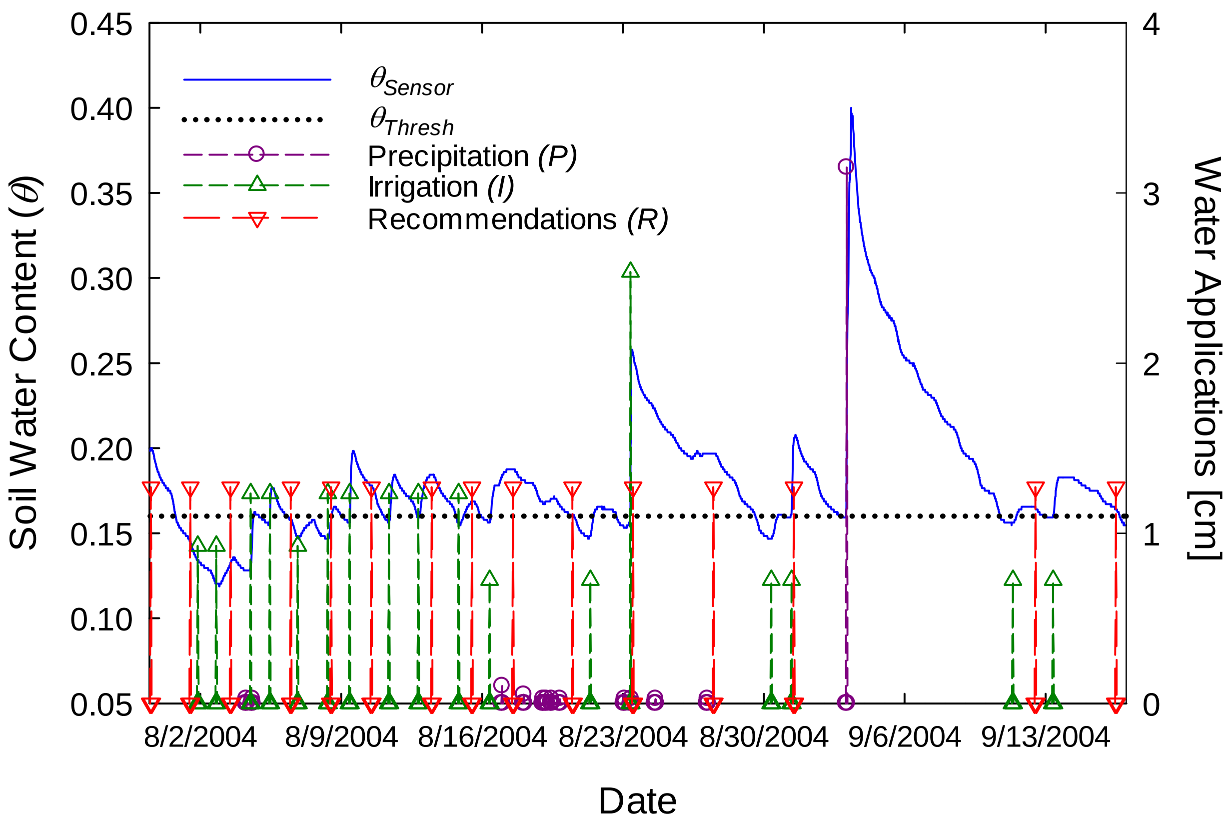
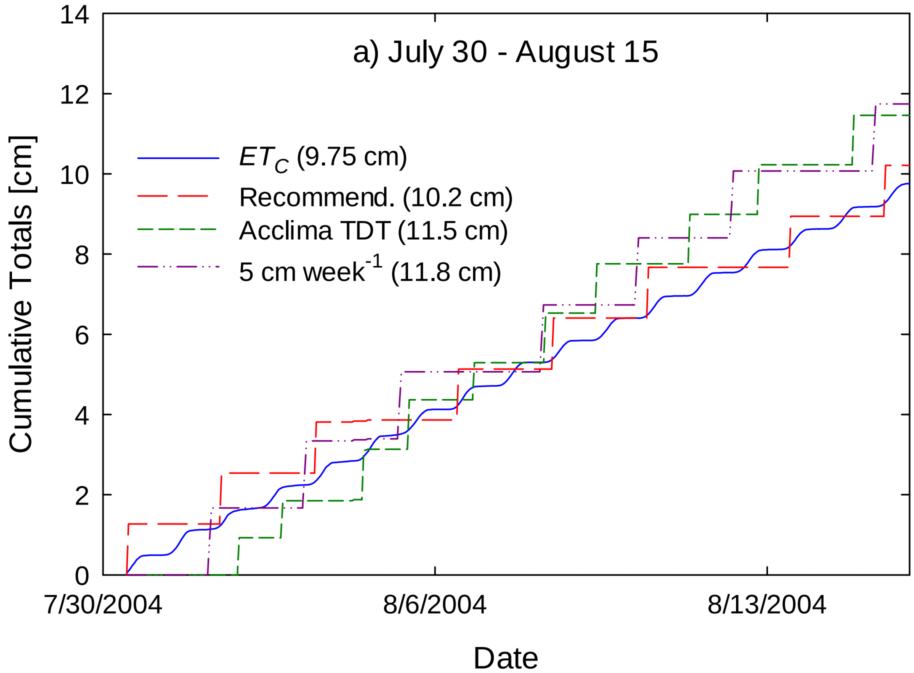


Figure 2. Volumetric soil water content estimated by the TDT sensor (θ_{Sensor}), threshold soil moisture content (θ_{Thresh}), irrigation, precipitation and irrigation recommendation events plotted over the entire experimental period (July 30-September 16). The θ values correspond to the left-hand y-axis and irrigation, precipitation and irrigation recommendation correspond to the right-hand y-axis.



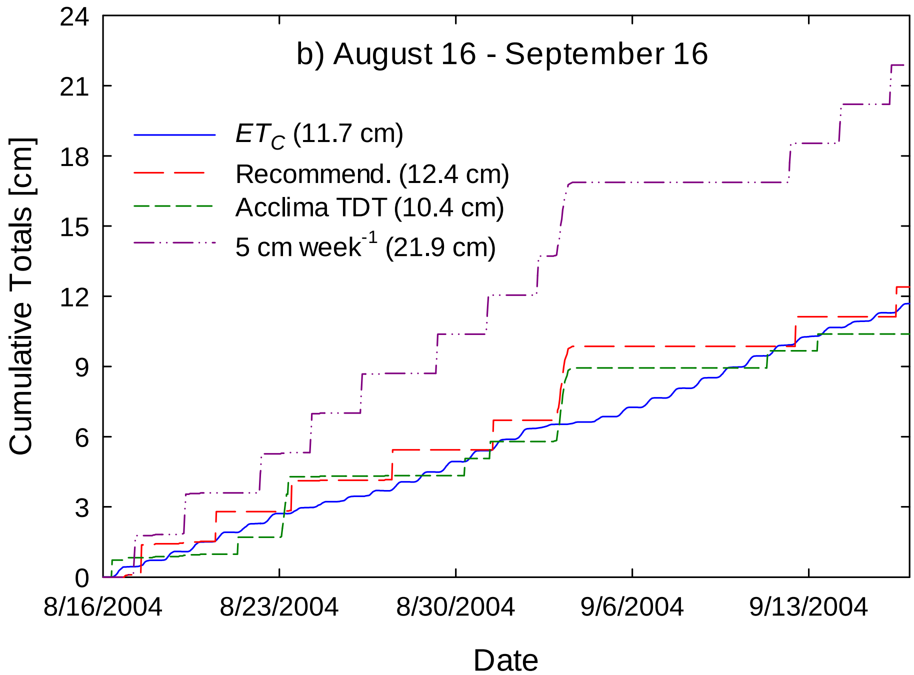


Figure 3. Cumulative crop evapotranspiration (ET_C) calculated from the weather station's *ET* estimates, cumulative irrigation recommendation (plus precipitation) based on ET_C and cumulative irrigation (plus precipitation) applied with the TDT system plotted from a) July 30-August 15 (impact sprinkler; 0.50 efficiency) and b) August 16-September 16 (gear-driven sprinkler; 0.80 efficiency). The cumulative totals at the end of each period are given in parentheses.

Table 1. Cumulative irrigation amounts and water conservation percentages using the Acclima Digital TDT Sensor to schedule irrigation.

	July 30-Aug. 15	Aug. 16-Sept. 16
Cumulative Amounts [cm]:		
ET_C	9.75	11.7
Recommendation	10.2	12.4
TDT System	11.5	10.4
5 cm week^{-1}	11.8	21.9
Water Conserved†:		
TDT vs. *ET*	-18%	11%
TDT vs. Recommendation	-13%	16%
TDT vs. 5 cm week^{-1}	2.5%	53%

†The percentages are for the TDT system relative to actual crop water use (*ET*) estimated with the weather station's *ET* estimates, recommendations based on *ET* and applying a fixed rate of 5 cm week^{-1}. Positive values indicate water conservation and negative values indicate over-application of water.

indicating the applied irrigation water did not reach the sensor, was on August 1 after which two irrigation events were required to bring θ back above θ_{Thresh}. The only times the sensor-estimated θ value dropped below θ_{Thresh} and remained below θ_{Thresh} following irrigation events was on August 1, 2 and 6. The reason the applied irrigation water did not reach the sensor on August 1, and the reason for θ_r not being recharged to a level above θ_{Thresh} following the irrigation events on August 1, 2 and 6, is attributed to the shorter irrigation durations (i.e. smaller water applications) and the lower efficiency of the impact sprinkler (0.50).

For comparison, cumulative *ET*, irrigation with the TDT system and recommended irrigation amounts are plotted versus time for July 30-August 15 when the impact sprinkler head was used (Figure 3a) and for August 16-September 16 when the gear-driven sprinkler head was used (Figure 3b). The cumulative values at the end of each time period are also listed (Table 1). After the first time period (July 30-August 15), approximately 1.3 cm of water in excess of the irrigation recommendations was applied by the TDT system, yielding an over-application of 13% relative to the recommendation (Table 1). After the second time period (August 16-September 16), approximately 2.0 cm of water was conserved by the TDT system, applying 16% less water (Table 1) relative to the irrigation recommendations. As a further comparison, the cumulative irrigation totals are listed in Table 1 assuming an average

Table 2. Average water cost in the US and in six cities in the Western US, and potential dollars saved per month using the TDT sensor to schedule irrigation.

Water Conserved Relative to Recommendation = 18.8 m^3 month^{-1}†			
Water Conserved Relative to 5 cm week^{-1} = 108 m^3 month^{-1}†			
City	**Water Costs [\$ m^{-3}]**	**Savings Relative to Recommendation‡ [\$ month^{-1}]**	**Savings Relative to 5 cm week^{-1}‡ [\$ month^{-1}]**
US Average	0.52	9.78	56.06
Denver	0.45	11.12	63.72
Las Vegas	0.40	5.31	30.45
Phoenix	0.28	7.52	43.10
Salt Lake City	0.36	8.42	48.25
Spokane	0.39	6.76	38.71
Tucson	0.59	7.01	40.16

†Water conserved per month value is calculated by taking the difference between the cumulative irrigation amounts reported in Table 1 and multiplying by a 1000 m^2 area (assumed value for the average size of a lawn).
‡Savings will vary with the size of plot being irrigated; calculations here are based on a 1000 m^2 area.

summertime peak residential irrigation rate of 5 cm week^{-1}. We assume this application rate is not reduced due to user negligence, even though *ET* rates decrease later in the season. Compared to this constant irrigation rate, the TDT system reduced water applications by 0.3 cm and 11.5 cm from July 30-August 15 and August 16-September 16, respectively, yielding 2.5% and 53% water savings, respectively.

