TECHNICAL SESSION PROCEEDINGS

Irrigation
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Catch3D for Evaluating Sprinkler Catch-Can Data

G.P. Merkley[1] and R.G. Allen[2]

Abstract

A new version of a computer program, called “Catch3D,” to evaluate sprinkler catch-can data and water application uniformity has been developed as a 32-bit application with a redesigned interface and new capabilities. Catch3D provides spreadsheet-style interactive data editing, complete statistical data analysis, and a rotatable 3-D view of overlapped and non-overlapped test values. Catch-can values may be arranged in a grid or one or more radial legs, and the application can handle center pivot data analysis, with dynamically-allocated memory features to accommodate even the largest data sets. The program can read and write data to text files, the Windows® “clipboard,” compressed files, and formats used by other programs. English, Spanish, and Portuguese language interfaces are included, as well as numerous other options. The program is available free of charge from a web site, but with a suggested nominal registration fee.

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Introduction

A computer application called "Catch-3D" with a text-based interface was developed in the 1980's by Richard G. Allen (1995) to statistically analyze sprinkler catch-can data for agricultural irrigation systems. The program allowed convenient comparisons of unoverlapped and overlapped water application profiles, using different statistical indices of uniformity and application efficiency, and also included a color-coded wireframe graphical representation of the data. Other computer programs have been developed in recent years by various individuals and organizations for comparing sprinkler nozzle packages, sprinkler spacings, pressures, and other factors which affect application uniformity and efficiency. Some of the programs are primarily oriented toward sprinkler systems for landscape irrigation, while others focus on features found in agricultural sprinklers.

The authors of this paper have collaborated on the development of an entirely new version of the Catch-3D software with a fully graphical interface and several new features, yet retaining the emphasis on application to the analysis of agricultural sprinkler systems. The new version of the program is described herein. The software and accompanying user's guide are currently available as a free download from a web site at http://www.irri-net.org/merkley/index.htm.

Evaluation of Sprinkler Irrigation Performance

The evaluation of sprinkler irrigation performance is usually accomplished by one or more measures of water application uniformity and or water application efficiency indices. So-called "catch-can" containers (Fig. 1) have traditionally been used to measure depth or volume of water, as applied through one or more sprinklers, with statistical methods applied to the analysis of the data. The resulting performance indices are used to compare with the same indices from previous times, with other sprinklers and or nozzles, with different environmental conditions (e.g. wind, humidity, air temperature), and or with sprinklers in differing installations. Performance indices can also be evaluated based on absolute criteria, such as minimum coefficient of uniformity, when available and appropriate. Theses indices can then lead to the identification of ways in which sprinkler performance might be improved through equipment and or operational changes, allowing for the possibility of improved water management and increased agricultural productivity under sprinkler irrigation.

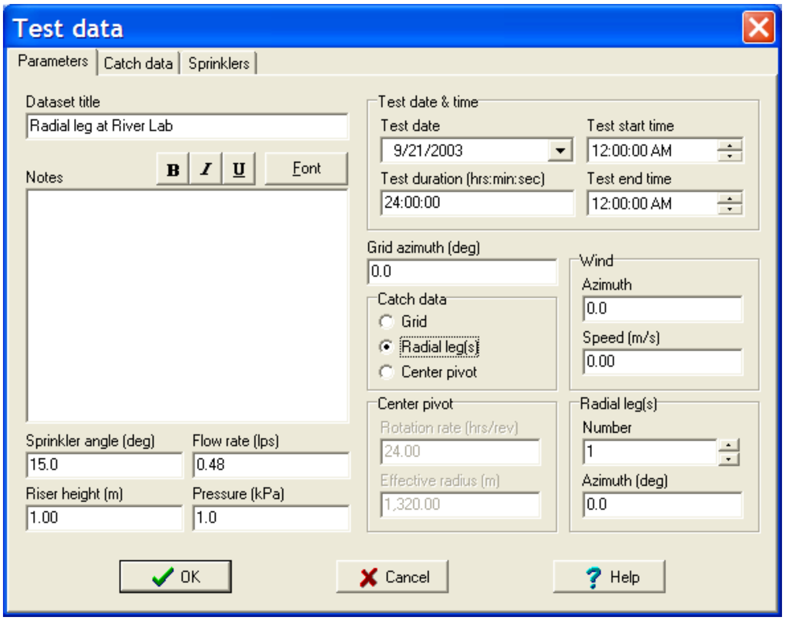
Figure 1. A catch-can test of a single sprinkler in the field.

Software Features

The software comes in only one version, but with a number of interface and technical options. The user can choose from English, Spanish, and Portuguese languages. The system of units can be metric or English, and catch data can be entered in milliliters, centimeters, or depth. When the catch data are in milliliters, the program converts volumes to depths according to a specified container opening area or diameter. Various field test parameters can be recorded in the program (Fig. 2), some of which are used in calculations and other for purposes of reference and documentation.

Catch data can be entered in Catch-3D through a spreadsheet-like grid of cells (Fig. 3). The Microsoft® Windows© clipboard can be used to transfer catch data to and from Catch-3D from spreadsheet or text editing software applications. This allows for convenient "cutting" and "pasting" of data values between applications, which can be useful for data entry, editing, graphing, and analysis.

Catch-can data can be imported into the program in two other common formats. Sprinkler evaluation data sets used in the Space Pro™ program (Oliphant 2001) can be imported into Catch-3D and analyzed. Many such files are available from a web site maintained by the Center for Irrigation Technology in Fresno, California: http://cati.csufresno.edu/cit/good/profiles.html. Data files from the previous versions of Catch-3D are also recognized and can be imported directly into the new version of the software for data analysis and display.



Test data

Dataset title: Radial leg at River Lab

Notes:

Test date & time
Test date: 9/21/2003
Test start time: 12:00:00 AM
Test duration (hrs:min:sec): 24:00:00
Test end time: 12:00:00 AM

Grid azimuth (deg): 0.0

Catch data
○ Grid
● Radial leg(s)
○ Center pivot

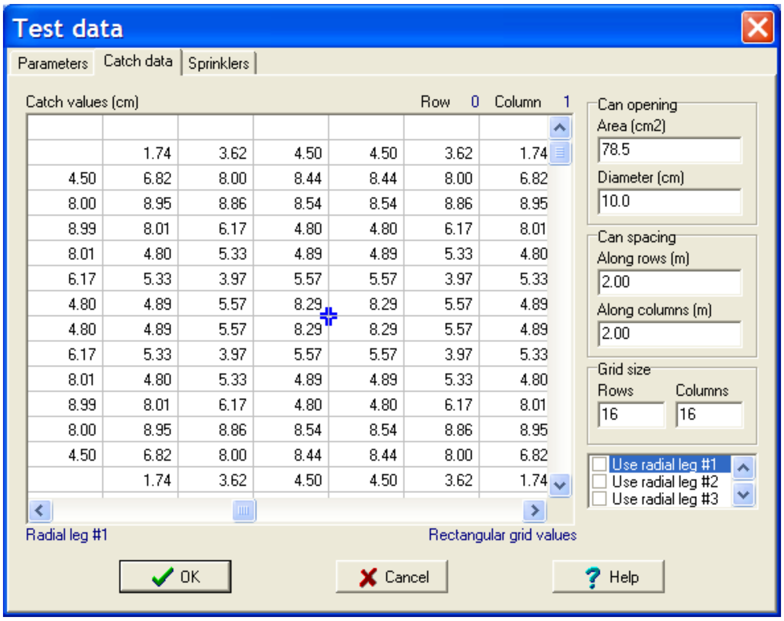
Wind
Azimuth: 0.0
Speed (m/s): 0.00

Center pivot
Rotation rate (hrs/rev): 24.00
Effective radius (m): 1,320.00

Radial leg(s)
Number: 1
Azimuth (deg): 0.0

Sprinkler angle (deg): 15.0
Flow rate (lps): 0.48
Riser height (m): 1.00
Pressure (kPa): 1.0

Figure 2. Catch-3D parameters window.



Test data

Catch values (cm)
Row 0 Column 1

	1.74	3.62	4.50	4.50	3.62	1.74
4.50	6.82	8.00	8.44	8.44	8.00	6.82
8.00	8.95	8.86	8.54	8.54	8.86	8.95
8.99	8.01	6.17	4.80	4.80	6.17	8.01
8.01	4.80	5.33	4.89	4.89	5.33	4.80
6.17	5.33	3.97	5.57	5.57	3.97	5.33
4.80	4.89	5.57	8.29	8.29	5.57	4.89
4.80	4.89	5.57	8.29	8.29	5.57	4.89
6.17	5.33	3.97	5.57	5.57	3.97	5.33
8.01	4.80	5.33	4.89	4.89	5.33	4.80
8.99	8.01	6.17	4.80	4.80	6.17	8.01
8.00	8.95	8.86	8.54	8.54	8.86	8.95
4.50	6.82	8.00	8.44	8.44	8.00	6.82
	1.74	3.62	4.50	4.50	3.62	1.74

Can opening
Area (cm2): 78.5
Diameter (cm): 10.0

Can spacing
Along rows (m): 2.00
Along columns (m): 2.00

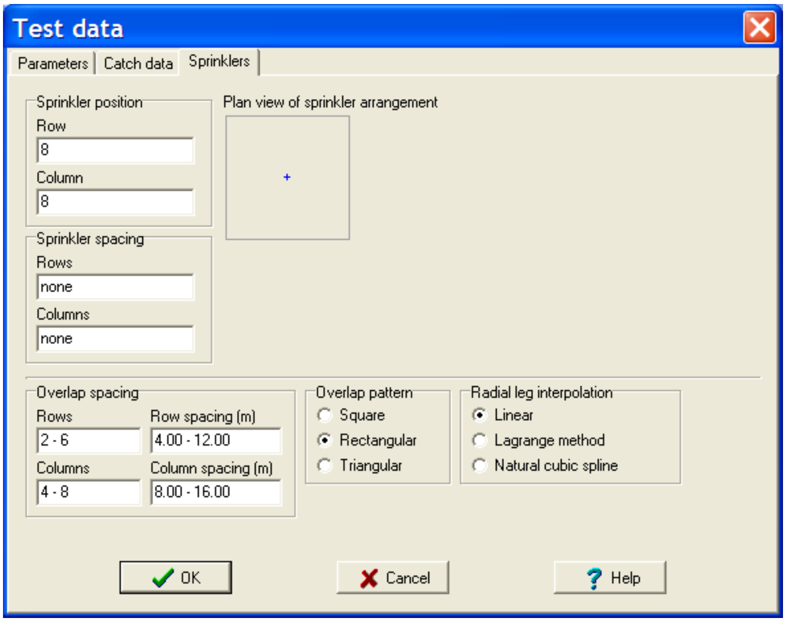
Grid size
Rows: 16
Columns: 16

☐ Use radial leg #1
☐ Use radial leg #2
☐ Use radial leg #3

Radial leg #1
Rectangular grid values

Figure 3. Catch-3D catch data window.

Simulated catch data overlap can be generated for one or more sprinkler overlap spacings by specifying single values or ranges for rows and columns. Alternatively, the user can specify single values or ranges for distances, in meters or feet, between sprinklers (Fig. 4). Sprinkler overlap patterns can be simulated for square, rectangular, and triangular spacings. The sprinkler position can be entered into the grid to indicate its location. When a row or column of sprinklers, such as along a lateral pipe, are used for a catch-can evaluation, those data can also be entered to show the arrangement of the sprinklers. This can be taken one step further to allow for a full grid of sprinklers in a sprinkler performance evaluation.



Sprinkler position
Row: 8
Column: 8

Sprinkler spacing
Rows: none
Columns: none

Overlap spacing
Rows: 2 - 6
Row spacing (m): 4.00 - 12.00
Columns: 4 - 8
Column spacing (m): 8.00 - 16.00

Overlap pattern
○ Square
● Rectangular
○ Triangular

Radial leg interpolation
● Linear
○ Lagrange method
○ Natural cubic spline

Figure 4. Catch-3D sprinklers window.