By multiplying the 2.0 cm (0.02 m; relative to recommendations) and 11.5 cm (0.115 m; relative to 5 cm week^{-1}) of water conserved for the second time period (August 16-September 16) by the area of a larger plot, 1000 m^2, and converting the time period to months, this translates to 18.8 m^3 month^{-1} and 108 m^3 month^{-1} of water savings relative to the irrigation recommendations and fixed irrigation rate, respectively. These values can be multiplied by average water prices to estimate the amount of money saved over the course of a month via irrigation scheduling with the TDT system (Table 2) relative to irrigation recommendations and a fixed irrigation rate.

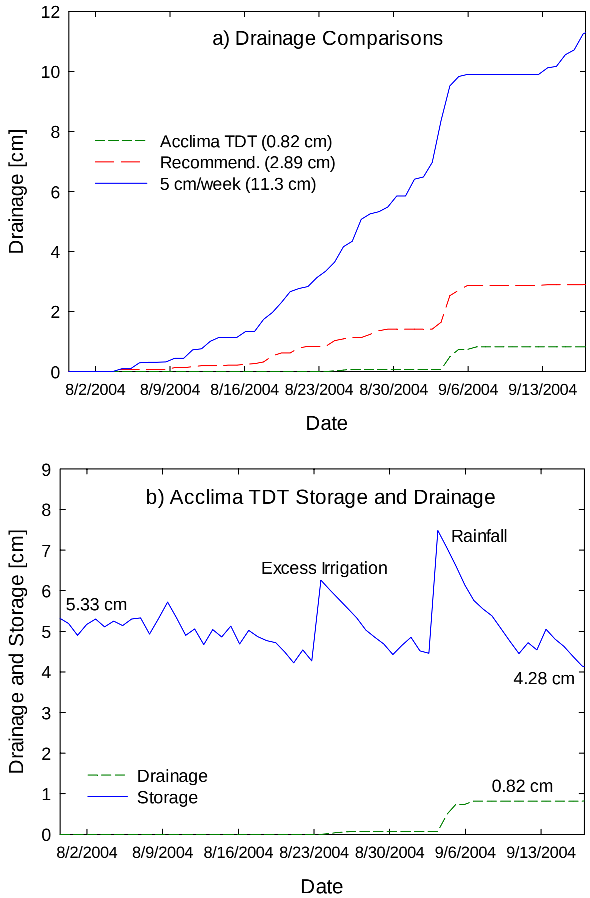


Figure 4. HYDRUS-2D predictions of a) drainage below the plant rooting depth (30 cm) in the profile for irrigation with the TDT system, the recommendation based on weather station *ET* estimates and a fixed application rate of 5 cm week^{-1}, and b) soil water storage over the entire time period of the experiment irrigating with the TDT system showing the drainage from a) only occurs when soil storage increases significantly following major water application events (August 23 and September 3) (beginning and ending values of storage are reported on the plot).

Using the HYDRUS-2D model the water balance for the plot was solved to calculate the change in soil water storage (ΔS). This value was used with irrigation, precipitation and *ET* values in order to estimate the drainage (*DR*) from the plant rooting depth of the profile. The *DR* values for irrigation with the TDT system, recommendations based on the weather station *ET* estimates and a fixed irrigation rate of 5 cm week^{-1} are plotted for comparison (Figure 4a). The simulation comparisons indicate no drainage would have occurred based on irrigation control with the TDT sensor, but with one excess irrigation event and rainfall, drainage was 0.82 cm. using the *ET*-based irrigation recommendations, intermediate drainage of 2.89 cm occurred and significant drainage of 11.3 cm occurred with the fixed irrigation rate of 5 cm week^{-1}. To illustrate when the drainage occurs, ΔS in the plant rooting depth of the profile was simulated for the TDT system, and is plotted along with *DR* (Figure 4b). This shows that drainage occurs when large amounts of water are applied to the plot, immediately following large irrigation or precipitation events (Figure 3; August 23 and September 3). The ΔS (Figure 4b) also confirms the TDT system's ability to maintain a relatively constant amount of water in the soil profile.

The soil volume from which the sensor derives a measurement (Figure 1) and the rooting depth of the crop must be considered when determining the depth to which the sensor is buried. Several studies have been performed to demonstrate the importance of sensor burial depth under different crops with differing irrigation methods (Haise and Hagan, 1967; Phene and Howell, 1984; Stieber and Shock, 1995; Coelho and Or, 1996). Burying the sensor too shallow will likely lead to too frequent irrigations owing to the relatively short drying time of the surface soil, while burying the sensor below the crop rooting depth will likely lead to too infrequent irrigations owing to the increased time required for deeper soil to dry. To illustrate these points, 1.27 cm of water (considered an average value for a single irrigation event) was applied to the profile and θ over the 30 cm plant rooting depth was plotted at different times for up to four days following the irrigation event (Figure 5). The data show that the θ contrast with time decreases significantly with profile depth. Below a profile depth of 20 cm, less than 0.03 θ units separate the entire range of θ_{Sim} values at different times, whereas between 0 and 10 cm at least 0.08 θ units separate the entire range θ_{Sim} values at different times. Keeping in mind that the root distribution density for the turf grass was maximum in the top 5 cm, sensors located too deep in the profile run the risk of a time lag response, leading to excess drying near the surface and potential drainage below the root zone. Also, if the sensor burial depth is increased, θ at the sensor increases and there is a narrower θ range between irrigation events. If the sensor burial depth is decreased, θ at the sensor decreases and there is a wider θ range between irrigation events. This indicates that as the burial depth of the sensor increases θ_{Thresh} should increase owing to a greater time requirement for deeper soil to dry, and as the burial depth of the sensor decreases θ_{Thresh} should

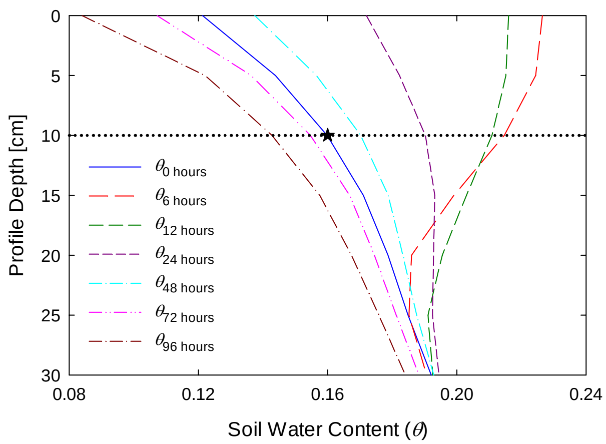


Figure 5. Simulated soil water contents (θ) in the plant rooting depth (0-30 cm) of the profile immediately before (0 hours) a water application of 1.27 cm and at several times (6-96 hours) following the application, showing the relationship between the threshold water content (θ_{Thresh}) and the sensor burial depth. The dotted horizontal line shows a burial depth of 10 cm and the star shows marks the threshold water content (θ_{Thresh}) of 0.16. As the burial depth of the sensor increases θ_{Thresh} should increase owing to a greater time requirement for deeper soil to dry, and as the burial depth of the sensor decreases θ_{Thresh} should decrease owing to a smaller time requirement for shallower soil to dry.

decrease owing to a smaller time requirement for shallower soil to dry. Under this simulation, increasing burial depth while keeping θ_{Thresh} equal to 0.16, would increase the time between irrigation events, whereas decreasing burial depth decreases time between irrigation events. At a constant depth, if θ_{Thresh} is increased, less time elapses between irrigation events and water is applied more often, and if θ_{Thresh} is decreased, more time elapses between irrigation events and water is applied less often.

In addition to depth, sensor placement with respect to location within a given plot is a critical factor to consider. In this experiment the sensor was located in the middle of the plot owing to the plot homogeneity. Sensor placement within a plot characterized by soil or microclimatic heterogeneities (e.g. differing soil textures; vegetation or structures shading areas) should be considered in light of conditions and the sensor should be placed in the driest area of the plot. As discussed above, irrigation should recharge θ in order to maintain θ_{Sensor} above an established θ_{Thresh} and balance *ET*. In heterogeneous plots this can be difficult via a single irrigation system, thus to ensure all areas within the plot receive required water amounts, irrigation should be controlled using the driest area. Ideally, different irrigation zones can be established for the same plot with zone delineations being based on soil and microclimatic heterogeneities. All zones are controlled by a single sensor within the driest zone and necessary irrigation adjustments (e.g. irrigation event duration) can be made to those zones outside the driest zone. Herein lies another advantage of θ estimations in irrigation scheduling, they are site-specific, whereas *ET* estimates derived from weather stations are often applied to sites far from the stations where climatic conditions may be different.

Conclusions

Electromagnetic (EM) measurements of bulk soil permittivity (ε) provide a means to estimate volumetric soil water content (θ), and therefore storage within the plant root zone, and directly infer evapotranspiration (*ET*) for use in irrigation scheduling. The Acclima Digital TDT Sensor is an EM-based θ sensor that provides exceptional ε measurement accuracy at a reduced cost. The sensor can be employed to schedule irrigation via connection to custom irrigation controllers. A threshold θ value (θ_{Thresh}) must be determined via consideration of soil properties and crops to be grown, and is programmed into the custom controller. The controller operates the irrigation system via communication with the sensor in response to θ changes with respect to θ_{Thresh}. When a gear-driven sprinkler head having an efficiency of 0.80 was used with the TDT sensor for irrigation control and scheduling, 16% less water was applied relative to using irrigation recommendations based on *ET* estimates from a weather station and 53% less water was applied using a fixed irrigation rate of 5 cm week^{-1}, thus conserving water and saving money. Despite the reduced application of water relative to irrigation recommendations, the grass plot was healthy and did not show signs of water stress. Performance of the system is dependent on the burial depth of the sensor and θ_{Thresh}. The θ_{Thresh} value is soil type dependent and should be established via consideration of θ at field capacity and permanent wilting point.

A numerical computer model (HYDRUS-2D) was used with estimated irrigation and precipitation inputs and estimated *ET* outputs to solve the soil profile water balance and predict drainage occurring below the estimated plant rooting depth of 30 cm. The simulated drainage from the 30 cm plant rooting depth in the soil profile was small for the TDT system, 0.82 cm, and only occurred following uncontrolled water application events. Drainage with the irrigation *ET*-based recommendations was intermediate, 2.89 cm, and drainage with the fixed irrigation rate was significant, 11.3 cm. The model provides a useful irrigation research tool for estimating the amount of water draining below the plant rooting depth and in demonstrating how θ_{Thresh} may vary with the sensor burial depth.

Acknowledgements

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References

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FOA Irrigation and Drainage Paper 56. Food and Agriculture Organization of the United Nations, Rome, Italy. pp. 300.

Blonquist Jr., J.M., S.B. Jones, and D.A. Robinson. 2005a. A time domain transmission sensor with TDR performance characteristics. Accepted in J. Hydrology.

Blonquist Jr., J.M., S.B. Jones, and D.A. Robinson. 2005b. Characterization and calibration of seven electromagnetic water content sensors: Part II. Evaluation. Accepted in Vadose Zone J.

Campbell, G.S., and R. Y. Anderson. 1998. Evaluation of simple transmission line oscillators for soil moisture measurement. Comput. Electron. Ag. 20:31-44.

Coelho, E.F., and D. Or. 1996. Flow and uptake patterns affecting soil water sensor placement for drip irrigation management. Trans. of the ASAE 39(6):2007-2016.

Dean, T.J., J.P. Bell, and A.J.B. Baty. 1987. Soil moisture measurement by an improved capacitance technique, part I. Sensor design and performance. J. of Hydrology 93:67-78.

Ervin, E.H., and A.J. Koski. 1998. Drought avoidance aspects and crop coefficients of Kentucky bluegrass and tall fescue in the semiarid west. Crop Science 38:788-795.

Gaskin, G.J., and J.D. Miller. 1996. Measurement of soil water content using a simplified impedance measuring technique. J. Ag. Engr. Res. 63:153-159.

Haise, H.R., and R.M. Hagan. 1967. Soil, plant and evaporative measurements as criteria for scheduling irrigation, p. 577-604, In R.M. Hagan, H.R. Haise, and T.W. Edminster, eds. Irrigation of Agricultural Lands. American Society of Agronomy, Madison, WI, USA.

Harlow, R.C., E.J. Burke, and T.P.A. Ferre. 2003. Measuring water content in saline soils using impulse time domain transmission techniques. Vadose Zone J. 2:433-439.

Hilhorst, M.A., J. Balendonck, F.H.W. Kampers. 1993. A broad-bandwidth mixed analog/digital integrated circuit for the measurement of complex impedances. IEEE J. Solid-State Circuits 28:764-769.

Hilhorst, M.A. 2000. A pore water conductivity sensor. Soil Sci. Soc. Am. J. 64:1922-1925.

Hook, W.R., T.P.A. Ferre, and N.J. Livingston. 2004. The effects of salinity on the accuracy and uncertainty of water content measurement. Soil Sci. Soc. Am. J. 68:47-56.

Kelleners, T.J., R.O.W. Soppe, D.A. Robinson, M.G. Schaap, J.E. Ayers, and T.H. Skaggs. 2004. Calibration of capacitance probe sensors using electric circuit theory. Soil Sci. Soc. Am. J. 68:430-439.

Kelleners, T.J., M.S. Seyfried, J.M. Blonquist Jr., J. Bilskie, and D.G. Chandler. In review. A physical framework to interpret water content reflectometer measurements in air, fluids, and soil. Soil Sci. Soc. Am. J.

Kjelgren, R., L. Rupp, and D. Kilgren. 2000. Water conservation in urban landscapes. HortScience 35:1037-1040.

Leib, B.G., J.D. Jabro, and G.R. Matthews. 2003. Field evaluation and performance comparison of soil moisture sensors. Soil Sci. 168:396-408.

McMichael, B., and R.J. Lascano. 2003. Laboratory evaluation of a commercial dielectric soil water sensor. Vadose Zone J. 2:650-654.

Or, D., and J.M. Wraith. 2002. Soil Water Content and Water Potential Relationships, p. 49-84, In A.W. Warrick, ed. Soil Physics Companion, Vol. 1. CRC Press, Boca Raton, Florida, USA.

Paul, W. 2002. Prospects for controlled application of water and fertiliser, based on sensing permittivity of soil. Comput. Electron. Ag. 36:151-163.

Phene, C.J., and T.A. Howell. 1984. Soil sensor control of high-frequency irrigation systems. Transactions of the ASAE 27(2):392-396.

Paltineanu, I.C., and J.L. Starr. 1997. Real-time soil water dynamics using multisensor capacitance probes: Laboratory calibration. Soil Sci. Soc. Am. J. 61:1576-1585.

Qualls, R.J., J.M. Scott, and W.B. DeOreo. 2001. Soil moisture sensors for urban landscape irrigation: Effectiveness and reliability. J. American Water Resources Association 37(3):547-559.

Robinson, D.A., S.B Jones, J.M. Wraith, D. Or, and S.P. Friedman. 2003. A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry. Vadose Zone J. 2:444-475.

Seyfried, M.S., and M.D. Murdock. 2001. Response of a new soil sensor to variable soil, water content, and temperature. Soil Sci. Soc. Am. J. 65:28-34.

Seyfried, M.S., and M.D. Murdock. 2004. Measurement of soil water content with a 50-MHz soil dielectric sensor. Soil Sci. Soc. Am. J. 68:394-403.

Šimůnek, J.S., M. Sejna, and M. Th. van Genuchten. 1999. The HYDRUS-2D software package for simulating the two-dimensional flow of water, heat, and multiple solutes in variably-saturated porous media, IGWMC-TPS 53, Version 2.0, International Ground Water Modeling Center, Colorado School of Mines, Golden, Colorado, USA.

Stieber, T.D., and C.C. Shock. 1995. Placement of soil-moisture sensors in sprinkler irrigated potatoes. American Potatoe J. 72(9):533-545.

Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. Water Resour. Res. 16:574-582.

Topp, G.C., D.R. Lapen, G.D. Young, and M. Edwards. 2001. Evaluation of shaft-mounted TDT readings in disturbed and undisturbed media, Second International Symposium and Workshop on Time Domain Reflectometry for Innovative Geotechnical Applications, Available at: http://www.iti.northwestern.edu/tdr/tdr2001/proceedings/ (verified 4 May 2005). Infrastructure Technology Institute-Northwestern University, Evanston, Illinois.

Topp, G.C., and T.P.A. Ferre. 2002. Water Content, p. 417-545, In J.H. Dane, and G.C. Topp. ed. Methods of Soil Analysis Part 4 Physical Methods. Soil Sci. Soc. Am. Inc., Madison, WI, USA.

Water Conservation from Precise Irrigation Scheduling Using a Subsurface Electromagnetic Soil Moisture Sensor

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Abstract

Instrumented weather stations are often used for evapotranspiration (*ET*) prediction in order to estimate crop water use for irrigation scheduling. A direct estimate of crop water use by subsurface measurements of soil water content has been limited by the high cost of reliable soil moisture sensors. Recent advances in electromagnetic (EM) sensor technology have made automated irrigation scheduling based on state-of-the-art soil moisture sensing capability a reality. Our objectives were: i) to compare irrigation scheduling based on weather station *ET* estimates with those from a novel time domain transmission (TDT) soil moisture sensor, and ii) to apply a computer-based numerical model to simulate any drainage occurring below the plant rooting depth. The TDT sensor was designed to schedule irrigation based on a threshold θ value (θ_{Thresh}). The sensor circuitry controlled the irrigation schedule by allowing a preprogrammed schedule to operate whenever the sensor-estimated θ (θ_{Sensor}) dropped below θ_{Thresh}. The TDT sensor was installed under Kentucky bluegrass with a nearby weather station providing estimates of *ET* for comparison over a period of approximately seven weeks. The HYDRUS-2D numerical simulation model was used for predicting drainage in the soil profile. The model input requirements include the flow domain geometry and boundary conditions, along with estimates of evaporation, transpiration, precipitation, irrigation and root water uptake data. Relative to *ET*-based irrigation recommendations, the TDT system applied approximately 16% less water when irrigating with a sprinkler having an efficiency of 0.80, and relative to a fixed irrigation rate of 5 cm week^{-1}, the TDT system applied approximately 53% less water. Modeling results of the TDT sensor control indicated that no detectable water drained below the estimated 30 cm rooting depth of turf grass when uncontrolled application events (e.g. rainfall) were ignored. Performance of the TDT system is dependent on the sensor burial depth and θ_{Thresh}. The θ_{Thresh} value is soil-type dependent and should be established via consideration of θ at field capacity and permanent wilting point. The potential water savings with the TDT system is not only important to water conservation, but can save irrigators an estimated \$5.00-\$100.00 per month based on average water prices in the US and a 1000 m^2 irrigated turf grass plot.

Introduction

Water conservation in relation to crop and turf grass irrigation has recently received much attention, especially in the Western United States, where extensive growth coupled with drought conditions in recent years has reduced the amount of water available for irrigation use (Ervin and Koski, 1998; Kjelgren et al., 2000). Environmental measurements such as evapotranspiration (Allen et al., 1998) and soil water content (Topp and Ferre, 2002) are gaining more utility as a means to infer plant water use and to properly schedule agricultural, municipal and residential irrigation. Such measurements not only conserve water, but also save growers and irrigators money by ensuring that plants are not excessively irrigated.

In situ soil water content estimates are accomplished using a variety of methods and sensors (Or and Wraith, 2002). Measurements and estimates of water content for use in irrigation scheduling have in the past been performed via gravimetric, neutron scattering, gypsum block and tensiometer methods. In recent years, water content estimates have advanced to include electromagnetic (EM) techniques such as time domain reflectometry (TDR) (Topp et al., 1980; Topp and Ferre, 2002; Robinson et al., 2003), time domain transmissometry (TDT) (Topp et al., 2001; Harlow et al., 2003; Hook et al., 2004; Blonquist et al., 2005a), transmission line oscillators (Campbell and Anderson, 1998; Seyfried and Murdock, 2001; Kelleners et al., in review), impedance- (Hilhorst et al., 1993; Gaskin and Miller, 1996; Hilhorst, 2000; Seyfried and Murdock, 2004) and capacitance-based approaches (Dean et al., 1987; Paltineanu and Starr, 1997; Kelleners et al., 2004; McMichael and Lascano, 2004).

Estimates of water content based on EM measurements provide real time, in situ measurements at a relatively affordable cost. Estimation of water content using EM sensors is based on the ability of sensors to measure the real part of the dielectric permittivity (ε), or an EM signal property directly relating to ε, which directly relates to volumetric soil water content (θ) owing to the ε contrast of soil constituents; $\varepsilon_a \approx 1$, $\varepsilon_s \approx$ 2-9 and $\varepsilon_w \approx$

80; where the subscripts *a*, *s* and *w* represent air, solids and water, respectively. The potential of EM θ sensors in irrigation scheduling has been demonstrated (Qualls et al., 2001; Paul, 2002; Leib et al., 2003).

The objectives of this research were: i) to compare cumulative water applications with irrigation scheduling based on evapotranspiration estimates from a weather station to scheduling based on soil moisture estimates from a time domain transmission (TDT) sensor, and ii) to apply a computer-based numerical model to simulate the water balance in the soil profile and estimate any drainage occurring below the plant rooting depth.

Materials and Methods

The Acclima® Digital TDT Sensor is a transmission line sensor that estimates θ based on bulk soil ε measurements, and has been shown to provide exceptional ε measurement accuracy when compared to research grade instrumentation (Blonquist et al., 2005a; Blonquist et al., 2005b). In order to make θ estimations and control irrigation, the Acclima Digital TDT Sensor must be connected to a custom controller; the Acclima CS3500 or Acclima RS500; in which is programmed a threshold soil water content value (θ_{Thresh}). The sensor makes continuous θ estimates, which are retrieved by the controller, and when the sensor estimates θ below θ_{Thresh}, the controller operates a preprogrammed irrigation schedule within the controller.

An Acclima Digital TDT Sensor was installed in an approximately 280 m^2 field plot of Kentucky bluegrass on the Utah State University Greenville Research Farm located in North Logan, Utah, USA. The sensor was installed in the soil horizontally with respect to the ground surface, approximately in the middle of the plot. The placement depth of the sensor was approximately 10 cm (Figure 1). The cross-section (Figure 1) displays the sensitivity of the sensor, or the soil cross-section in which 90% of the electromagnetic energy contributing to the θ estimation is contained. The sensor head measures approximately 9.0 cm in the horizontal direction and 2.0 cm in the vertical direction (Figure 1), which gives indication of the volume of soil contributing to the measurement, but the sensor is much more sensitive to the soil immediately surrounding the probe where the darker shaded area represents a greater concentration of electromagnetic energy (Figure 1). The θ_{Thresh} value was estimated using field capacity θ and permanent wilting point θ values for the soil type in the field plot and Kentucky Bluegrass. The θ values at field capacity and permanent wilting point for the soil were estimated to be 0.24 and 0.08, respectively, and the θ_{Thresh} value was estimated as 0.16, halfway between field capacity and permanent wilting point.