Sprinkler performance evaluations are often based on one or more radial legs of catch containers, instead of a full rectangular grid, so as to reduce the time and effort involved in the data collection. Data from up to four radial legs of catch-can containers, centered at a single sprinkler location, can be entered into the Catch-3D program, and then automatically rotated to produce a rectangular grid of approximate catch values. When multiple radial leg data are available, the data from each leg are interpolated according to the azimuth angle of the leg to produce a smooth, rectangular grid of application depth values. Interpolation between catch values along each radial leg, as applied to the generation of a rectangular grid of data, is selected by the user from these options:

1. Linear
2. Lagrange method
3. Natural cubic spline

The performance indices produced by Catch-3D include the following:

1. Christiansen’s Coefficient of Uniformity (CU)
2. Distribution Uniformity (DU)
3. Standard deviation
4. Kurtosis
5. Skew
6. Application efficiency of the low ¼ (AELQ)
7. Application efficiency of the low ½ (AELH)

A coefficient of uniformity equation, as found in ASAE's Standards (1994), number S436, is included in the program for the evaluation of catch data from center pivot sprinkler systems. For detailed technical descriptions of the above indices, the interested reader can consult one or more of these publications: Merkley & Allen (2003), ASAE (1994), Keller & Bliesner (1990), and Merriam & Keller (1978), among other references on the subject.

The effective portion of the applied water (Keller & Bliesner 1990), which takes into account water losses due to wind drift and evaporation, is estimated based on the flow rate from the sprinkler(s), the duration of the test, and the calculated volume of water that arrived at the catch-can containers during the same period of time.

The program provides fully rotatable three-dimensional wireframe views of both raw (unoverlapped) and overlapped catch data. Coordinate rotation is achieved intuitively and interactively through mouse movements in the main window of the program whereby problems such as "gimbal-lock," which can eliminate a degree of freedom in 3D rotation, is avoided through the use of an algorithm based on quaternions. The wireframe view can be in black and white or colored, and can also be presented on the screen as a solid surface. The vertical scale can be exaggerated, if desired, in order to highlight the detail of the variations in water application depth from a catch-can data set. The user can also zoom in and out on the 3D view, and shift the view position left, right, up, and down. Figure 5 shows an example of a wireframe view in Catch-3D, in which a catch-can test produced results for a sprinkler operating at an insufficient pressure, giving a "donut" or partial torus shape to the profile.

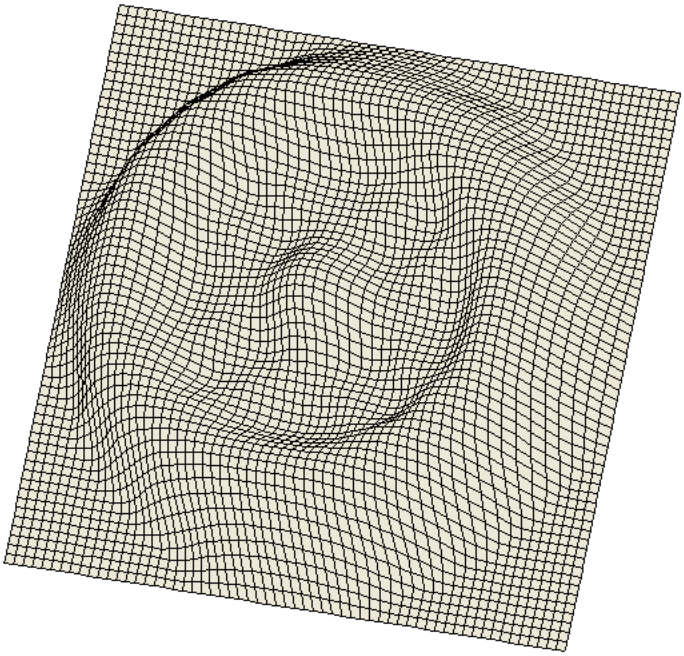


Figure 5. A wireframe view of a grid of catch-can values.

Other data views include a normal distribution curve superimposed upon a histogram of ranked catch data (unoverlapped or overlapped) and a text-based display of the performance indices. The user can toggle repeatedly between the three main views for the unoverlapped data and for any of the overlap patterns that might have been generated.

The fineness of the catch-can grid can be repeatedly doubled in the program through the application of bicubic spines which interpolate between existing grid points to increase the mesh density. This can allow for the analysis of more sprinkler overlap possibilities, especially when the catch containers are spaced far apart. It allows for a more uniform graphical representation of overlap profiles of different sprinkler spacings which would inherently contain different grid densities.

Sprinkler evaluation results can be written to a text file or printed, with options for the types of indices which can be included. Graphical views of water depth profiles and histograms can also be directly printed from Catch-3D, or files with the same graphical information can be created in two common formats.

Summary

A new version of the Catch-3D software was written for the analysis and display of sprinkler catch-can data. Several performance indicators are generated by the software for unoverlapped and overlapped depth profiles, with three main data views, including a rotatable three-dimensional wireframe representation of a grid of water depth values. The new version of the software is available as a free download from http://www.irri-net.org/merkley/index.htm.

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Water Resource Development and Irrigation Management For Sprinkler and Subsurface Drip Irrigation

Larry M. Curtis, Charles H. Burmester, David H. Harkins,
B.E. Norris, James W. Baier, Wheeler Foshee

Cotton is a major agricultural commodity in the Tennessee Valley of North Alabama. Annual yield fluctuations are quite common and often these fluctuations are related to drought or irregularly distributed rainfall. With financial and technical support from the Tennessee Valley Authority (TVA), an irrigation research and demonstration facility was constructed in 1995 at an Auburn University Research and Extension Center (TVREC) located in that part of the state. This facility is being used to evaluate the potential for enhanced irrigation water resources, to evaluate water quality in an off stream storage reservoir and to conduct research related to water management alternatives for sprinkler and subsurface drip irrigated cotton. Using this facility, water quality analysis and irrigation research has been underway since 1996 with data reported for 1998 through 2002.

Three experiments involving application and use of sprinkler and subsurface drip irrigation on typical silty clay loam soils for cotton production are ongoing at the Tennessee Valley Research and Extension Center, Belle Mina, Alabama. *

The experiments are as follows:

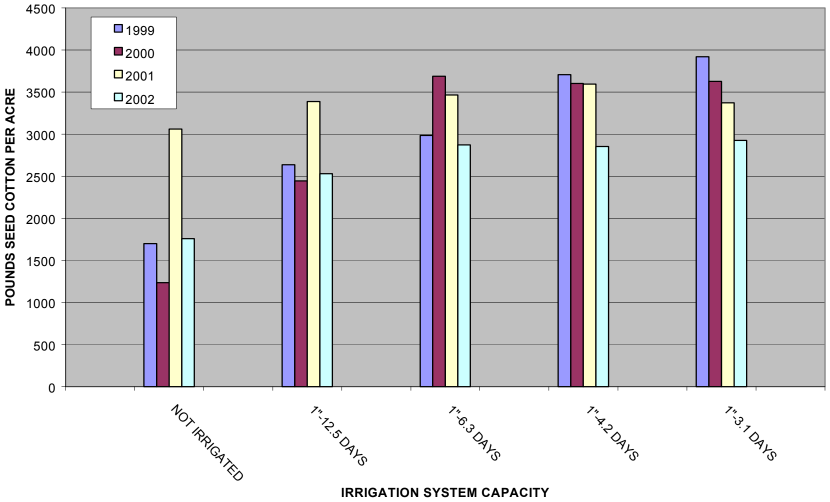
Experiment 1. Sprinkler irrigation water requirements and irrigation scheduling. This experiment was established in 1999 to evaluate a range of irrigation application capabilities to identify the minimum design flow rate that will produce optimum yields. Treatments included four sprinkler irrigation capabilities and a non-irrigated treatment. Irrigation was managed using soil moisture sensors and Moiscot (a spreadsheet-based scheduling method). The irrigation capabilities 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. This one inch represents the maximum amount of irrigation that could be applied in the time indicated.

The results for 1999, 2000, 2001, and 2002 are presented in Figure 1. The 2002 data presented is not directly comparable because the experimental design was changed in 2002. Irrigated yields in 2002 were significantly higher than non-irrigated yields but the highest yields were less than in previous 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.

Least Significance Difference (LSD) Test—LSD Tests (on a year by year basis) for each year are indicated below. Treatment means (# seed cotton per acre) within columns followed by the same letter are not significantly different, P≤0.05.

	Year		
Treatment	**1999**	**2000**	**2001**
Non-Irrigated	1699.1 A	1236.0 C	3061.3 B
1”-12.5 Days or 1.5 GPM/Acre	2636.7 A	2443.7 B	3386.3 AB
1”-6.3 Days or 3.0 GPM/Acre	2984.3 B	3688.3 A	3466.0 A
1”-4.2 Days or 4.5 GPM/Acre	3708.0 B	3603.0 A	3594.7 A
1”-3.1 Days or 6.0 GPM/Acre	3920.0 C	3626.3 A	3371.3 AB

SPRINKLER IRRIGATION
COTTON YIELD RESULTS
FIGURE 1



Experiment 2. Subsurface drip irrigation (SDI) placement and irrigation water requirements. This experiment was initiated in 1998 to evaluate placement of SDI relative to crop row direction and to evaluate water requirements for cotton production using SDI. Drip tubing was buried 15 inches deep with emitters at two-foot intervals along the tubing. Tubing placement treatments were (1) between every other row—80 inch spacing between drip lines and (2) perpendicular to rows –80 inch spacing between drip lines.

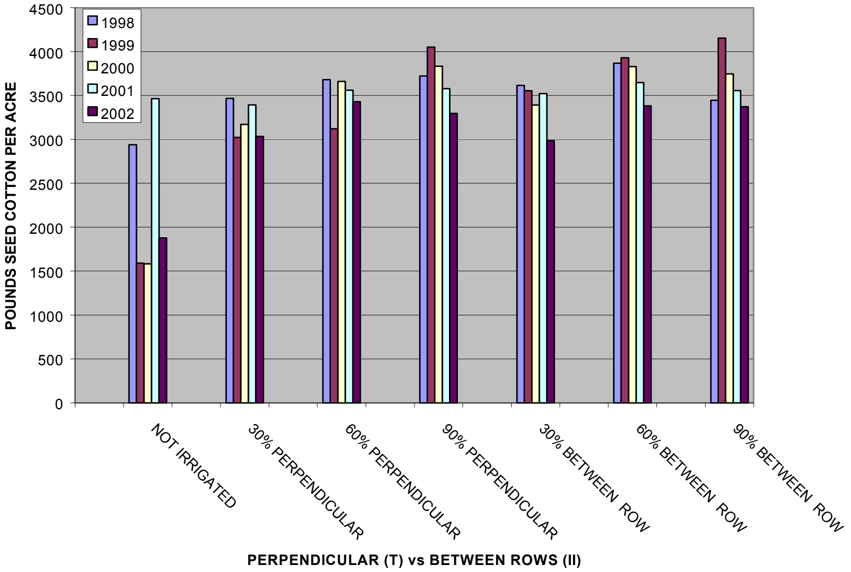
Irrigation treatments were based on daily applications equal to 30%, 60%, and 90% of pan evaporation after full crop canopy with adjustments based on percent canopy prior to full canopy cover. Yield results for five years (1998 through 2002) are presented in Figure 2.

Significant yield increases were achieved in 1998, 1999, 2000 and 2002 for all irrigated treatments as compared to dry treatments. In years 1999 and 2000, a significant linear yield response was measured for treatments with drip tape perpendicular to rows when daily application amounts increased from 30% to 90% pan evaporation. Also in 1999 and 2000 a similar trend, though not significant was noted for treatments where drip tape was placed between every other row.

Least Significant Difference (LSD) Test-LSD (on a year by year basis) for each year are indicated below. Treatment means (# seed cotton per acre) within columns followed by the same letter are not significantly different, $P \leq 0.05$.

	Year				
Treatment	**1998**	**1999**	**2000**	**2001**	**2002**
Non-irrigated	2846.3 B	1599.8 C	1624.5 C	3512.3 A	1891.3 B
30T	3469.0 A	3023.8 B	3170.8 B	3393.8 A	3034.5 A
60T	3680.8 A	3123.0 B	3660.8 AB	3560.3 A	3429.0 A
90T	3722.5 A	4053.5 A	3834.8 A	3580.0 A	3298.3 A
30II	3614.8 A	3556.3 AB	3391.5 AB	3522.3 A	2986.3 A
60II	3868.0 A	3930.0 A	3830.3 A	3647.3 A	3382.0 A
90II	3446.0 AB	4155.0 A	3747.8 AB	3557.3 A	3374.0 A

DRIP PLACEMENT AND IRRIGATION SCHEDULING
FIGURE 2



Experiment 3. Subsurface drip irrigation (SDI) tape products and fertigation. A SDI study initiated in 1998 was designed to compare five different drip irrigation tape products with a fertigation component included. This study was installed in an area where continuous crops have been produced for many years. Emitters were located two feet along the tape with tape buried 15 inches between every other row. Rows 340 feet in length were used to better simulate field conditions. Fertilizer management for each tape product was evaluated using a single (conventional) surface applied sidedress versus multiple sidedress applications injected through the SDI system. A tape product was also used on the surface using a conventional fertilizer treatment. Fertility treatments are indicated below:

	---------------------------**Irrigated**---			**Non-irrigated**
	Fertigated	Conventional	Drip tape on surface[2]	
Preplant	75#N + 60#K	75#N + 60#K	75#N + 60#K	75# + 60#K
Sidedress[1]	60#N + 60#K	60#N + 60#K	60#N + 60#K	60#N

[1] All sidedress was applied at early to mid square for conventional and drip tape treatments; the sidedress treatment was divided into eight equal applications for the fertigated treatments beginning at early to mid square.

[2] The surface tape treatment was discontinued after 2000 because of damage and leaks caused by insects and animals.

In 1998 little difference between fertility treatments was observed. In 1998 sufficient rainfall occurred late in the growing season so that fertilizer in the upper layers of the soil was more readily available. In 1999, extremely dry conditions in the upper layers of the soil profile made conventional applied fertilizer less available resulting in yield reduction compared to fertilizer applied through the irrigation system. In 2001 initiation of fertigation through the tape was inadvertently delayed more than two weeks. Even though the fertigation schedule was modified to insure that all scheduled fertilizer was applied, the delay reduced fertigated yields. Yields in 2002 were similar to previous years with little difference in fertilizer treatments but significant yield improvement over the non-irrigated treatment.

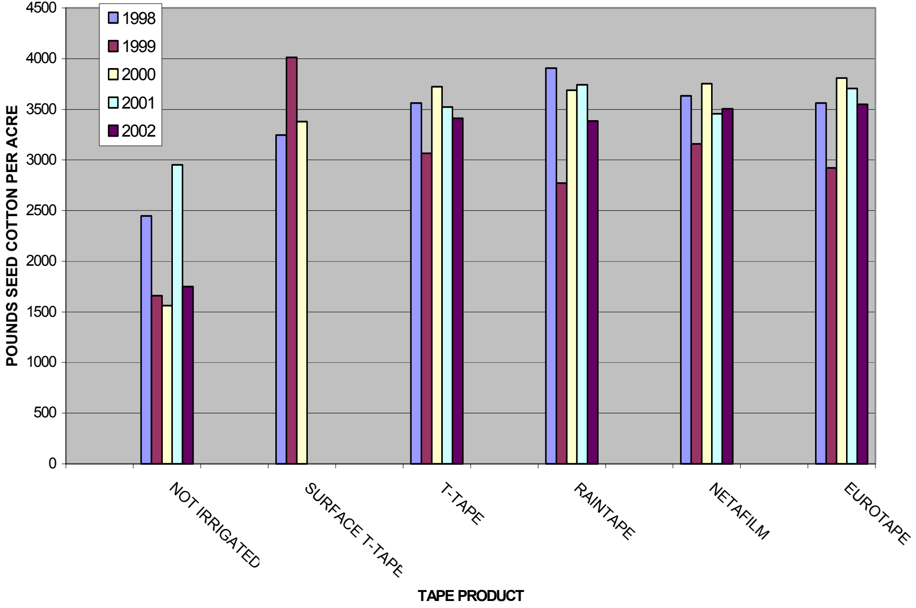
Significant yield differences were observed each year between non-irrigated plots and tape plots with fertility treatments. Figures 3 and 4 illustrate yield results for 1998 through 2002 for conventional and fertigated treatments. To date only minimal differences have been observed between the different drip irrigation tape products.

Least Significance Difference (LSD) Test—LSD Tests (on a year by year basis) for each year are indicated below. Treatment means (# seed cotton per acre) within columns followed by the same letter are not significantly different, P≤0.05.

Treatment		**Year**				
Tape Product	**Fertility**	**1998**	**1999**	**2000**	**2001**	**2002**
Non Irrigated	Conventional	2448.0 D	1658.8 E	1561.3 C	2950.0 E	1749.0 B
Surface T-Tape	Conventional	3244.5 C	4013.8 AB	3377.5 B	-	-
T-Tape	Conventional	3561.5 B	3064.8 C	3723.5 AB	3521.5 AB	3411.3 A
Rain Tape	Conventional	3904.8 A	2770.0 D	3689.8 AB	3742.5 A	3386.8 A
Netafim	Conventional	3633.8 AB	3153.8 C	3752.5 AB	3454.5 ABC	3506.0 A
Eurotape	Conventional	3563.3 B	2922.8 DC	3810.3 A	3704.8 A	3548.3 A
T-Tape	Fertigated	3543.3 B	3956.8 AB	3550.3 AB	3175.8 EDC	3329.8 A
Rain Tape	Fertigated	3769.8 AB	4183.0 A	3569.8 AB	3137.3 ED	3563.5 A
Netafim	Fertigated	3699.3 AB	3844.0 B	3685.0 AB	3315.3 BDC	3542.3 A
Eurotape	Fertigated	3743.8 AB	4061.5 AB	3651.0 AB	3329.5 BDC	3555.8 A

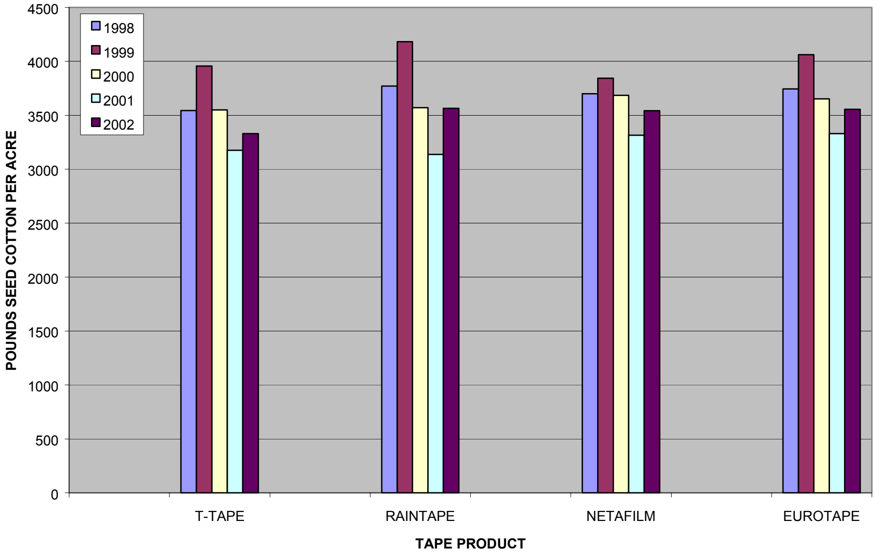
DRIP TAPE COMPARISON CONVENTIONAL FERTILITY PROGRAM AND TAPE COMPARISON

FIGURE 3



FERTIGATED PROGRAM AND TAPE COMPARISON

FIGURE 4



[*] The variety selections for each experiment are indicated below:

	Variety Selection		
	-Experiment 1- Sprinkler Study	**-Experiment 2-** SDI Placement & Water Management	**-Experiment-3** SDI Tape-Fertigation Study
1998		DPL33B	DPL33B
1999	DPL33B	DPL33B	DPL33B
2000	DPL428B	DPL33B	DPL428B
2001	DPL428B	DPL33B	DPL428B
2002	DPL451BR	DPL451BR	DPL451BR

Affordable Drip Irrigation for Small Farms in Developing Countries

By

Jack Keller[1] and Andrew A. Keller[2]

Abstract: Many farmers in India and elsewhere surface irrigate their small fields with water from wells having small average discharges. They are being assisted in converting to very low-cost drip systems that are non-proprietary and manufactured locally. These drip systems are affordable and payback is quick in view of the reported water savings of 50 to 80 percent and yield increases of 30 to 50 percent. The systems operate at pressure heads of less than 3 meters (10 feet), require minimal filtration, use cheap recycled plastic sub-mains (manifolds), and use simple drip-tape with short lengths of microtubes for emitters. This presentation covers the following aspects of these low-cost drip systems: a) farmers' experiences and profitability; b) technology development and marketing assistance; c) system specifications and component costs; d) local manufacturing requirements and costs; e) system performance characteristics; and f) design tools and procedures.

Background

It is estimated that three-quarters of the farmers in developing countries cultivate less than 2 hectares (5 acres) of land. For example, a typical farm in Bangladesh supports six people on what they can earn and eat from one acre of land. Typically the family income is only $200 to $300 a year, far too little to afford the modern irrigation devices that are often promoted by development experts. However, without improved irrigation, they cannot gain full access to green revolution inputs. Furthermore, many development experts expect that in an open marketplace, small inefficient farms will be taken over by larger and more efficient farms. But in the face of rapid population growth, actual farm size in developing countries is steadily decreasing! The failure of the development community to take these simple facts into account is a major factor constraining emergence of practical solutions to both improved irrigation performance and to hunger and poverty.

About twenty percent of the world's 6 billion people live in families with incomes of less than a dollar a day, and 800 million people regularly go hungry. Roughly eighty percent of this core group of 800 million hungry and poor people live in rural areas in developing countries and earn their livelihoods from agriculture. The green revolution, with its high yielding varieties of seeds combined with access to improved irrigation and fertilizer tripled global grain production and tripled the incomes derived by farmers with sufficient water supplies and relatively large land holdings. But for the most part it left farmers who only have access to small plots of land and limited water supplies standing on the sidelines. (See Postel, et al 2001.)

Introduction

An area of land that can be fully irrigated from a given volume of applied water can be significantly increased by converting from traditional surface irrigation to drip irrigation. Of even greater importance from a basin-wide water resources perspective, the production per unit of water depleted by evaporation, transpiration and salt-loading is often increased by 30 to 50%. Furthermore, the availability of drip irrigation systems in small affordable packages unlocks these potential benefits for literally millions of resource-poor farmers. In addition

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[1] Jack Keller is CEO of Keller-Bliesner Engineering, LLC and a Board member of International Development Enterprises (IDE).

[2] Andrew A. Keller is Vice President of Keller-Bliesner Engineering, LLC and a Professional Associate of IDE.

it opens the potential benefits of irrigation even where water supplies were considered insufficient or too costly to acquire for traditional irrigation methods to be practical.