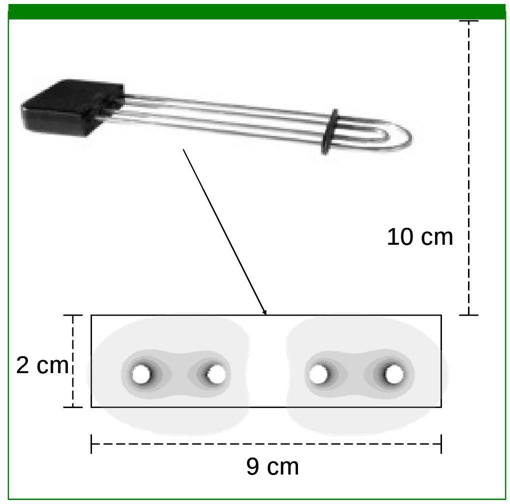

Figure 1. Cross-section of the TDT sensor oriented horizontally in relation to the ground surface. The cross-section shows the four rods and the area containing 90% of the electromagnetic energy that contributes to the measurement (gray-scale). The solid line surrounding the rods represents the sensor head and the approximate outer dimensions are outlined in black and labeled. The soil contributes less to the measurement further from the rods as indicated by the gray intensity scale, thus the water content estimation is largely dependent on soil properties adjacent to the rods.

Initially, irrigation was accomplished using a single impact sprinkler head (Rainbird® 30IBH with a 3/16” nozzle) outputting approximately 480 $cm^3\ s^{-1}$ (7.6 gpm), but midway through the experiment the sprinkler was changed to a lower flow rate gear-driven sprinkler head (Hunter® PGP with #9 nozzle) outputting approximately 375 $cm^3\ s^{-1}$ (5.9 gpm). The change was made in order to improve application efficiency. The application efficiencies of the impact and gear-driven sprinkler heads at the position of the TDT sensor, approximately 5.5 m from the sprinkler, were estimated at 0.50 and 0.80, respectively, by dividing the flow rate at the sprinkler head by the application rate measured at the position of the TDT sensor.

The experiment was conducted over a period of forty-nine days from July 30 through September 16, during which θ_{Sensor} and irrigation event data were estimated and logged with the CS3500 Controller. Evapotranspiration and precipitation were estimated and logged with a Campbell Scientific ET106 Evapotranspiration Station operated by Utah State

University and used by the State of Utah's Division of Water Resources to determine irrigation recommendations. The CS106 calculates *ET* via inputs from meteorological sensors onboard the station. The weather station is located approximately 200 m from the experimental plot under similar conditions over a large Kentucky bluegrass plot, thus the data supplied by the weather station are considered representative of the experimental plot.

We compared recommended irrigation amounts (including precipitation) based on *ET* estimates from the weather station to the actual amount of water applied to the plot using the θ estimates made with the TDT sensor, where the impact sprinkler head was used from July 31 to August 15 and the gear-driven sprinkler head was used from August 16 to September 16. We also compared irrigation amounts when applying water at a fixed rate of 5 cm week^{-1} over the duration of the experiment to the water applied using the TDT system. In addition to comparing irrigation amounts, we applied a computer program, HYDRUS-2D Model (Šimůnek et al., 1999), to simulate and compare drainage below the plant rooting depth under the three described irrigation strategies (recommendations based on weather station, TDT sensor θ estimates and 5 cm week^{-1}).

Results and Discussion

The ability of the TDT system to maintain θ above the established θ_{Thresh} is indicated by the field data presented in Figure 2 where changes in θ, irrigation events with the TDT system (water amount that the plot actually received) and recommended irrigation events (water amount the plot would have received had the recommendations been used) based on *ET* estimates from the weather station are plotted versus time (July 30-September 16).

The only time the sensor-estimated θ value did not increase following an irrigation event,

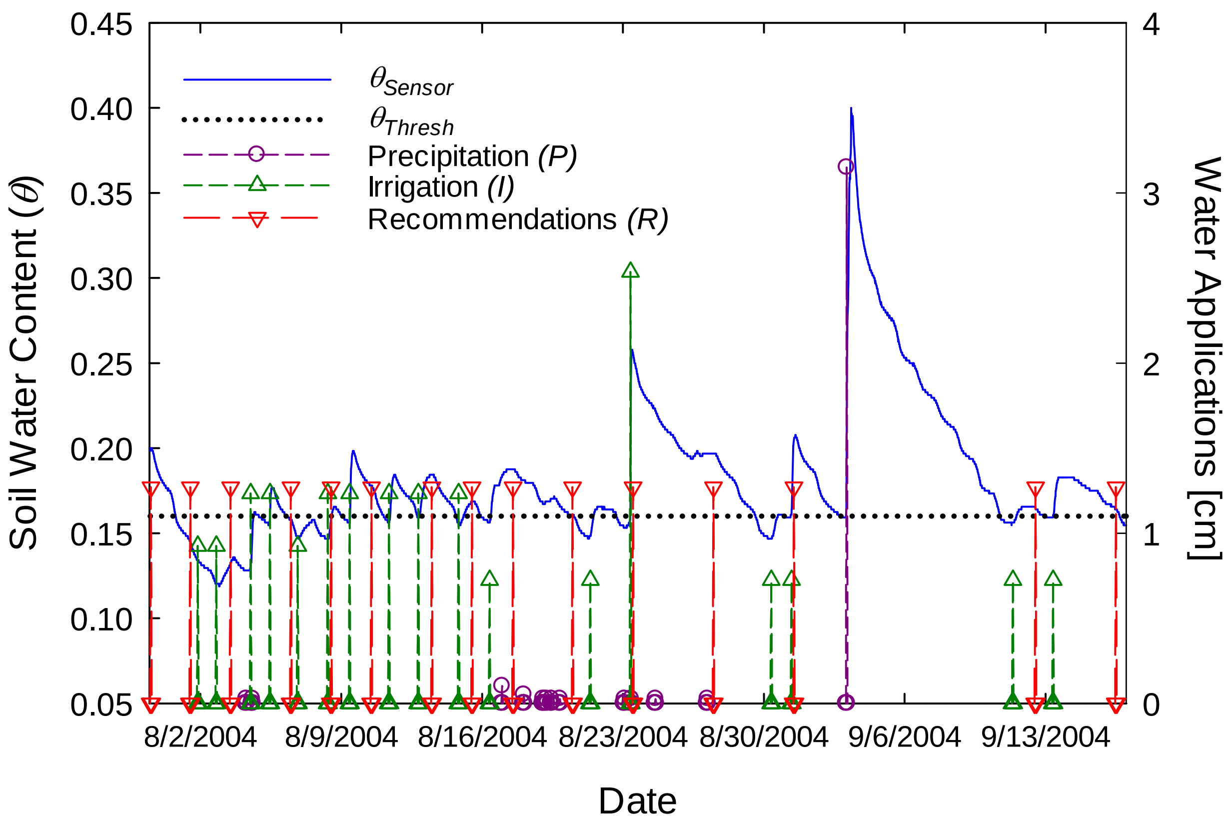

Figure 2. Volumetric soil water content estimated by the TDT sensor (θ_{Sensor}), threshold soil moisture content (θ_{Thresh}), irrigation, precipitation and irrigation recommendation events plotted over the entire experimental period (July 30-September 16). The θ values correspond to the left-hand y-axis and irrigation, precipitation and irrigation recommendation correspond to the right-hand y-axis.

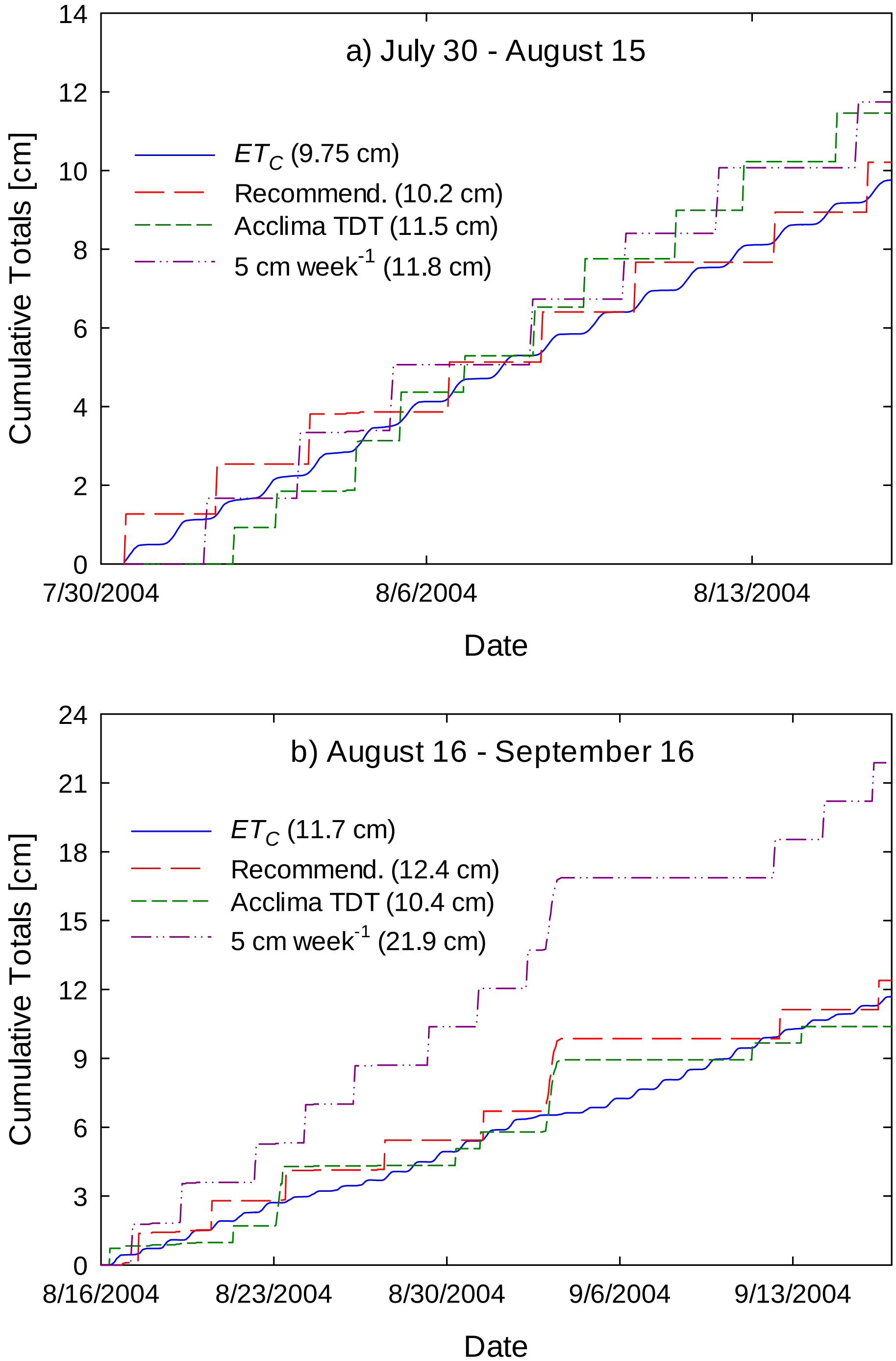

Figure 3. Cumulative crop evapotranspiration (ET_C) calculated from the weather station's *ET* estimates, cumulative irrigation recommendation (plus precipitation) based on ET_C and cumulative irrigation (plus precipitation) applied with the TDT system plotted from a) July 30-August 15 (impact sprinkler; 0.50 efficiency) and b) August 16-September 16 (gear-driven sprinkler; 0.80 efficiency). The cumulative totals at the end of each period are given in parentheses.