The drip systems described herein are low-cost, available in small packages, operate at very low pressure, and are easy to understand and maintain. These features are what distinguish them from commercial "state of the art" drip irrigation systems. Compromises are made in operational convenience, manufacturing tolerances, and the uniformity of irrigation applications to achieve these advantages. However, the water conservation and productivity gains from converting from traditional small-scale surface irrigation to low-cost drip irrigation may even be greater than the comparative gains from converting large-scale commercial surface irrigation to state of the art drip irrigation systems.

Systems for Small Landholders

A potential drip irrigation customer who had limited access to capital can purchase an expandable drip system capable of irrigating a garden plot of 20 to 100 m^2 for from \$2.00 to \$10.00. Poor farmers who only have small plots can afford to invest in them and after they gain technical competence and sufficient financial capacity they can use the profit generated to expand the system. These systems are also affordable enough to be attractive to home gardeners with access to small patches of land adjacent to their dwellings (or elsewhere) to invest in them.

The "drip kits" that irrigate 20 to 40 m^2 only need a 20-liter (5-gallon) water supply bucket or tank. For intermediate sized drip kits that irrigate 100 to 400 m^2 (1/10-acre) a 50-to 200-liter water supply tank supported about 1.0 meter (3.3 feet) above the ground is sufficient (see Figure 1). It is practical to manually fill the water supply tanks of such drip kits. However, for larger systems a pumped or gravity fed water supply is needed to either periodically fill the tanks[3], or be directly connected to the sub-main. Still, these low-cost systems are only suitable for irrigating plots of 2 hectares (5 acres) or less.

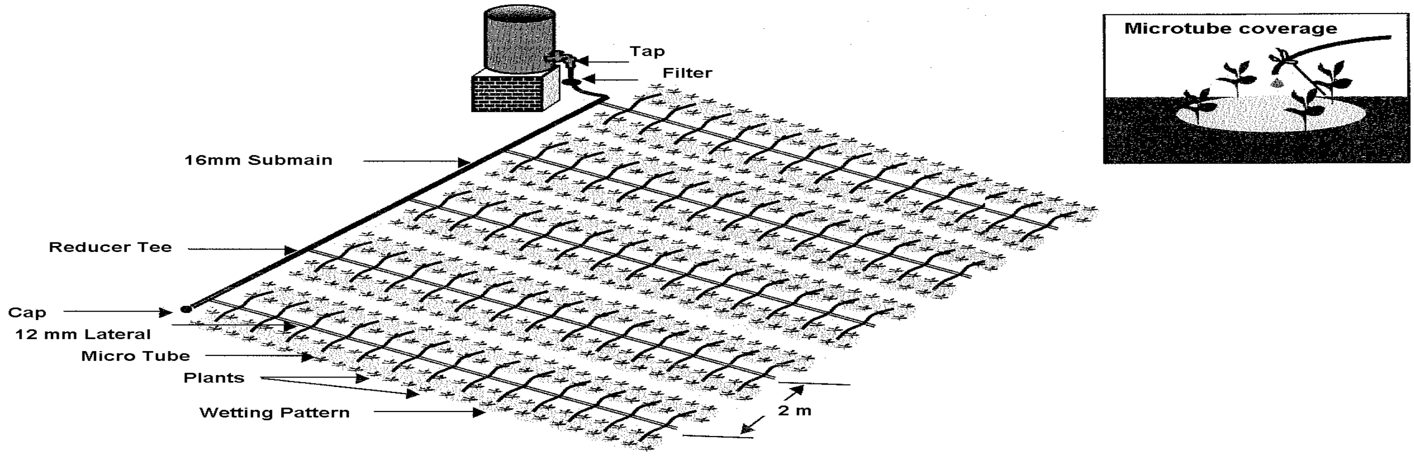

Figure 1. Schematic of a low-cost micro-tube drip irrigation system.

As a Board member (Jack) and a Professional Associate (Andrew) of International Development Enterprises (IDE), we periodically provide technical assistance to IDE-India[4]. A principal objective of IDE-India is to

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[3] Pressure-type manually operated treadle-pumps, which are easily capable of providing enough water to irrigate up to 2,000 m^2 (1/2-acre) of vegetable crops when operated about four hours per day during peak water use periods, are available for roughly \$50.

[4] IDE and IDE-India are non-government development organizations (NGOs). IDE is the international entity and IDE-India is an associated organization that is managed separately and operates mainly in India.

refine, test, and promote *generic* low-cost irrigation technologies. These include low-cost microtube-drip kits (see Figure 1) and customized microtube-drip systems supplied directly from wells. This presentation is focused primarily on the customized low-cost microtube-drip (*L-Cm-drip*) systems. We have used a case study approach that covers the following aspects related to them: farmers' experiences and profitability; technology development and marketing; specifications including manufacturing requirements and costs; performance characteristics; and design tools and procedures.

Farmers' Experiences

In the semi-arid region of the state of Maharashtra, India the average small land holding is less than a hectare (2.5 acres). The following comments are based on discussions that occurred during the past year with over 25 purchasers of the low-cost microtube drip (*L-Cm-drip*) systems promoted by IDE-India[5]. Most of them had previous experience producing vegetable crops (such as tomatoes, eggplant, okra, squash, etc.) using traditional surface irrigation supplied from hand-dug, open wells fitted with electric or diesel powered pumps. Many smallholders were using portable small diameter (63 to 75 mm) flexible or rigid recycled-plastic pipe to convey the water to their vegetable plots. During the dry season their wells produced very little water[6], and the sizes of their vegetable plots ranged from roughly 200 m^2 (1/20-acre) to 2,000 m^2 (1/2 acre). All of the farmers interviewed said the conversion to drip irrigation was very cost-effective and many of them had increased annual net return from additional vegetable production that were several times the investment cost!

Farmers reported yield increases of roughly 50 to 100 percent and decreases in water use of 40 to 80 percent compared to experiences with traditional surface irrigation systems. Their gross returns from the typical vegetable crops grown under *L-Cm-drip* systems ranged between \$0.25 and \$1.00 per m^2 for each crop season, with a typical annual return of roughly \$0.50 per m^2 for a single crop and \$1.00 per m^2 per year for double cropping. The net returns from a given area under double cropping were roughly \$0.50 per m^2 greater under the *L-Cm-drip* systems than with their traditional surface irrigation systems. However, in most cases water was the limiting resource and they have been able to double or even triple the irrigated area by converting from surface to *L-Cm-drip* irrigation[7] and generate increased net returns of \$1.00 per m^2 of newly irrigated land. In addition to the increased crop production they found the *L-Cm-drip* systems to be much easier and less time consuming to operate than traditional surface systems, particularly where water supplies were very limited.

A farmer[8] who also had some regular drip-tape with built in emitters said he knew the uniformity of application from his newly purchased *L-Cm-drip* system was not as good, but he had observed that the water savings and productivity were almost the same. He also noted the sophisticated drip-tape required relatively high pressure heads with careful filtration and special acid treatment to keep it operating properly; but the *L-Cm-drip* system can be operated at much lower pressure heads and it does not need such special filtration and care. Therefore, considering its ease of use and low-cost (less than 20% of a sophisticated system cost) he intends to continue buying *L-Cm-drip* systems to expand his irrigated area. (He also noted that the sophisticated drip-tape would probably last three times as long but it was still not worth the difference in cost.)

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[5] The IDE development strategy focuses on utilizing a business or market approach for assisting farmers with small land holdings (smallholders) in improving their incomes and livelihoods.

[6] A typical hand-dug-open well might only produce 5 to 20 m^3 per day. This will only last for one or two hours of pumping at a rate of 2 to 4 liters per second (30 to 60 gpm).

[7] A note of caution is in order here. By increasing the irrigated area the total water consumed by crop ET will increase proportionally. From a basin-wide water resource perspective this will not increase the production per unit of water consumed if the so called 'losses" from the less efficient traditional surface irrigation were being reused. The losses are only "real losses" if the water is discharged to salt sinks or consumed by salinization or unwanted evaporation and transpiration.

[8] Mr. B. Harat whose farm is near Jalina, Maharashtra.

We observed that microtube clogging was not a problem[9] with any of the *L-Cm-drip* systems in Maharashtra that were using short microtubes with internal diameters between 1.2 and 1.5 mm even though they were being supplied directly from open wells and not equipped with filters. Most of them did not even have simple in-line screens for safety purposes. The few microtube emitters that clogged were simply replaced if flushing did not unclog them.

Expected Longevity of *L-Cm-drip* Systems

We estimate that the longevity of the lay-flat lateral tubing (called drip-tape hereafter) that IDE-India recommends for *L-Cm-drip* systems serving row and vegetable crops is up to four vegetable cropping seasons or roughly two years. The estimated longevity of the heavier wall tubing recommended for horticultural crops is roughly four years. These estimates are based on discussions with IDE-India field agents and the following observations in the field:

- A farmer's[10] experience with a 1.6-hectare (4-acre) field where he has used an *L-Cm-drip* system for three different crop seasons beginning in 2001 (cotton followed by two crops of watermelon). The system was actually operated for a total of 12 months. It had 16 mm diameter drip-tape with a wall thickness of 110 micron (4+ mils). He had just replaced it (in March 2003) with the recommended drip-tape, which has 125-micron (5-mil) wall thickness because the original lateral tubing was mechanically damaged (not because of weathering). He is confident that new drip-tape will last for four cropping seasons or at least two years. He also installed an *L-Cm-drip* system in a banana planting using the recommended heavier 250-micron (10-mil) drip-tape and is confident it will last for four to five years.
- The experience of a farmer[11] who used 140-micron drip-tape with punched holes instead of microtubes. He only had a lateral for every six rows to irrigate his 1-hectare (2.5-acre) lentil field. The drip-tape was shifted six times per irrigations and he applied four irrigations to the lentils. Thus each lateral was moved dozens of times, but the drip-tape is still in excellent condition with practically no signs of deterioration and he was planning on using it in a similar manner next cropping season.

Technical Development and Marketing

The marketing approach to development used by IDE and others is beautifully presented and explained in the Swiss Agency for Development and Cooperation's Report by Heierli (2000). This report includes program descriptions with examples of successes along with the performance indicators used. This and other reports describing the marketing approach to development as well as smallholder irrigation technologies are available on the Small Irrigation Market Network (SIMI-net) web site: http://www.siminet.org/fs_start.htm.

The strategy of subsidizing the cost of conventional drip irrigation systems so farmers with small plots can afford and use them has generally proven to be unsustainable. It has not been a very efficient mechanism for addressing the needs of smallholders, nor has it resulted in the expected improvements in irrigated agricultural performance. For economically sustainable success, the uptake of drip irrigation systems by smallholders should be demand driven and without direct subsidies. Thus the systems must be financially feasible (or affordable), and farmers should be willing to pay the full ongoing cost (including reasonable profit margins) associated with producing and marketing them once the market demand is well established. There are circumstances resulting from extreme poverty, disasters, and socio/economic/political situations when farmers

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[9] A few farmers elected to simply punch holes in their thin wall drip-tape instead of using microtubes as emitters and they were experiencing sever problems with clogging.

[10] The farm is near Jalgon, Maharashtra and it is owned and operated by Mr. Uttam Digambar Bari.

[11] Mr. Narayan Bahi Jeram Bahi Dogariya, whose farm is near Rajkot, Gujarat.

are unable to pay the "full ongoing costs" and are thus subsidized. But experience has generally been that system uptake and continued use are not sustained in such circumstances when the subsidies are discontinued.