Table 1. Cumulative irrigation amounts and water conservation percentages using the Acclima Digital TDT Sensor to schedule irrigation.

	July 30-Aug. 15	Aug. 16-Sept. 16
Cumulative Amounts [cm]:		
ET_C	9.75	11.7
Recommendation	10.2	12.4
TDT System	11.5	10.4
5 cm week^{-1}	11.8	21.9
Water Conserved†:		
TDT vs. *ET*	-18%	11%
TDT vs. Recommendation	-13%	16%
TDT vs. 5 cm week^{-1}	2.5%	53%

†The percentages are for the TDT system relative to actual crop water use (*ET*) estimated with the weather station's *ET* estimates, recommendations based on *ET* and applying a fixed rate of 5 cm week^{-1}. Positive values indicate water conservation and negative values indicate over-application of water.

indicating the applied irrigation water did not reach the sensor, was on August 1 after which two irrigation events were required to bring θ back above θ_{Thresh}. The only times the sensor-estimated θ value dropped below θ_{Thresh} and remained below θ_{Thresh} following irrigation events was on August 1, 2 and 6. The reason the applied irrigation water did not reach the sensor on August 1, and the reason for θ_r not being recharged to a level above θ_{Thresh} following the irrigation events on August 1, 2 and 6, is attributed to the shorter irrigation durations (i.e. smaller water applications) and the lower efficiency of the impact sprinkler (0.50).

For comparison, cumulative *ET*, irrigation with the TDT system and recommended irrigation amounts are plotted versus time for July 30-August 15 when the impact sprinkler head was used (Figure 3a) and for August 16-September 16 when the gear-driven sprinkler head was used (Figure 3b). The cumulative values at the end of each time period are also listed (Table 1). After the first time period (July 30-August 15), approximately 1.3 cm of water in excess of the irrigation recommendations was applied by the TDT system, yielding an over-application of 13% relative to the recommendation (Table 1). After the second time period (August 16-September 16), approximately 2.0 cm of water was conserved by the TDT system, applying 16% less water (Table 1) relative to the irrigation recommendations. As a further comparison, the cumulative irrigation totals are listed in Table 1 assuming an average

Table 2. Average water cost in the US and in six cities in the Western US, and potential dollars saved per month using the TDT sensor to schedule irrigation.

Water Conserved Relative to Recommendation = 18.8 m^3 month^{-1}†			
Water Conserved Relative to 5 cm week^{-1} = 108 m^3 month^{-1}†			
City	**Water Costs [\$ m^{-3}]**	**Savings Relative to Recommendation‡ [\$ month^{-1}]**	**Savings Relative to 5 cm week^{-1}‡ [\$ month^{-1}]**
US Average	0.52	9.78	56.06
Denver	0.45	11.12	63.72
Las Vegas	0.40	5.31	30.45
Phoenix	0.28	7.52	43.10
Salt Lake City	0.36	8.42	48.25
Spokane	0.39	6.76	38.71
Tucson	0.59	7.01	40.16

†Water conserved per month value is calculated by taking the difference between the cumulative irrigation amounts reported in Table 1 and multiplying by a 1000 m^2 area (assumed value for the average size of a lawn).
‡Savings will vary with the size of plot being irrigated; calculations here are based on a 1000 m^2 area.

summertime peak residential irrigation rate of 5 cm week^{-1}. We assume this application rate is not reduced due to user negligence, even though *ET* rates decrease later in the season. Compared to this constant irrigation rate, the TDT system reduced water applications by 0.3 cm and 11.5 cm from July 30-August 15 and August 16-September 16, respectively, yielding 2.5% and 53% water savings, respectively.

By multiplying the 2.0 cm (0.02 m; relative to recommendations) and 11.5 cm (0.115 m; relative to 5 cm week^{-1}) of water conserved for the second time period (August 16-September 16) by the area of a larger plot, 1000 m^2, and converting the time period to months, this translates to 18.8 m^3 month^{-1} and 108 m^3 month^{-1} of water savings relative to the irrigation recommendations and fixed irrigation rate, respectively. These values can be multiplied by average water prices to estimate the amount of money saved over the course of a month via irrigation scheduling with the TDT system (Table 2) relative to irrigation recommendations and a fixed irrigation rate.

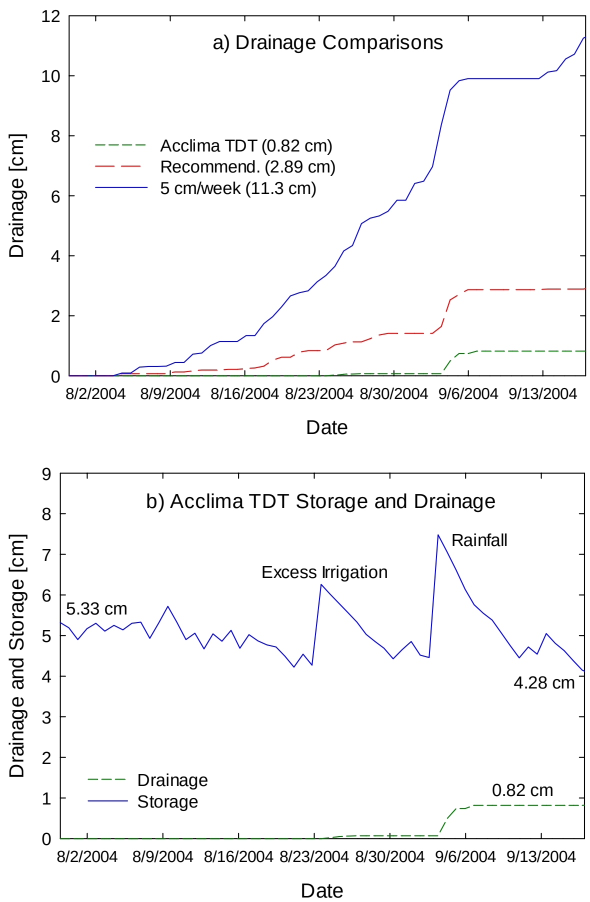

Figure 4. HYDRUS-2D predictions of a) drainage below the plant rooting depth (30 cm) in the profile for irrigation with the TDT system, the recommendation based on weather station *ET* estimates and a fixed application rate of 5 cm week^{-1}, and b) soil water storage over the entire time period of the experiment irrigating with the TDT system showing the drainage from a) only occurs when soil storage increases significantly following major water application events (August 23 and September 3) (beginning and ending values of storage are reported on the plot).

Using the HYDRUS-2D model the water balance for the plot was solved to calculate the change in soil water storage (ΔS). This value was used with irrigation, precipitation and *ET* values in order to estimate the drainage (*DR*) from the plant rooting depth of the profile. The *DR* values for irrigation with the TDT system, recommendations based on the weather station *ET* estimates and a fixed irrigation rate of 5 cm week^{-1} are plotted for comparison (Figure 4a). The simulation comparisons indicate no drainage would have occurred based on irrigation control with the TDT sensor, but with one excess irrigation event and rainfall, drainage was 0.82 cm. using the *ET*-based irrigation recommendations, intermediate drainage of 2.89 cm occurred and significant drainage of 11.3 cm occurred with the fixed irrigation rate of 5 cm week^{-1}. To illustrate when the drainage occurs, ΔS in the plant rooting depth of the profile was simulated for the TDT system, and is plotted along with *DR* (Figure 4b). This shows that drainage occurs when large amounts of water are applied to the plot, immediately following large irrigation or precipitation events (Figure 3; August 23 and September 3). The ΔS (Figure 4b) also confirms the TDT system's ability to maintain a relatively constant amount of water in the soil profile.

The soil volume from which the sensor derives a measurement (Figure 1) and the rooting depth of the crop must be considered when determining the depth to which the sensor is buried. Several studies have been performed to demonstrate the importance of sensor burial depth under different crops with differing irrigation methods (Haise and Hagan, 1967; Phene and Howell, 1984; Stieber and Shock, 1995; Coelho and Or, 1996). Burying the sensor too shallow will likely lead to too frequent irrigations owing to the relatively short drying time of the surface soil, while burying the sensor below the crop rooting depth will likely lead to too infrequent irrigations owing to the increased time required for deeper soil to dry. To illustrate these points, 1.27 cm of water (considered an average value for a single irrigation event) was applied to the profile and θ over the 30 cm plant rooting depth was plotted at different times for up to four days following the irrigation event (Figure 5). The data show that the θ contrast with time decreases significantly with profile depth. Below a profile depth of 20 cm, less than 0.03 θ units separate the entire range of θ_{Sim} values at different times, whereas between 0 and 10 cm at least 0.08 θ units separate the entire range θ_{Sim} values at different times. Keeping in mind that the root distribution density for the turf grass was maximum in the top 5 cm, sensors located too deep in the profile run the risk of a time lag response, leading to excess drying near the surface and potential drainage below the root zone. Also, if the sensor burial depth is increased, θ at the sensor increases and there is a narrower θ range between irrigation events. If the sensor burial depth is decreased, θ at the sensor decreases and there is a wider θ range between irrigation events. This indicates that as the burial depth of the sensor increases θ_{Thresh} should increase owing to a greater time requirement for deeper soil to dry, and as the burial depth of the sensor decreases θ_{Thresh} should

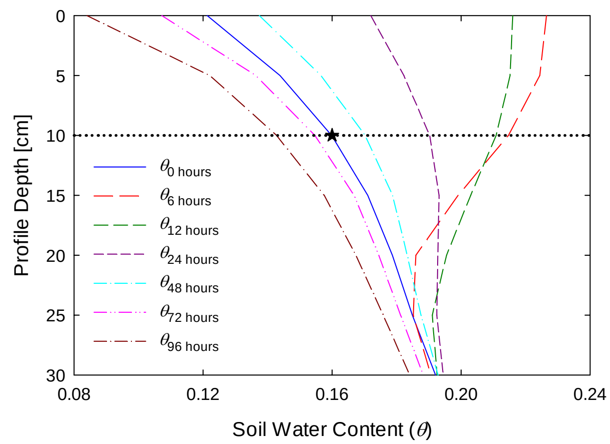

Figure 5. Simulated soil water contents (θ) in the plant rooting depth (0-30 cm) of the profile immediately before (0 hours) a water application of 1.27 cm and at several times (6-96 hours) following the application, showing the relationship between the threshold water content (θ_{Thresh}) and the sensor burial depth. The dotted horizontal line shows a burial depth of 10 cm and the star shows marks the threshold water content (θ_{Thresh}) of 0.16. As the burial depth of the sensor increases θ_{Thresh} should increase owing to a greater time requirement for deeper soil to dry, and as the burial depth of the sensor decreases θ_{Thresh} should decrease owing to a smaller time requirement for shallower soil to dry.

decrease owing to a smaller time requirement for shallower soil to dry. Under this simulation, increasing burial depth while keeping θ_{Thresh} equal to 0.16, would increase the time between irrigation events, whereas decreasing burial depth decreases time between irrigation events. At a constant depth, if θ_{Thresh} is increased, less time elapses between irrigation events and water is applied more often, and if θ_{Thresh} is decreased, more time elapses between irrigation events and water is applied less often.