General Design Strategy

L-Cm-drip systems provide subsistence farmers with an affordable means for irrigating their small plots in order to reap the associated potential crop production increases and water savings. The general technical and economic criteria IDE-India employed in this successful development effort are:

- The systems are designed around the best available components, with preference given to local manufacturing that only require relatively unsophisticated facilities, but not at the expense of affordability and functionality.
- The assemblage, sales, and service tactics required for the systems are compatible with local micro-enterprises and require limited skill and capital to design, service, and maintain.
- The systems are designed to optimize economic returns based on the availability and opportunity costs of both local capital (which may be higher than 100% per year) and labor (which is often ≥ $1.00/day).
- The income generation potential of the systems (compared to the systems they replace) at least covers the investment cost in one irrigation season.
- The systems are available in a range of small packages (from as little as 20 square meters to a couple of hectares). They are also expandable so the area served can be enlarged as farmers gain confidence in the technology and become more financially capable.
- The systems are simple and easily understood, operated, and maintained by unsophisticated users.
- The required inlet pressure head for *L-Cm-drip* systems ranges from 1 to 4 meters.
- They provide the potential for high irrigation efficiencies and superior crop yields.

Developing the *L-Cm-drip* System Market Demand

Rather than direct subsidies, IDE-India provides what are in effect indirect subsidies to farmers by covering the costs of developing and promoting *L-Cm-drip* systems and establishing the market demand for them. The strategy they used prior to establishing the production capacity and implementing the marketing program included the following:

- Identifying promising technologies that had the potential to improve productivity if packaged for small plots of land and affordable to the potential smallholders. While the *L-Cm-drip* systems may appear simple, developing this affordable and user-friendly product line required inventive concepts followed by talented engineering.
- Promising low-cost drip systems were then field-tested and modified to trim cost, increase functionality, and better address field requirements so they would be more acceptable to smallholders.
- The most promising systems were again field-tested and then market-tested prior to initiating supply chain development and promotional programs for them.
- The design strategy is described above, but it essentially never ends because of remaining possibilities for reducing costs and increasing the functionality of *L-Cm-drip* systems in response to suggestions and insights gained from the manufacturers, dealers, assemblers, and farmers who work with them.

This role played by IDE-India using donor funding was necessary since the *L-Cm-drip* system was designed around more or less generic (without patent protection) components. Thus micro-enterprise manufacturers (or importers and assemblers) and vendors could not have afforded to invest in the necessary product and market development activities because these costs would not be recoverable after the market demand was established. If the innovators attempted to maintain sufficient profits to cover these development costs, competitors would arrive on the scene and undercut their prices. However, this competition is actually a positive aspect of the market creation approach that led to development of the *L-Cm-drip* system. It continuously stimulates inventiveness by attempting to increase cost-effectiveness and functionality.

Specifications and Costs

One might consider the *L-Cm-drip* systems recommended and promoted by IDE-India to be a regression back to systems previously used in the US and elsewhere. This is because the laterals are simple plastic tubing and microtubes are used for emitters. But this is not the whole story of *L-Cm-drip* systems. They represent refinements by utilizing modern plastic technologies, generic off-the-shelf auxiliary components that have been developed for modern drip systems, and various innovations that utilize simple manufacturing techniques and increase layout flexibility.

The ideas underlying the development of *L-Cm-drip* systems resulted form a blend of: a) IDE-India's experience using standard wall polyethylene (PE) tubing with long microtube emitters such that a single lateral could serve two crop rows (see Figure 1); and b) some innovative farmers' experiences using drip laterals made from very thin-wall clear plastic tubing produced for packaging a confectionary treat called "Pepcee or Pepsi". Instead of using emitters, holes are punched in the "Pepcee" tubing with a needle. The resulting water application is not uniform and the tubing begins to disintegrate in a few weeks; furthermore, algae grow in it. But these systems are successful because they only cost about \$0.01 per m^2 (\$40 per acre) and last long enough to germinate a cotton crop six weeks before the monsoon rains begin, which increases yields by 25 to 50 percent.

IDE-India recognized the cost advantages of the "Pepcee" systems but they were not suitable for irrigating a vegetable crop for a full season. So IDE-India focused on blending the cost effectiveness of the thin-wall tubing using modern plastic technologies and microtube emitters with relatively large internal diameters in developing the *L-Cm-drip* systems. The lay-flat tubing is a mixture of linear low density PE (LLDPE) and low density PE (LDPE) with carbon-black so it is strong and resists stress cracking, deterioration from ultraviolet light, and internal algae buildup. Under low operating pressure heads the discharge rates from the microtube emitters are about ideal, clogging problems are minimal, and on relatively level small fields the application uniformity is high. Furthermore, the systems are very affordable, with the laterals plus sub-main (see Figure 1) costing less than \$0.04/m^2 (\$400/hectare or \$160/acre) installed.

Recommended Specifications

The general specifications recommended by IDE-India for *L-Cm-drip* system components are:

- **Lay-flat lateral tubing:**
    - The recommended composition is 80 units of LLDPE, 20 units of LDPE and 2.5 units of Master Batch containing 50% carbon black. Virgin film grade plastic should be used and the tubing scrap should not be recycled in the process, but used for making other products.
    - Recommended wall thicknesses:
        - For regular row and vegetable crops use 125 ± 5 microns (5 ± 0.2 mils); and
        - For horticultural crops (such as banana, vines and fruit trees) use 250 ± 5 microns (5 ± 0.2 mils).
    - The width of the tubing when flat should be 26 ± 0.5 mm, which gives a minimum inflated inside diameter of 16 mm.
- **Microtube emitters:**
    - Recommended internal diameters (IDs):
        - For regular row and vegetable crops use 1.2 mm ID microtubes; and

        - For horticultural crops use 1.5 mm ID microtubes.
    - Recommended microtube lengths:
        - For regular row and vegetable crops use 20-cm (8-inch) long pre-cut microtubes with a tight overhand knot[12] when a lateral is used for each crop row. The microtubes should be 10-cm (4-inches) longer than half the row-width where two rows are served by each lateral as shown in Figure 1.
        - For horticultural tree crops use 1.0 to 1.5 m (3.3 to 5 feet) long tubes. For bananas and papayas use 0.75 to 1.5 m (1.5 to 5 foot) long tubes, depending on the plant and drip-tape spacing and microtube layout. (Typically, there are four microtubes per tree for citrus and deciduous tree fruit and only one per plant for bananas and papayas.
    - Microtubes must be installed in the field when the drip-tape is inflated and inserted so 2.5 to 5 cm (1 to 2 inches) are inside the drip-tape with their inlet ends pointing downstream.

Costs[13]

The cost of *L-Cm-drip* systems is very low. Some insights into how this low cost is achieved in India are:

- *L-Cm-drip* tape is a simple continuous tube and with microtube emitters installed in the field rather than standard drip-tape with integral emitters that requires expensive manufacturing machinery. Although installing *L-Cm-drip* is labor intensive, in India a skilled installer can install about 1000 m^2 (one-fourth acre) of *L-Cm-drip* per day at a labor cost of $2.00/day.
- The *L-Cm-drip* tape without emitters and the simple emission devices are economical because they can be manufactured using inexpensive machinery. Furthermore, the rolls of drip-tape and microtubes are very compact and easy to transport, even on a motor bike. The drip-tape is manufactured using the same blow extrusion process used to make plastic films and bags. In India the locally made extruders range in price from $3,200 to $6,400 and produce from 1.25 to 5 Kg of drip-tape per hour respectively. They require two operators, each earning roughly $0.25 per hour– one to manually maintain the required width and wall thickness of the drip-tape and the other to manage and change the take-up reels.
- The cost and profit margins in the supply chain are very low in India. For example, the cost of the virgin plastic in a kilogram (Kg) of the drip-tape is about $1.30 and the cost to the farmer including installation is about $2.60/Kg, only twice the raw material cost.
- Approximately 160 m of 125-micron (5-mil) drip-tape can be extruded form 1 Kg of plastic, so the drip-tape costs 2.60/160 = $1.60/100 m ($0.50/100 ft). Bulk microtube stock cost about $15.00 per 1,000 meters, which when cut into 20-cm (8-inch) lengths makes 5,000 microtube emitters. Thus the installed cost of drip-tape with 30-cm (12-inch) between microtube emitters is only $2.60/100 m ($0.80/100 ft).
- The smallholders IDE-India focuses on seldom have fields over one acre and the typical row length ranges from 30 m to 100 m[14].
- The drip-tape has a 16 mm ID and the friction head loss at a given flow rate is only half[15] that of regular 16 mm drip tubing with an ID of 14 mm.
- The required inlet pressure head is usually only 1 to 3 meters so very simple pipe fittings and connections can be used. For example, the sub-main pipes can be made using recycled plastic and the

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[12] The overhand knots are tied so about 5 cm of the microtubes are inserted inside of the drip-tape pointing downstream. The knots produce an angular bend in the microtubes so they lay flat along the drip-tape.

[13] As of March 2003 the conversion rate for $US to Indian Rupees was: $1.00 = 46Ru; however, in India's rural sector, when the purchasing price parity of a Rupee is considered, 46Ru will buy roughly $4.00 worth of services.

[14] Row lengths up to 50 m can be served from one end, but for longer rows, pairs of drip-tape laterals must be fed from a sub-main laid across and near the middle of the rows.

[15] The tubing friction head loss is a function of $1/ID^{4.75}$ and $(14/16)^{4.75} = 0.5$.

pipe sections do not need to be glued, which further reduces costs and makes it is easy to rearrange the system after each crop cycle. Some other advantages of low pressure operation include:

- There are no problems with leakage or splitting of the drip-tape at the sub-main connections or where the microtubes are inserted.
- Microtube with wide flow paths are used for the emitters, thus minimizing screening and filtration requirements.
- Low quality standard sized irrigation fittings and pipe extruded from recycled plastic can be used for the sub-mains and drip-tape connections to them. For example:
  - Both flexible semi-lay-flat and rigid pipes made from recycled plastic are suitable for sub-mains. The 75-mm semi-lay-flat tubing only costs \$0.20/m but only lasts for 2 to 4 years, while 63-mm rigid pipe cost \$0.40/m and lasts from 6 to 8 years.
  - Regular 16-mm grommet connectors that cost \$0.03 each are used for connecting the drip-tape to the sub-mains. Short pieces of light weight 16-mm by 0.5-mm wall drip tubing are ideal for securing the drip-tape on the grommet connectors with a knot.

Performance Characteristics

We recommend that the micro-irrigation performance standards, such as those proposed by the American Society of Agricultural Engineers, be relaxed for *L-Cm-drip* systems designed for smallholders in developing countries. Thus we propose the following performance standards be institutionalized and "officially accepted" so smallholders are eligible for bank loans and government assistance to finance *L-Cm-drip* systems.

Uniformity Standards for Smallholder Drip Systems

The uniformity of water distribution or Emission Uniformity (EU) (Keller and Bliesner, 1990) is typically used as a primary measure of the potential performance of drip irrigation systems. EU is dependent on the combined effects of:

- The water supply head available;
- The elevation differences throughout the irrigated area;
- The friction losses in the pipe distribution network; and
- The discharge characteristics and manufacturer's (and assembler's) coefficient of uniformity of the water emission devices.

Usually systems serving small plots can be laid out so that elevation differences throughout the irrigated area are relatively small and both ground slopes and flows are in the same direction. Thus elevation decreases that increase the available head can be used to offset pipe friction losses. The "rule of thumb" criteria for designing a sub-unit of a *L-Cm-drip* system is to try to maintain the pressure head difference due to pipe friction losses and elevation differences between –25% and +50% of the average microtube emitter pressure, H_a..

Coefficient of Variation Uniformity, *CvU*

We recommend using the *coefficient of variation*, v, of the individual emitter discharges from the field test data as the measure of uniformity for post-installation evaluation of *L-Cm-drip* systems:

$$v = sd/q_a \qquad (1)$$

Where q_a is the average rate (lph) of catch for the population and sd is the estimated standard deviation of the catch rates (lph) of the population.

The v is easy to calculate using a calculator or a computer spreadsheet program. Furthermore, it is a useful parameter with consistent physical significance[16] for populations of normally distributed data and it is a generally known and accepted measure of the variability within a population. Therefore, we subscribe to the use of a term we refer to as the Coefficient of Variation Uniformity (*CvU*)[17] as the standard measure of application uniformity for smallholder drip irrigation systems:

$$CvU = 100(1.0 - v) \tag{2}$$

The relationship between the field emission uniformity, *EU'*, presented by Keller and Bliesner (1990) and *CvU* for relatively normally distributed field catch data is:

$$EU' \approx 100(1.0 - 1.27v) \tag{3}$$

Combining equations 1 and 2 gives:

$$EU' \approx 100 - 1.27(100 - CvU) \tag{4}$$

Recommended Values of CvU for *L-Cm-drip* Systems

According to Keller and Bliesner (1990) conventional drip irrigation systems serving relatively small fields with uniform topography should be designed to produce *EU'* values above 85%, which is equivalent to a *CvU* of 88%. However, they also suggest that for systems serving relatively large fields with undulating topography design *EU* values as low as 70%, which is equivalent to a *CvU* of 76%, are acceptable. Thus it is clear that system acceptability is dependent on site, equipment selection, and cropping conditions rather than a rigid adherence to fixed *EU* values.

In view of the above we recommend adapting the following general performance criteria, originally presented by Keller, et al, 2001, for field evaluation of *L-Cm-drip* systems serving smallholder plots:

- *CvU* above 88% is excellent;
- *CvU* between 88% and 80% is good;
- *CvU* between 80% and 72% is fair; and
- *CvU* between 72% to 62% is marginally acceptable.

Design Tools

Many of the people in the supply chain for *L-Cm-drip* systems have little knowledge of pipeline hydraulics and the use of the typical equations engineers use for designing irrigation systems. In view of this we are developing pre-engineered design tables that are intuitive and convenient to use. We anticipate that by using these design tools it will be relatively easy to train inexperienced IDE-India staff and other field personnel as well as assemblers and dealers so they can provide rather expert designs for their farmer clients. The purpose of this section is to provide a sample of the types of design tools we are developing for *L-Cm-drip* systems.

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[16] The physical significance of v is derived from the classic bell-shaped normal distribution curve in which approximately 68% of the catch rates fall within $(1 \pm v)q_a$; approximately 95% of the catch rates fall within $(1 \pm 2v)q_a$; essentially all of the observed catch rates fall within $(1 \pm 3v)q_a$; and the average of the low one-quarter of the catch rates is approximately equal to $(1 - 1.27v)q_a$.

[17] Wu and Barragan (2000) have also proposed using the equivalence of *CvU* for micro-irrigation systems and recognized the above relationship between *EU* and *Cv*.

L-Cm-drip Lateral Design Tables

We have already developed a unique program for designing *L-Cm-drip* lateral design tables. The tables are designed to enter with the lateral inlet pressure head, H_L, lateral length, L_L, and microtube emitter spacing, S_e. Development of the tables requires an iterative process to compute the total lateral flow rate, Q_L, given H_L, L_L, and S_e. Starting with H_L values is most convenient for designing *L-Cm-drip* systems since the design strategy is to begin with the system operating pressure head, H_S, that satisfies the desired system flow rate, Q_S, and uniformity, EU_L, under the given field conditions. Entering design tables with H_L may seem unusual for designers in the US because we usually begin our design by computing the required q_a to meet peak crop water requirements assuming some desired *EU.* Also developing design tables for different q_a values does not require an iterative solution because if q_a, L_L, *and* S_e are given, then Q_L, and the remaining hydraulic characteristics can be computed directly by assuming $q = q_a$ at all emitters. In addition to the lateral design tables for level rows, which we have already developed (see Table 1), we are also developing tabular tools for the design of sub-mains and for positioning sub-mains on sloping fields.

The pre-engineered *L-Cm-drip* system design tables we have developed for IDE-India are based on the following input variables:

- Lateral inlet pressure head, H_L, such as: 0.50 m, 0.75 m; 1.0 m, 1.5 m, 2.0 m; 2.5 m, and 3.0 m;
- Microtube emitter spacing, S_e ,such as: 45 cm (1.5 ft), 60 cm (2.0 ft), 75 cm (2.5 ft), and 90 cm (3 ft);
- Lateral length, L_L ,such as: 20 m, 30 m; 40 m, and 50 m;
- Lateral drip-tape inside diameter, which is 16.00 mm for 125-micron drip-tape and 15.75 mm for 250-micron drip-tape;
- Minor loss due to the insertion of the microtube emitters into the drip-tape, which is expressed as an equivalent length estimated to be 0.1 m;
- Microtube emitter pressure head/discharge relation based on bench tests and entered either as a curve or equation; and
- Coefficient of variation of the microtube emitters, v, based on bench test data.

The following information is developed for each of the above lateral configurations assuming the *L-Cm-drip* laterals are lying along crop rows that are nearly level:

- Total lateral discharge, Q_L, in liters per minute (lpm);
- Average emission device discharge, q_a, in liters per hour (lph);
- Lateral friction head loss, h_f, in meters (m); and
- Design emission uniformity of the *L-Cm-drip* lateral, EU_L, as a percentage, %.

The EU_L is computed using the same equation for the design emission uniformity developed by Keller and Keller (1974) and Keller and Bliesner (1990), which is commonly used for drip irrigation system design purposes in the US and elsewhere. However, EU_L is a metric for lateral uniformity rather than for the whole system or sub-unit of a system, which would include pressure variations due to elevation differences along the laterals as well as pressure differences along the sub-main supplying them. The equation for computing EU_L is:

$$EU_L = 100(1.0 - 1.27v)\ q_n/q_a \qquad (5)$$

Where EU_L is the design emission uniformity, %; v is the microtube emitter coefficient of variation; q_n is the minimum microtube emission rate computed from the minimum pressure along the lateral based on the emitter's nominal flow rate versus pressure curve, lph; and q_a is the average microtube emission rate, lph.

Table 1. Row and vegetable microtube drip-tape hydraulic design tables for laterals on zero slope.

Inlet Head, H_L (m)	Microtube Spacing S_e (cm)	Lateral/Row Length 20 m				Lateral/Row Length 30 m				Lateral/Row Length 40 m				Lateral/Row Length 50 m			
		Q_L (lpm)	q_a (lph)	h_f (m)	EU_L (%)	Q_L (lpm)	q_a (lph)	h_f (m)	EU_L (%)	Q_L (lpm)	q_a (lph)	h_f (m)	EU_L (%)	Q_L (lpm)	q_a (lph)	h_f (m)	EU_L (%)
0.50	**45**	2.17	2.96	0.04	94	3.04	2.72	0.11	91	3.62	2.44	0.18	87	3.98	2.15	0.26	81
	60	1.66	3.01	0.02	95	2.38	2.86	0.07	93	2.95	2.65	0.13	90	3.34	2.41	0.19	87
	75	1.37	3.04	0.02	95	1.96	2.93	0.05	94	2.45	2.78	0.09	92	2.88	2.58	0.15	89
	90	1.12	3.06	0.01	96	1.64	2.98	0.03	95	2.10	2.86	0.07	93	2.51	2.69	0.12	91
0.75	**45**	2.91	3.97	0.07	94	4.05	3.63	0.18	91	4.78	3.22	0.30	86	5.22	2.82	0.41	80
	60	2.23	4.06	0.04	95	3.19	3.83	0.11	93	3.93	3.52	0.21	90	4.41	3.19	0.30	86
	75	1.84	4.09	0.03	95	2.63	3.94	0.08	94	3.28	3.71	0.15	92	3.81	3.42	0.24	89
	90	1.51	4.12	0.02	96	2.20	4.01	0.06	95	2.81	3.83	0.11	93	3.34	3.58	0.19	90
1.00	**45**	3.59	4.90	0.10	94	4.96	4.44	0.25	90	5.82	3.92	0.41	85	6.32	3.42	0.56	79
	60	2.76	5.01	0.06	95	3.93	4.71	0.16	93	4.80	4.30	0.30	89	5.37	3.88	0.43	85
	75	2.28	5.06	0.04	95	3.23	4.85	0.11	94	4.02	4.55	0.21	91	4.66	4.17	0.34	88
	90	1.87	5.10	0.03	96	2.72	4.94	0.08	94	3.45	4.71	0.16	93	4.09	4.38	0.27	90
1.50	**45**	4.82	6.58	0.16	94	6.60	5.91	0.41	90	7.67	5.17	0.67	84	8.28	4.47	0.89	77
	60	3.71	6.74	0.10	95	5.25	6.30	0.27	92	6.37	5.70	0.48	88	7.07	5.11	0.68	84
	75	3.07	6.81	0.07	95	4.34	6.50	0.19	94	5.36	6.07	0.35	91	6.16	5.52	0.55	87
	90	2.52	6.87	0.05	95	3.65	6.64	0.14	94	4.61	6.29	0.27	92	5.43	5.82	0.44	89
2.00	**45**	5.94	8.10	0.23	94	8.07	7.23	0.58	89	9.32	6.28	0.93	83	10.01	5.41	1.22	76
	60	4.58	8.32	0.14	95	6.44	7.73	0.38	92	7.77	6.96	0.68	88	8.59	6.21	0.95	83
	75	3.79	8.42	0.10	95	5.34	8.01	0.27	93	6.56	7.43	0.50	90	7.51	6.73	0.77	86
	90	3.11	8.49	0.07	95	4.50	8.19	0.20	94	5.66	7.72	0.39	92	6.64	7.11	0.62	89
2.50	**45**	6.98	9.52	0.31	94	9.43	8.45	0.76	89	10.83	7.30	1.20	83	11.60	6.27	1.57	75
	60	5.39	9.79	0.19	95	7.55	9.06	0.50	92	9.07	8.12	0.89	87	9.98	7.22	1.23	82
	75	4.46	9.91	0.14	95	6.27	9.40	0.36	93	7.68	8.69	0.66	90	8.75	7.84	1.00	86
	90	3.67	10.01	0.10	95	5.29	9.62	0.26	94	6.64	9.05	0.51	92	7.75	8.30	0.81	88
3.00	**45**	7.96	10.86	0.39	93	10.71	9.59	0.94	89	12.25	8.26	1.48	82	13.08	7.07	1.92	75
	60	6.15	11.19	0.24	95	8.60	10.32	0.63	92	10.29	9.21	1.10	87	11.29	8.16	1.52	82
	75	5.10	11.33	0.17	95	7.15	10.72	0.45	93	8.73	9.88	0.82	90	9.91	8.88	1.24	85
	90	4.20	11.45	0.12	95	6.04	10.99	0.33	94	7.56	10.30	0.64	92	8.79	9.42	1.01	88
4.00	**45**	9.80	13.36	0.56	93	13.08	11.71	1.33	88	14.86	10.02	2.06	81	15.80	8.54	2.64	73
	60	7.59	13.80	0.35	94	10.54	12.65	0.90	91	12.53	11.22	1.55	86	13.69	9.90	2.11	81
	75	6.30	13.99	0.25	95	8.78	13.18	0.65	93	10.67	12.08	1.16	89	12.06	10.80	1.73	85
	90	5.19	14.15	0.18	95	7.44	13.53	0.48	94	9.27	12.64	0.90	91	10.73	11.49	1.43	87
5.00	**45**	11.51	15.69	0.74	93	15.26	13.67	1.74	88	17.26	11.63	2.66	80	18.28	9.88	3.37	72

Table 1 shows a portion of a pre-engineered lateral for an *L-Cm-drip* system. It is based on an average $v = 0.031$ and pressure head versus emitter discharge curves determined for a series of bench tests at pressure heads ranging from 0.5 to 2.0 m for 20-cm (8-inch) long microtube emitters with an internal diameter (ID) of 1.2 mm installed in drip-tape. The ID used for the drip-tape laterals was 16.0 mm and the microtube/drip-tape connection loss was assumed to be equal to an equivalent length of 0.1 m of drip-tape.