In addition to depth, sensor placement with respect to location within a given plot is a critical factor to consider. In this experiment the sensor was located in the middle of the plot owing to the plot homogeneity. Sensor placement within a plot characterized by soil or microclimatic heterogeneities (e.g. differing soil textures; vegetation or structures shading areas) should be considered in light of conditions and the sensor should be placed in the driest area of the plot. As discussed above, irrigation should recharge θ in order to maintain θ_{Sensor} above an established θ_{Thresh} and balance *ET*. In heterogeneous plots this can be difficult via a single irrigation system, thus to ensure all areas within the plot receive required water amounts, irrigation should be controlled using the driest area. Ideally, different irrigation zones can be established for the same plot with zone delineations being based on soil and microclimatic heterogeneities. All zones are controlled by a single sensor within the driest zone and necessary irrigation adjustments (e.g. irrigation event duration) can be made to those zones outside the driest zone. Herein lies another advantage of θ estimations in irrigation scheduling, they are site-specific, whereas *ET* estimates derived from weather stations are often applied to sites far from the stations where climatic conditions may be different.

Conclusions

Electromagnetic (EM) measurements of bulk soil permittivity (ε) provide a means to estimate volumetric soil water content (θ), and therefore storage within the plant root zone, and directly infer evapotranspiration (*ET*) for use in irrigation scheduling. The Acclima Digital TDT Sensor is an EM-based θ sensor that provides exceptional ε measurement accuracy at a reduced cost. The sensor can be employed to schedule irrigation via connection to custom irrigation controllers. A threshold θ value (θ_{Thresh}) must be determined via consideration of soil properties and crops to be grown, and is programmed into the custom controller. The controller operates the irrigation system via communication with the sensor in response to θ changes with respect to θ_{Thresh}. When a gear-driven sprinkler head having an efficiency of 0.80 was used with the TDT sensor for irrigation control and scheduling, 16% less water was applied relative to using irrigation recommendations based on *ET* estimates from a weather station and 53% less water was applied using a fixed irrigation rate of 5 cm week^{-1}, thus conserving water and saving money. Despite the reduced application of water relative to irrigation recommendations, the grass plot was healthy and did not show signs of water stress. Performance of the system is dependent on the burial depth of the sensor and θ_{Thresh}. The θ_{Thresh} value is soil type dependent and should be established via consideration of θ at field capacity and permanent wilting point.

A numerical computer model (HYDRUS-2D) was used with estimated irrigation and precipitation inputs and estimated *ET* outputs to solve the soil profile water balance and predict drainage occurring below the estimated plant rooting depth of 30 cm. The simulated drainage from the 30 cm plant rooting depth in the soil profile was small for the TDT system, 0.82 cm, and only occurred following uncontrolled water application events. Drainage with the irrigation *ET*-based recommendations was intermediate, 2.89 cm, and drainage with the fixed irrigation rate was significant, 11.3 cm. The model provides a useful irrigation research tool for estimating the amount of water draining below the plant rooting depth and in demonstrating how θ_{Thresh} may vary with the sensor burial depth.

Acknowledgements

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References

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FOA Irrigation and Drainage Paper 56. Food and Agriculture Organization of the United Nations, Rome, Italy. pp. 300.

Blonquist Jr., J.M., S.B. Jones, and D.A. Robinson. 2005a. A time domain transmission sensor with TDR performance characteristics. Accepted in J. Hydrology.

Blonquist Jr., J.M., S.B. Jones, and D.A. Robinson. 2005b. Characterization and calibration of seven electromagnetic water content sensors: Part II. Evaluation. Accepted in Vadose Zone J.

Campbell, G.S., and R. Y. Anderson. 1998. Evaluation of simple transmission line oscillators for soil moisture measurement. Comput. Electron. Ag. 20:31-44.

Coelho, E.F., and D. Or. 1996. Flow and uptake patterns affecting soil water sensor placement for drip irrigation management. Trans. of the ASAE 39(6):2007-2016.

Dean, T.J., J.P. Bell, and A.J.B. Baty. 1987. Soil moisture measurement by an improved capacitance technique, part I. Sensor design and performance. J. of Hydrology 93:67-78.

Ervin, E.H., and A.J. Koski. 1998. Drought avoidance aspects and crop coefficients of Kentucky bluegrass and tall fescue in the semiarid west. Crop Science 38:788-795.

Gaskin, G.J., and J.D. Miller. 1996. Measurement of soil water content using a simplified impedance measuring technique. J. Ag. Engr. Res. 63:153-159.

Haise, H.R., and R.M. Hagan. 1967. Soil, plant and evaporative measurements as criteria for scheduling irrigation, p. 577-604, In R.M. Hagan, H.R. Haise, and T.W. Edminster, eds. Irrigation of Agricultural Lands. American Society of Agronomy, Madison, WI, USA.

Harlow, R.C., E.J. Burke, and T.P.A. Ferre. 2003. Measuring water content in saline soils using impulse time domain transmission techniques. Vadose Zone J. 2:433-439.

Hilhorst, M.A., J. Balendonck, F.H.W. Kampers. 1993. A broad-bandwidth mixed analog/digital integrated circuit for the measurement of complex impedances. IEEE J. Solid-State Circuits 28:764-769.

Hilhorst, M.A. 2000. A pore water conductivity sensor. Soil Sci. Soc. Am. J. 64:1922-1925.

Hook, W.R., T.P.A. Ferre, and N.J. Livingston. 2004. The effects of salinity on the accuracy and uncertainty of water content measurement. Soil Sci. Soc. Am. J. 68:47-56.

Kelleners, T.J., R.O.W. Soppe, D.A. Robinson, M.G. Schaap, J.E. Ayers, and T.H. Skaggs. 2004. Calibration of capacitance probe sensors using electric circuit theory. Soil Sci. Soc. Am. J. 68:430-439.

Kelleners, T.J., M.S. Seyfried, J.M. Blonquist Jr., J. Bilskie, and D.G. Chandler. In review. A physical framework to interpret water content reflectometer measurements in air, fluids, and soil. Soil Sci. Soc. Am. J.

Kjelgren, R., L. Rupp, and D. Kilgren. 2000. Water conservation in urban landscapes. HortScience 35:1037-1040.

Leib, B.G., J.D. Jabro, and G.R. Matthews. 2003. Field evaluation and performance comparison of soil moisture sensors. Soil Sci. 168:396-408.

McMichael, B., and R.J. Lascano. 2003. Laboratory evaluation of a commercial dielectric soil water sensor. Vadose Zone J. 2:650-654.

Or, D., and J.M. Wraith. 2002. Soil Water Content and Water Potential Relationships, p. 49-84, In A.W. Warrick, ed. Soil Physics Companion, Vol. 1. CRC Press, Boca Raton, Florida, USA.

Paul, W. 2002. Prospects for controlled application of water and fertiliser, based on sensing permittivity of soil. Comput. Electron. Ag. 36:151-163.

Phene, C.J., and T.A. Howell. 1984. Soil sensor control of high-frequency irrigation systems. Transactions of the ASAE 27(2):392-396.

Paltineanu, I.C., and J.L. Starr. 1997. Real-time soil water dynamics using multisensor capacitance probes: Laboratory calibration. Soil Sci. Soc. Am. J. 61:1576-1585.

Qualls, R.J., J.M. Scott, and W.B. DeOreo. 2001. Soil moisture sensors for urban landscape irrigation: Effectiveness and reliability. J. American Water Resources Association 37(3):547-559.

Robinson, D.A., S.B Jones, J.M. Wraith, D. Or, and S.P. Friedman. 2003. A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry. Vadose Zone J. 2:444-475.

Seyfried, M.S., and M.D. Murdock. 2001. Response of a new soil sensor to variable soil, water content, and temperature. Soil Sci. Soc. Am. J. 65:28-34.

Seyfried, M.S., and M.D. Murdock. 2004. Measurement of soil water content with a 50-MHz soil dielectric sensor. Soil Sci. Soc. Am. J. 68:394-403.

Šimůnek, J.S., M. Sejna, and M. Th. van Genuchten. 1999. The HYDRUS-2D software package for simulating the two-dimensional flow of water, heat, and multiple solutes in variably-saturated porous media, IGWMC-TPS 53, Version 2.0, International Ground Water Modeling Center, Colorado School of Mines, Golden, Colorado, USA.

Stieber, T.D., and C.C. Shock. 1995. Placement of soil-moisture sensors in sprinkler irrigated potatoes. American Potatoe J. 72(9):533-545.

Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. Water Resour. Res. 16:574-582.

Topp, G.C., D.R. Lapen, G.D. Young, and M. Edwards. 2001. Evaluation of shaft-mounted TDT readings in disturbed and undisturbed media, Second International Symposium and Workshop on Time Domain Reflectometry for Innovative Geotechnical Applications, Available at: http://www.iti.northwestern.edu/tdr/tdr2001/proceedings/ (verified 4 May 2005). Infrastructure Technology Institute-Northwestern University, Evanston, Illinois.

Topp, G.C., and T.P.A. Ferre. 2002. Water Content, p. 417-545, In J.H. Dane, and G.C. Topp. ed. Methods of Soil Analysis Part 4 Physical Methods. Soil Sci. Soc. Am. Inc., Madison, WI, USA.

Improved Sprinkler Uniformity Can Save Water and Energy

In 2003, a sprinkler irrigation efficiency study was conducted by the The Center for Irrigation Technology on behalf of the California Department of Water Resources. The purpose of the study was to determine actual water savings at 6 California golf courses that retrofitted their sprinklers with after market nozzles designed to improve water uniformity.

Superintendents at each of the courses had decided to upgrade their sprinklers with the high uniformity nozzles because of the poor performance of their existing sprinkler systems and the resulting deterioration of the turf quality. One of the participants in the study was the Los Angeles Country Club. Their sprinkler system was operating at a relatively low 55 psi and the un-uniform sprinkler pattern (as evidenced by repeating wet and dry spots between sprinklers) was apparent on every fairway of the 36 hole course. The factory nozzles were tested. The DU and SC were measured at 73% and 1.5. The retrofit nozzles were later tested. The DU and SC improved to 85% and 1.2. After the retrofit, turf quality was noticeably improved.

Using the SC method, average water savings at all six courses was estimated at 30% and the DU method was estimated at 9%. The case study actually proved that the average water savings was 6.5%. Individual golf course water savings ranged from positive 21.4% to -11.3%. The extreme range of savings between courses was due to the fact that a lack of uniform irrigation forces irrigation managers to choose one of the following options:

1) To irrigate the dry spots to an acceptable level of green by severely over irrigation the rest of the turf grass.

2) To irrigate the initial development of any wet areas, and severely stressing the drier areas, or

3) To irrigate to the initial development of any wet areas then utilize hand directed watering at considerable expense to irrigate the dry areas to an acceptable level of green color.

None of these three options is desirable. Improved irrigation uniformity may not provide large savings in applied water if the course is generally under-irrigated (large dry areas). However, it is likely to significantly reduce the need for hand-watering, which is inefficient, costly, and disruptive to the golfer.

In reality, the calculated savings align closely to observations made by one of the superintendents who acknowledged consciously reducing ETo by 5% after installing the new nozzles. The course that experienced an increase in water application had suffered such bad uniformity that the superintendent was never able to apply the required amount of water to maintain acceptable turf quality. After the retrofit, the superintendent was able to apply adequate water to the driest zones and subsequently used more water than previously. Such extremes are not common and a substantial water savings can usually be expected.