To use the table for designing an *L-Cm-drip* system the designer enters it with the plant spacing and lateral length that fits the field size and shape. Then the designer searches for the combination of H_L, Q_L, and EU_L that appears most reasonable for the field layout while considering the following:

- Microtube emitters with large unobstructed passageways have relatively high discharges even under very low operating pressure heads. Therefore, it is not practical to use laterals much longer than 50 m for *L-Cm-drip* systems. If rows are longer than 50 m the sub-main must be laid out to bisect the field rather than being placed at the head of the rows. If rows are longer than 100 m, a second sub-main is needed.
- The ideal pressure head for *L-Cm-drip* systems is between 1 and 3 m.
- The system discharge, Q_S, is equal to the lateral discharge, Q_L, times the number of laterals along the sub-main. Thus to find a reasonable Q_L, divide the available Q_S by the number of laterals that will be required to irrigate the field. If the available Q_S is insufficient irrigate half the field at a time. .
- It is desirable to have the design emission uniformity, EU_L, as high as practical. Assume that in view of minor elevation variations and losses in the sub-main, the *CvU* of field test data will be close to the EU_L. Thus the designer can use EU_L values from the table in place of recommended *CvU* presented earlier as a guide to evaluating the anticipated system performance with the lateral configuration selected.

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Cotton and Winter Wheat Irrigation Scheduling Improvements in Uzbekistan

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Abstract

Investigations of water use (evapotranspiration or ET) and irrigation scheduling of furrow irrigated winter wheat (*Triticum aestivum L.*) and of drip irrigated cotton (*Gossypium hirsutum, cv. Akdarya-6*) were conducted at the Central Experiment Station of the Uzbekistan Cotton Growing Research Institute (UNCGRI) on a deep silt loam soil in 2000, 2001, and 2002. Water use was established using the soil water balance approach on a weekly basis. Deep measurements of the soil profile water content were accomplished using soil moisture neutron probes (SMNP), which were calibrated in polyvinyl chloride (PVC) access tubes for the soil and each soil horizon. Water use was measured by the soil water balance method. Soil water measurements were compared with percentages of field capacity to determine irrigation rates and times during the growing season. The results revealed that drip irrigation of cotton under the given circumstances improved water use efficiency and seed-cotton yield. Under drip irrigation, the optimal mode of cotton irrigation scheduling was to irrigate at 70%, 70%, and 60% of field capacity during each of the three major growth stages, respectively. This mode saved 35% of the irrigation water in comparison with surface irrigated cotton grown under the same condition. Seed-cotton yield was increased by 21% relative to the surface irrigated cotton. Optimal development and high crop productivity of winter wheat was reached when irrigations were scheduled at soil moisture levels of 75, 75, and 60% of field capacity during the three major crop growth stages, respectively. More irrigation did not result in additional yield from the crop.

Key words: Neutron Scattering, Calibration, Drip Irrigation, Profile Water Content, Crop Water Use, Seed Cotton Productivity, Microirrigation

Introduction

Sixty percent of Uzbekistan is (semi-) desert. Almost all agricultural production is due to irrigation on approx. four million hectares, which makes irrigation water supply and management the prevailing factors limiting crop yields in the country. Cotton and wheat are the major crops, followed by corn, alfalfa, sugar beet, vegetables and fruits. With annual rainfall of 110 to 220 mm, Uzbekistan's climate is that of the dry mid-latitude desert, which is characterized by hot summers and cold winters. Agriculture in Uzbekistan was and still is the largest sector in Uzbekistan's economy.

Two major river systems: the Amu-Darya and Syr-Darya, supply all the water used for hydro-electric power generation and most of the water used for irrigation. There are some groundwater wells also used for irrigation.

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These two rivers also supply the neighboring countries of Kyrgyzstan, Tajikistan, Afghanistan, Turkmenistan and parts of Kazakhstan. Since 1991, these Central Asian countries have continued a dispute on meeting increasing water demands. Since then, lack of water has gradually devastated the irrigation-dependent cotton, winter wheat and other major crop production. In addition, lack of water has engendered the ecological catastrophe within the Aral Sea Basin, at the tail end of the river systems of Uzbekistan.

Investigation of crop water scheduling in relation to lack of irrigation water has only recently been conducted in Uzbekistan. Also, winter wheat production, which was small before the 1990s, has recently become second only to cotton in cropped land area. Cotton – winter wheat rotations are the subject of much current study; and we have recently reported results of our wheat research in a Workshop devoted to this topic (Kamilov et al., 2002). The main goal of this research was to measure cotton and winter wheat water use in Uzbekistan, and to determine irrigation scheduling parameters associated with optimal yield and irrigation water use efficiency.

Materials and Methods

Field experiments on cotton and winter wheat were conducted at the Central Experiment Station of Uzbekistan's Cotton Growing Research Institute in 2000, 2001, and 2002 at Tashkent. The soil is an old irrigated typical gray soil, a medium loam; and the water table is more than 15-m deep (automorphic type of soil formation).

As a starting point for investigations of irrigation scheduling, we adopted the field capacity (F_C) index, which was 0.298 m^3 m^{-3} over the root zone of this soil. Irrigations were scheduled when soil moisture in the root zone was depleted by the crop to specific fractions of F_C (for instance, irrigation at 70% of F_C) for each of the three main plant growth periods defined below.

The experiments with cotton were carried out in three replicates and comprised two irrigation scheduling treatments with drip irrigation, and one treatment with surface irrigation for comparison. The drip irrigation system, comprising one line of surface drip tape per row, was installed in the field after completion of early season inter-row cultivation. Each treatment consisted of scheduling irrigations at specific percentages of F_C during each of three plant growth periods as follows:

1. 65-65-60% of F_C (drip irrigation)
2. 70-70-60% of F_C (drip irrigation)
3. 70-70-60% of F_C (conventional irrigation)

where the first of the three levels of F_C (e.g., **65**-65-60%) was used from germination to squaring stage of the crop; the second level (e.g., 65-**65**-60%) was used from squaring to the flowering-fruiting stage; and the third level (e.g., 65-65-**60**%) was used during maturation of cotton bolls. Each replicated plot was 240 m^2 (4.8 m by 50 m). Irrigation water quantity applied through drip irrigation was measured by an in-line propeller-type flow meter. Water quantity for the surface irrigation treatment and runoff were measured using the weir of Chippoletty. Fertilizer was applied at rates of 200 kg ha^{-1} N, 140 kg ha^{-1} P, and 100 kg ha^{-1} K. All other cultural practices were conducted similar to the common practices in the area.

The experiments with winter wheat were carried out in three replicates and comprised four treatments. Each treatment consisted of scheduling furrow irrigations at specific percentages of F_C during each of three plant growth periods as follows:

1. 65-65-60% of F_C
2. 70-70-60% of F_C
3. 75-75-60% of F_C
4. 80-80-70% of F_C

where the first of the three levels of FC (e.g. **65**-65-60%) was used from germination to shooting stage of the crop; the second level (e.g. 65-**65**-60%) was used from shooting to the milk-wax stage of grain ripeness; and the third level (e.g. 65-65-**60**%) was used from the milk-wax stage to full grain ripeness. Plot area in the experiments was 240 m^2 (4.8 m by 50 m). Irrigation water quantity used for each treatment was measured with a weir (Weir of Chippoletty). Fertilizer was applied at rates of 200 kg ha^{-1} N, 140 kg ha^{-1} P, and 100 kg ha^{-1} K. Water use was measured by the soil water balance method.

Considering ET as crop water use, P as precipitation, I as Irrigation, R as the sum of runoff and runon, F as flux across the lower boundary of the soil profile (control volume), and ΔS as change in soil water stored in the profile, we know that the soil water balance must sum up to zero:

$$ET + \Delta S + R - P - I - F = 0 \qquad (1)$$

where the sign conventions are as given in Evett (2002), including the conventions that (1) ET is taken as positive when water is lost to the atmosphere through transpiration and/or evaporation, and (2) ΔS is positive when soil water storage increases over the season. Re-arranging this equation gives the crop water use or ET as:

$$ET = -\Delta S + P + I - R + F \qquad (2)$$

A key thrust of our investigations was the measurement of soil profile water content. For this purpose we used the SMNP (Campbell Pacific Nuclear International, model Hydroprobe-503DR1.5), which was calibrated for each soil and soil horizon. Calibration of the SMNP was performed using methods described in Evett and Steiner (1995) and Hignett and Evett (2002). For calibration, PVC access tubes were installed in the field to 2.0-m depth, in two replicates in each of two plots of 10 square meters each. A wet site plot was irrigated to field capacity to below the 2-m depth using irrigation water. A non-irrigated plot was prepared as the dry site by crop and field management during the preceding season. Volumetric water content of the soil profiles was measured by volumetric/gravimetric methods for comparison with count ratios measured with the SMNP. Calibration equations were calculated for the important soil layers. These were used for determination of profile water content and thus calculation of irrigation rates and times for cotton during the growing season. Measurements of volumetric water content of the soil profile were conducted twice a week and in two replicates during the experiments by SMNP to 2-m depth and for each 20-cm soil layer separately. Before each measurement, a standard count (C_S) of the SMNP was determined in five replicates.

Results and Discussion

SMNP Calibration

Reasonably precise calibration equations were obtained for all soil horizons. The root mean squared error (RMSE) of regression ranged from 0.010 to 0.014 m^3 m^{-3} (Table 1). Distinctly different soil horizons were identified. Also, due to nearness to the surface, equations for the 10-cm depth were different in slope from equations for deeper layers. The old irrigated gray soil of Tashkent Province is uniform in texture, ranging from silt to silty clay loam throughout the profile, and is probably derived from loess, either in place or in alluvial deposits.

Nodules and veins of $CaCO_3$ were noted during sampling at depths of >70 cm. Since the soil is a uniform silt loam, the different calibration curve for depths >70 cm is probably due to the increase in $CaCO_3$ concentration. Similar effects of calcium minerals on SMNP calibration slopes have also been noted in the semi-arid Great Plains of the United States, where slopes were likewise lower for soil layers rich in $CaCO_3$ (Evett and Steiner, 1995; Evett, 2000). The effect is probably due to the presence of oxygen in these minerals, which is relatively effective in causing thermalization of fast neutrons. The lowered calibration slope values would be expected in this case because the presence of oxygen would increase the concentration of thermal neutrons and thus increase neutron counts without the presence of water.

Table 1. Calibration equations for soil moisture neutron probe (SMNP) for Tashkent. Equations are in terms of volumetric water content (θ, $m^3\ m^{-3}$) and count ratio (C_R). Measurements were at 20-cm increments between depths noted below.

Location	Depth (cm)	Equation	r^2	RMSE* ($m^3\ m^{-3}$)
Tashkent #H390104791**	10	$\theta = 0.013 + 1.1752C_R$	0.989	0.011
	30 – 70	$\theta = -0.176 + 0.3759C_R$	0.958	0.014
	90 – 170	$\theta = -0.039 + 0.2463C_R$	0.911	0.010

* RMSE is root mean squared error of regression.

** The # sign denotes the SMNP serial number.

An example of data gathered with the SMNP for crop water use determination is illustrated. Water content remained well below the maximum allowed by the soil porosity, which was calculated from measured bulk density (Fig. 1). Application of the soil water balance equation, using measured irrigation, rainfall and soil water content changes, allowed calculation of water use for the season.