Return on Investment

None of this improvement in uniformity can persuade a General Manager unless there is a payback on investment. In order to estimate the payback period, we need to know the value of the acre feet saved and the initial investment. A simple payback equation would look something like:

Number of years = Investment / Annual Return

For example, let's assume the one-time investment cost of nozzle replacement at $12,000. The cost of water and energy is $361 an acre foot. The total volume of water saved each year is 16.6 acre feet.

Two years = $12,000

Thus, if a golf course superintendent was operating under the average conditions outlined above, the payback period for investing $12,000 to re-nozzle the sprinkler system would be two years based on the volume and cost of water and energy saved. Water and energy costs higher than this would provide a shorter payback period, while lower water and energy costs would require a longer payback period to recoup the investment. Also, higher or lower initial re-nozzling costs would affect this estimate.

Energy Costs

All water used for the purpose of irrigation in a golf course is pumped. Therefore, every gallon of water delivered tot the field has some energy cost associated with it. The more water and pressure we use, the more energy we consume. Conversely, reducing the amount of water applied and/or reducing the operating pressure will minimize the total cost of energy. During the energy crisis of the 1980's, Toro introduced a low pressure sprinkler that performed well at 50 psi and saved much energy. Operating pressures of today's golf course irrigation systems never drop below 65 psi.

Conclusions

While the numbers present a quantitative view of the benefits of improving irrigation uniformity through selected nozzle changes, the superintendents provided insight into the perceived benefits of a more uniform irrigation system. Selected quotes include:

"Dry spots and wet spots are much less numerous"

“We are able to run sprinkler heads longer without puddling”
”Turf areas had many donuts throughout the course. The new nozzles evenly distributed the water reducing and eliminating this issue on my golf course”
“After installing the new nozzles I was able to reduce the ET demand 5% lower than the previous year.”
”Significantly improved coverage”
“Less water around the head with mud and mess”
“Better performance in higher elevation pressure sensitive areas”
“Well worth the investment”
“It has reduced our hand watering requirements, perhaps savings around $8,000 per year”

Not all the superintendents were able to document a net savings in water and energy from the installation new nozzles, but all five superintendents did see improvements in the quality of their turf grass from better water distribution. They indicated no hesitation in recommending re-nozzling of sprinklers to other superintendents who are facing the same lower uniformity issues seen in the study.

The basic lessons learned were:

1. It is very important to know the distribution uniformity of your existing irrigation system.

2. If improvement is warranted and the existing sprinklers are in good condition, re-nozzling with proven nozzle designs should be considered.

EPA Market Enhancement Program Update

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The EPA has been developing a program to transform the marketplace for water-efficient products. EPA intends to conduct market-enhancement activities to make the efficient use of water an attribute of choice among purchasers of water-using products, and to provide standards for water-efficient products that can be used nationwide. Urban irrigation will be a important area for this program. Adoption of new and existing water-efficient technolgies and practices in irrigation systems provides an opportunity for substantial reduction in water-use in residential and commercial irrigation systems. The presentation will provide an update on the EPA market enhancement program.

How To Design, Implement and Evaluate a Smart Controller System

Tom Ash, HydroPoint Data Systems, Inc., Director of Conservation Alliances, 1726 Corporate Circle, Petaluma, CA 94954

Smart irrigation controllers are touted as the ultimate solution to water conservation, healthy landscapes, and urban runoff control. There are a number of products on the market that claim to work magic with landscape water, but evaluating these products can be time-consuming and requires extensive landscape irrigation expertise. Moreover, despite the significant dollars spent on studies, their results may vary widely depending on study design. In this presentation, the speaker will describe basic requirements for conducting effective studies of smart controller systems.

Using actual cases from successful and unsuccessful controller studies by municipal and private water utilities, the speaker will point to lessons learned and advantages gained so that the audience comes away with a solid blueprint for conducting a successful evaluation. Topics include:Testing requirements · Unsuccessful test case study examples · Successful test case study examples Lessons learned.

PREDICTING WATER SAVINGS WITH WEATHER-BASED IRRIGATION CONTROLLERS

Leslie Martien, and William B. DeOreo, P.E., Aquacraft, Inc Water Engineering and Management, Boulder Colorado

Introduction

Much of the Southwest and Western United States has experienced several years of drought, a burgeoning population, and a growing awareness that long-term water conservation is more effective than short-term restrictions. These factors have resulted in the need for tools to assist landscape designers, irrigation contractors, and homeowners and business owners with ways to reduce water used for irrigation while still maintaining attractive landscapes. Municipalities need tools that will insure that they will continue to have sufficient water supplies to meet their customers' demands.

Weather based irrigation controllers (WBIC) appear to be one of several promising tools currently available for reducing water waste by municipal irrigators. Manufacturers tend to make very optimistic claims about their performance, but there is a need to consider these claims in a critical manner, and evaluate exactly what their real savings potential might be, and under what conditions these savings can be achieved. This paper uses data from the Discovery House, a demonstration house in Loveland, Colorado, to show the role that a *properly installed* WBIC plays in water savings at a residential landscape when used in combination with a water efficient landscape and a good irrigation design.

The combination of water efficient landscape design and properly installed and programmed real-time weather based irrigation control combined with a site-specific theoretical irrigation requirement can be used to achieve significant and reliable water savings over the typical residential landscape. In the paper the authors discuss:

- That water efficiency can be optimized with a weather based irrigation controller only by combining it with a water efficient landscape design and a good irrigation system installation.

- The process of establishing a theoretical irrigation requirement; i.e. a water budget for the site, is essential and will provide a target for irrigation applications.
- The three essential factors (design, installation, and control) that must be considered in order to achieve reliable water savings from a water efficient landscape design.
- The irrigation controller is only one element in a water efficient landscape design, and must be combined with both a good landscape plan and a good system installation to be effective.

The authors worked with a local landscape designer to establish a water budget based on the theoretical irrigation requirement for the landscape, installed a weather based irrigation controller (WBIC) at the site, and tracked water use on a new residential property in the Colorado Front Range during the irrigation season of 2004. The site was used as a case study to evaluate the efficacy of a water budget tailored to the landscape which was calculated with site-specific landscape factors and historic evapotranspiration (ET) data. Irrigation application was adjusted with an onsite, weather-based irrigation controller, using real-time ET.

The Test Home

The home used for this study was named the Discovery House and was built by a homebuilder as part of a demonstration of a range of water and energy efficiency devices. The homebuilder[1] is well known for being innovative and with a strong incentive to offer buyers homes that are as efficient as possible. As one element of the demonstration home the builder hired a landscape architect to design a water efficient landscape.[2] Aquacraft installed a WBIC at the site, programmed it with the proper parameters,[3] and tracked the water used for irrigation over the 2004 irrigation season.

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[1] McStain Neighborhoods, Lafayette, CO, contact Justin Wilson, 303-449-5900.
[2] Nature's Design, Jamestown, CO, contact Becky Martinek, 303-459-3333
[3] WeatherTRAK controller, HydroPoint Data Systems, Petaluma, CA, contact Chris Manchuck, 707-769-9696.

The Landscape Design

The design was aimed at producing a water efficient landscape through the use a variety of trees, shrubs, vines and low water use plants on the majority of the area. Turf was used only in the area where it was most useful for play and aesthetics. The site has an irrigated area of 3,990 square feet with four separate irrigation zones. The two turf zones total 480 square feet (12% of the landscape) and are irrigated with conventional spray heads; the non-turf zones total 3,510 square feet (88% of the landscape) and are irrigated with drip irrigation. The landscape was designed to follow the principles of Xeriscape with careful attention paid to plant selection and placement as well as soil preparation and efficient irrigation design.

Irrigation System Installation

A professional irrigation contractor installed the irrigation system. The system was then evaluated by a trained irrigation auditor for compliance with the design and to insure the proper coverage and distribution uniformity of the spray zones. In addition, the contractor installed a rain sensor that was attached to the irrigation controller.

The Irrigation Controller

Aquacraft installed and programmed the WBIC thereby insuring that all of the program information: soil type, plant type, precipitation rates, and microclimate, were measured correctly and entered separately for each zone. Default values for the precipitation rate were not used; rather the precipitation rates for the spray zones were measured with catch cans and verified by flow rate tests. The precipitation rates for the drip zones were calculated by measuring the flow rate and number of emitters and determining the area of coverage of each emitter.

The WBIC controller used at this site received local ET information via a pager network on a daily basis. The ET data were calculated using a proprietary model developed by the manufacturer that predicts ET at any location. This broadcast ET information was used in conjunction with the horticultural data programmed for the system that then created a real time irrigation schedule and application rate for each zone.

The authors obtained similar data from the nearest ET weather station, operated by the Northern Colorado Water Conservation District to determine the ET_o for the site. These data were used in calculating the water budget as well as the theoretical irrigation requirement that was use to compare the performance of the WBIC discussed later in this paper.

The Tools – Determining Landscape Water Use

Many residential landscapes consist of large areas of cool season turf bordered by shrubs and interplanted with trees. Irrigation systems are often scheduled to run 15 minutes per zone with only minor adjustments to the schedule throughout the season. By comparing the typical irrigation application to this type of site with the theoretical irrigation requirement of a water efficient landscape and irrigation system, predicting the potential water savings from any landscape becomes straightforward.

Developing the Theoretical Irrigation Requirement

The amount of water required to maintain a particular landscape is known as the theoretical irrigation requirement, and over the course of the irrigation season it is used to determine the water budget for the site. There are numerous factors that influence the water requirements for the landscape and these factors must be considered when determining the theoretical irrigation requirement. These factors have been found to have a very significant affect on the amount of replacement water that needs be applied to maintain a healthy landscape. They include:

- Microclimate (K_{mc}),
- Species factor (K_s), and
- Density factors (K_d)

The microclimate can vary significantly from one irrigation zone to the next in a landscape and is affected by wind, shade, reflected heat, and a variety of localized conditions. The species factor represents the rate at which various plant species lose water (transpire) through their leaf and stem surfaces and therefore the amount of replacement irrigation required to maintain the health of the plant. Finally, the density factor refers to the percent of ground covered by plants in a particular irrigation zone. This will tend to increase as the landscape matures.

Once each of these factors is determined for each zone and they are multiplied together to calculate a zone factor, K_z.[4] It is then a simple matter to multiply the historic annual reference ET_o for the site by the zone factor, and divide by the efficiency of the irrigation zone to calculate the theoretical irrigation requirement for each zone. For example, Zone 1 at the Discovery House was a turf zone newly planted with cool season grass. The density factor for turfgrass is 1.0, the microclimate for this zone is 0.95 due to some light shading from some small trees and a fence, and the species factor used was 0.95[5] yielding a zone factor or 0.86. The ET_o (18.7 gpsf) was based on historic weather data obtained from a local weather station for cool season turfgrass. Multiplying the ET_o by the zone factor (K_z) of 0.86 and dividing the result by the irrigation efficiency of 70 percent results in a seasonal water budget for Zone 1 of 5,479 gallons. This process was repeated for each zone and the results are shown in Table 1. The annual theoretical irrigation requirement determines the water budget for the landscape over the course of the entire irrigation system when the zone coefficient K_z is applied to historic ET. The total theoretical irrigation requirement or water budget for this site was 28,178 gallons.

[4]For the purposes of this paper, K_z is equivalent to the landscape factor, K_L, defined by the Irrigation Association as $K_s \times K_d \times K_{mc} = K_L$ for each zone. We refer to the landscape coefficient of the overall site as the ratio of the theoretical irrigation requirement to the reference irrigation requirement.
[5]This is higher than the species factor recommended for "high turfgrass" by the Irrigation Association but was chosen due to the fact that the landscape had just been recently installed and was in the establishment period.

Table 1: Determining the plant water requirement for each zone of test home

	Irrig Area	Plant Type[6]	K_d	K_{mc}	K_s	K_z	ET_o (gpsf)	Irrigation Efficiency	Water Budget (gal)
Zone 1	240	CSG	1.0	0.90	0.95	0.86	18.69	70%	5,479
Zone 2	240	CSG	1.0	0.90	0.95	0.86	18.69	70%	5,479
Zone 3	1,755	HWUS	0.50	0.75	0.63	0.24	18.69	90%	8,610
Zone 4	1,755	HWUS	0.50	0.75	0.63	0.24	18.69	90%	8,610
Total	**3,990**								**28,178**

Reference Water Requirement and Potential Water Savings

The reference water requirement is based on the irrigation requirement for a similar size property planted in cool season turf grass or other plants with a similar K_s. As noted above, the ET for this type of landscape is approximately 30 inches per irrigation season or 18.7 gallons per square foot. This results in a reference water requirement for this 3,990 square foot test site of 74, 573 gallons. Taking difference between the reference water requirement and the theoretical irrigation requirement shows the potential savings that can be achieved from a water efficient landscape. In the case of the Discovery House the potential savings amounts to 74,573 – 28,178 = 46,395 gallons of water per year. Because the reference water requirement is based on the amount of irrigation required on a square foot basis it is possible to predict the savings for an entire landscape or on a zone-by-zone basis. Table 2 shows the information that must be known or calculated in order to predict the water savings for any landscape.

Table 2: Reference ET_o and theoretical irrigation requirements for test site

Reference ET_o	ET_o	Inches	30
ET Application Rate	ET_o	Gpsf	18.69
Irrigated Area	A_i	square feet	3,990
Reference Water Requirement	ET_{req}	Gallons	74,573
Theoretical Irrigation Requirement	V_t	Gallons	28,178
Predicted Savings		Gallons	**46,395**

[6] CSG – cool season grass; HWUS – high water use shrubs

Landscape Coefficient

The landscape coefficient is the *ratio* of the theoretical irrigation requirement to the reference requirement. In other words, the landscape coefficient is the percentage of the water used by a standard bluegrass lawn required to maintain the particular landscape at the site. The landscape coefficient of the Discovery House yields was 0.38. The landscape coefficient can be calculated for any site using this method and provides municipalities with an excellent predictive tool of water needed for landscape irrigation in relation to a standard value.

Weather Based Irrigation Control

When a landscape is irrigated efficiently the application of water should match the requirements of the plants in the landscape over the entire irrigation season. Since ET varies over the season, so will the irrigation requirement. By looking at the historical ET over several years one can develop seasonal water requirements. Calculating the theoretical irrigation requirement on a real-time basis serves several purposes:

- It takes into consideration fluctuations in historic ET_o which is simply an average of the ET data gathered over a period of several years.
- It can provide a tool for making percent adjustments to the irrigation controller on sites that are not equipped with a WBIC
- It provides a means of monitoring the irrigation application throughout the season

responded to changes in ET. The actual application rate was lower because the WBIC was programmed for to match the actual landscape not cool season grass. The high application rate early in the season took place during the installation of the new landscape and was the result of a manual override on the WBIC.

Figure 1 is a graph of the actual water applied at the discovery house over the 2004 irrigation season. The bottom line shows the actual application and the top line shows the reference requirement based on cool season grass. With the exception of the start of the season when the system was catching up, the figure shows how closely the WBIC responded to changes in ET. The actual application rate was lower because the WBIC was programmed for to match the actual landscape not cool season grass. The high application rate early in the season took place during the installation of the new landscape and was the result of a manual override on the WBIC.

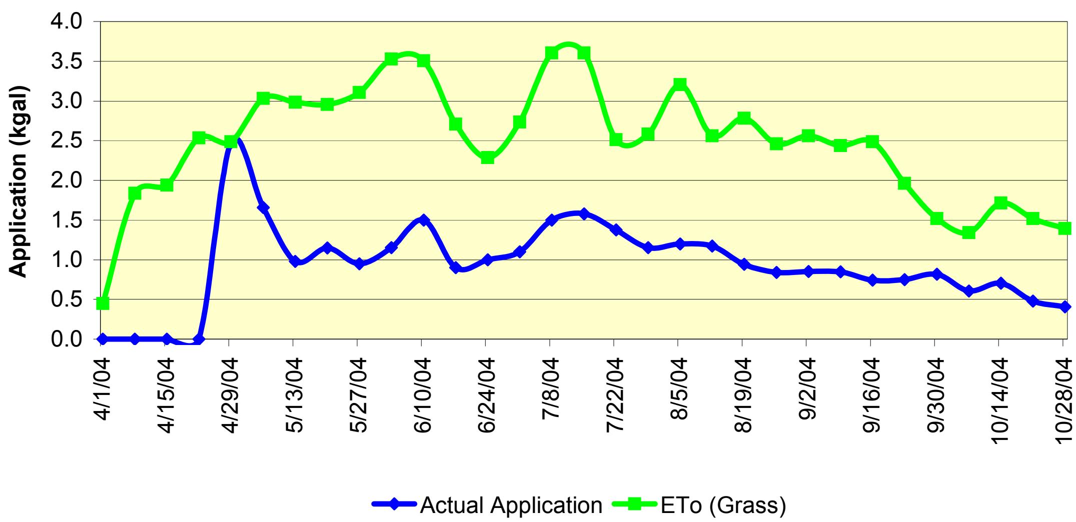

Figure 1: Weekly application versus ET_o for the Discovery House

The Savings – Analysis of the Results

Of particular interest to municipalities is whether or not predicted savings are achievable. In order to avoid or at least reduce the need for severe restrictions during times of drought, water suppliers can more readily predict residential water demand during the peak irrigation season if a water budget has been developed for a site.

Tracking Water Use

The theoretical irrigation requirement was calculated for the Discovery house site over the entire irrigation season on a weekly basis. This was the water budget for the site and was calculated by multiplying the landscape coefficient of the site (38%) by the weekly

ET_o. Weekly meter readings obtained by the builder were used to determine the actual application. Irrigation at this site began on April 22 and continued through October 28, 2004. Tracking water use at this site was simplified due to the fact that the house was unoccupied during the period of this study and therefore all metered water could be attributed to irrigation. The fact that the house was unoccupied also insured that no changes were made to the programming of the WBIC. Also, the water meter data were provided by the builder, there were no occupants to perform manual "adjustments" to the system, and Aquacraft never visited the site during the irrigation season. This provided us with a good test case of how the system ran in an unsupervised mode.

In Figure 2 the weekly theoretical irrigation application for the test site was plotted against the actual application. This shows a very close correlation between the predicted water use for the site and the water that was actually applied. The only period where the actual application was significantly different than the theoretical requirement was during the start up phase at the beginning of the season. At this time it was assumed that the soil moisture was depleted and additional irrigation was needed to meet the plant requirements.

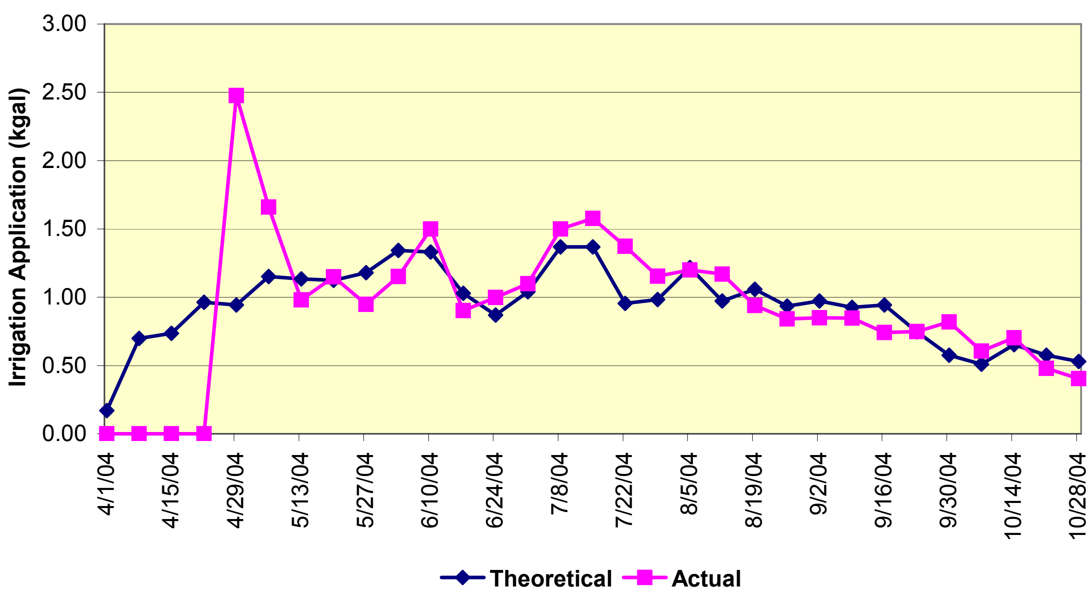

Figure 2: Theoretical requirement based on real-time ET_o versus actual irrigation application

At the end of the irrigation season the actual irrigation application for the site was 28,820 gallons and the theoretical requirement was 29,010 gallons – a difference of less than one percent. A standard landscape would have required over 75,000 gallons, so the Discovery home saved over 46,000 gallons of water (0.14 af).

Conclusion

Increasingly, it is becoming the responsibility of landscape and irrigation professionals to provide homeowners with water efficient landscapes, good irrigation systems and intelligent irrigation controllers. Minimizing water use for irrigation, while maintaining a high quality landscape appearance, is a good way for conserve urban water supplies. Both the demand and supplies problems can be addressed by use of new technology.

Weather based irrigation technology is a promising tool for increasing efficient irrigation. The results of this study make it clear, however, that a weather based irrigation controller is fully capable of applying the appropriate amount of water for irrigation when properly programmed. It is less clear that simply installing and programming a WBIC will necessarily result in significant savings unless it is used in conjunction with a good water efficient landscape design and an appropriate irrigation budget. In fact, in many cases a WBIC may result in water use increasing.

The Discovery House used only 38% of the irrigation water that a comparable house with a standard blue grass lawn would have used. This represents a savings of 62% from a standard design, or over 46,000 gallons of water per year. These saving could be used to support other development or maintain a storage reserve in the system reservoirs.

Creating a water budget for a landscape is essential to manage water use. Factors such as plant type, microclimate, and plant density must be considered an integral part of the calculating the water budget (or theoretical irrigation requirement) for the landscape.

Developing a landscape water budget will help homeowners, landscape and irrigation professionals, and utilities gauge the amount of water that is needed to maintain a healthy landscape, and how well their irrigation systems are performing in matching the actual applications to the theoretical requirements.

Using the landscape coefficient and theoretical irrigation requirement to develop a water budget provides homeowners with a way to gauge and track water use on their landscape and is an excellent way of alerting them to potential problems with their irrigation system.

The fundamentally fact must be emphasized that no technology, no matter how elegant, can optimize irrigation water use. Only when all of the components of efficient irrigation are used together will we be able to maximize the savings from landscape irrigation. Without a water efficient design the system will never be able to make major savings from reference requirements. A poorly constructed system, with poor distribution uniformity will force owners to choose between efficiency and a attractive appearance. A controller that does not adjust irrigation applications to match actual requirements will just represent a liability. On the other hand, a water efficient design in combination with a good irrigation system and an intelligent controller can achieve major saving, like those demonstrate in this case study.

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