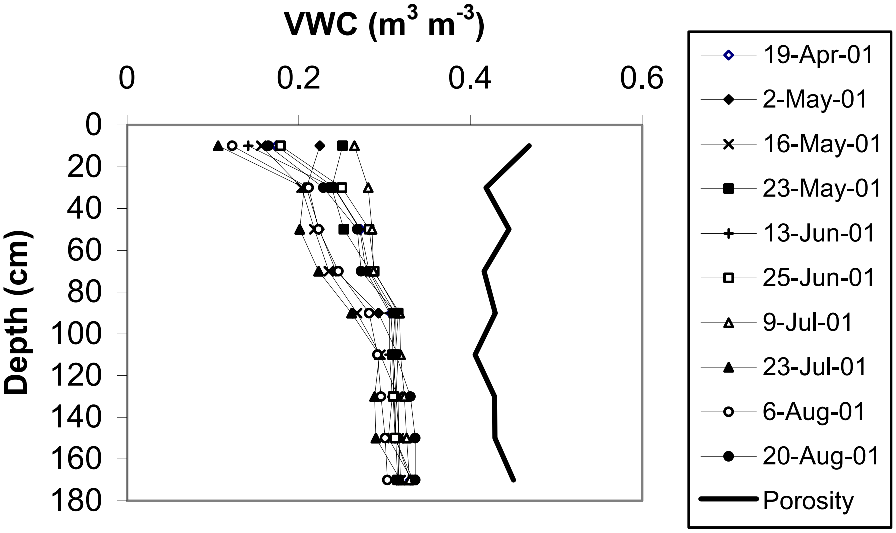

Figure 1. Evolution of profile volumetric water content (VWC) at the UNCGRI, Tashkent during the cotton irrigation season in 2001.

Crop water use and yield

The sum of runoff and runon (R) and the flux (F) were assumed to be zero for the soil of Tashkent Province and, therefore, the soil water balance equation gave the crop water use as:

$$ET = -\Delta S + P + I \qquad (3)$$

Precipitation data (P) were taken from the Meteorological Station of the Institute, which is located at the Central Experiment Station. During the cotton vegetation season, precipitation was 64 mm, 27 mm, and 102 mm in 2000, 2001, and 2002, respectively. During the wheat experiment periods (October – June) precipitation was 249 mm and 716 mm in 2000-2001 and 2001-2002, respectively.

Values of change in soil water stored in the profile (ΔS) were calculated with the use of the integral calculus method. Values of water content at the beginning of each growing season were similar in all treatments and so were lumped across treatments.

Cotton

Having calculated the ΔS for each treatment of the experiment, we determined the ET for the 0 to 150-cm deep soil control volume (Table 2).

Table 2. Water use (ET) of cotton in Tashkent.

			2000			2001			2002		
Treatment #	% of F_C Treatments	Irrigation Method	ΔS (mm)	Irrigation (mm)	ET (mm)	ΔS (mm)	Irrigation (mm)	ET (mm)	ΔS (mm)	Irrigation (mm)	ET (mm)
1	65-65-60%	Drip	105	225	183	76	330	281	-72	298	472
2	70-70-60%	Drip	63	250	251	23	375	379	-47	322	471
3	70-70-60%	Surface	92	410	381	15	542	554	-16	507	624

Results of the experiment showed that, for drip irrigated treatments, top yield in all years was reached for treatment 2 (Table 3). Treatment 1 was considered to be deficit scheduling of irrigation due to its lower yield, which was still larger than that for furrow irrigation. For drip irrigation, additional yield received (average for three years) with treatment 2 (75-75-60% of F_C) in comparison with scheduling of irrigation at 65-65-60% of F_C was 0.38 t ha^{-1} (12.4% increase). Average additional yield for drip irrigation (treatment 2) compared with surface irrigation was 0.60 t ha^{-1} (20.9% increase) using the same irrigation scheduling treatment of 70-70-60% of F_C. Moreover, irrigation water use efficiency was always larger for drip irrigation than for furrow irrigation. Total water use efficiency (Table 4) declined in 2002 when growing season rainfall was the largest (rainfall in the growing season was 64, 27, and 102 mm in 2000, 2001, and 2002, respectively).

Some experiments have shown that drip irrigation does not increase cotton yield relative to well managed surface irrigation (Howell et al., 1987; Bucks et al., 1988). Others have shown that drip irrigation may increase lint yields and water use efficiency by large amounts compared with those from sprinkler or surface irrigation (Bordovsky, 2001; Smith et al., 1991). In our experiment, drip irrigation showed its superiority over surface irrigation applied with conventional methods in Uzbekistan. Therefore, drip irrigation should be further explored as an effective means to control quantity of irrigation water.

Table 3. Yield, irrigation and irrigation water use efficiency of cotton at Tashkent .

Treatment number	Treatment (% F_C)	Irrigation method	Irrigation (m^3 ha^{-1})	Seed cotton yield (t ha^{-1})	Irrigation water requirement per unit yield (m^3 t^{-1})	Irrigation water use efficiency (kg m^{-3})
			Year of 2000			
1	65-65-60	Drip	2250	3.12	721	1.38
2	70-70-60	Drip	2500	3.60	694	1.44
3	70-70-60	Furrow	4100	2.95	1390	0.71
			Year of 2001			
1	65-65-60	Drip	3300	3.29	1003	0.99
2	70-70-60	Drip	3750	3.67	1022	0.97
3	70-70-60	Furrow	5420	3.02	1750	0.55
			Year of 2002			
1	65-65-60	Drip	2980	2.86	1042	0.96
2	70-70-60	Drip	3220	3.15	1022	0.98
3	70-70-60	Furrow	5010	2.65	1891	0.53

Table 4. Yield, water use, and total water use efficiency of cotton Tashkent.

Treatment #	Treatment (% F_C)	Irrigation method	ET (m^3 ha^{-1})	Seed cotton yield (t ha^{-1})	Total water requirement per unit yield (m^3 t^{-1})	Total water use efficiency (kg m^{-3})
			Year of 2000			
1	65-65-60	Drip	1832	3.12	587	1.70
2	70-70-60	Drip	2508	3.60	697	1.44
3	70-70-60	Furrow	3812	2.95	1292	0.77
			Year of 2001			
1	65-65-60	Drip	2810	3.29	854	1.17
2	70-70-60	Drip	3786	3.67	1032	0.97
3	70-70-60	Furrow	5544	3.02	1836	0.54
			Year of 2002			
1	65-65-60	Drip	4720	2.86	1650	0.61
2	70-70-60	Drip	4710	3.15	1495	0.67
3	70-70-60	Furrow	6240	2.65	2358	0.42

Winter Wheat

Evapotranspiration (ET) calculated for the 0 to 150-cm deep soil control volume was nearly twice as large in 2002 as in 2001 (Table 5). Some of this may have been due to luxury consumption of water by the crop during the 2001-2002 growing season, which received 716 mm of precipitation, almost three times the amount of precipitation as in the 2000-2001 season. The ET values for the 2000-2001 growing season, ranging from 426 to 492 mm, compare well with values ranging from 424 to 524 mm for irrigated winter wheat grown at Bushland, Texas (Evett et al., 1995). The larger values of ET calculated for the 2001-2002 growing season are excessive and are probably due to unrecorded runoff, which was not measured in the wheat studies, although it was measured in the cotton studies reported here.

Table 5. Water use (ET) of winter wheat in Tashkent.

		ΔS (mm)		ET (mm)	
Treatment number	% of FC treatments	2001	2002	2001	2002
1	65-65-60%	33.1	20.4	426	881
2	70-70-60%	28.2	21.2	453	885
3	75-75-60%	24.3	20.5	467	882
4	80-80-70%	21.5	22.0	492	899

Largest yields were reached for treatments 3 and 4, which were concluded as optimal and high moisture mode, respectively (Table 6). Treatments 1 and 2 were considered to be deficit scheduling of irrigations. Additional yield received (average for two years) at the optimal mode (75-75-60% of FC) in comparison with the rigid scheduling of irrigation (65-65-60% of FC) was 0.77 t ha-1 (19.5%).

Table 6. Irrigation and productivity of winter wheat at Tashkent, Uzbekistan

	Irrigation		Grain Yield		Water requirement per unit yield		Irrigation water use efficiency	
Treatment	m^3 ha^{-1}	m^3 ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	m^3 Mg^{-1}	m^3 Mg^{-1}	kg m^{-3}	kg m^{-3}
% FC	2001	2002	2001	2002	2001	2002	2001	2002
65-65-60	2100	1750	4.01	3.89	5.24	3.89	1.91	2.57
70-70-60	2320	1900	4.58	4.18	5.06	4.55	1.98	2.20
75-75-60	2420	1960	4.99	4.45	4.85	4.4	2.06	2.27
80-80-70	2650	2050	5.01	4.6	5.29	4.46	1.89	2.24

Conclusions

1. Overall, our investigations with cotton conducted in the old irrigated typical gray soil of Tashkent Province showed that calibration of the SMNP was successful and acceptably precise for research objectives. The SMNP was useful for determining water content dynamics of soil profiles, scheduling irrigation during growing seasons, and obtaining accurate data on water use.

2. On average over three seasons, scheduling drip irrigation following the 70-70-60% of F_C treatment resulted in saving 35% of the irrigation water in comparison with surface irrigated cotton grown under the same conditions. Irrigation water use efficiency was increased by 89% compared with that of surface irrigation when scheduling was done using the (70-70-60% of F_C) rule for both. The seed-cotton yield was increased by 21% relative to the surface irrigated cotton.

3. Experimental results of the two years of investigations showed that optimal development and high crop productivity of winter wheat was reached when irrigations were scheduled at soil moisture levels of 75, 75, and 60% of field capacity during the three major crop growth stages, respectively. More irrigation did not result in additional yield from the crop.

Acknowledgements

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EFFECT OF DRIPLINE DEPTH ON FIELD CORN PRODUCTION IN KANSAS

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ABSTRACT

A four-year yield study (1999-2002) was conducted to examine the effect of dripline depth on subsurface drip-irrigated field corn on the deep silt loam soils of western Kansas. An additional year (2003) was included in the analysis of long term dripline flowrates and temperatures at the soil/water interface along the dripline. Germination of the field corn with the subsurface drip irrigation system was not examined in this field study. Results indicate that dripline depths ranging from 8-24 inches are acceptable for field corn production on silt loam soils in the region. There was a tendency for slightly decreased corn yields for the deepest dripline depth (24 inches). The results suggest other factors external to the study might have a larger influence on selection of dripline installation depth. These other factors might include producer preferences, tillage schemes, rodent management, perceived need for surface wetting for germination, and installation draft requirements and costs.

INTRODUCTION

Subsurface drip irrigation (SDI) is a relatively new technology in the central Great Plains but producers are beginning to adopt and adapt the technology to their farms. Most of the SDI research for field corn conducted at Kansas State University has been with driplines at a 16-18 inch depth in deep silt loam soils. Generally, at this depth the soil surface stays dry and this helps to eliminate evaporative losses. However, low flow driplines at this depth for the typical 5-foot dripline spacing centered between 30-inch corn rows will not adequately wet the corn seed zone for germination. In many years, irrigation is not required to establish a summer crop in the central Great Plains as May-June have the highest precipitation amounts during the year in this semi-arid, summer precipitation pattern climate. Some producers in the region wish to have the capability to use SDI for germination in those isolated dry years and feel shallower dripline depths may enhance those prospects. However, the question arises about what effect dripline depth has on corn production, water use and also on system management and maintenance for the long term. SDI system life is an extremely important factor in the economics of SDI for the lower value commodity crops such as field corn. In 1999, Kansas State University initiated a field study to evaluate the effect of dripline depth 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 1999-2003. Cropping system and soil water results will be reported for the years 1999-2002. Long-term flow measurements will be reported for the 5 seasons (1999-2003) and soil temperature measurements will be reported for 2003.

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 five microirrigation dripline depths of 8, 12, 16, 20 or 24 inches replicated four times in a complete randomized block design. Plot length was 139 ft and plot width was eight corn rows spaced 2.5 ft apart (20 ft).

The subsurface drip irrigation (SDI) system was installed in the spring of 1999 prior to corn planting in May. Low flow (0.22 gpm/100 ft) Toro Ag[1] dripline with a 12 inch emitter spacing and 7/8 inch inside diameter (Aquatraxx EA7XX1222) was installed with a 5 ft dripline spacing with a shank type injector at the specified treatment depths. The emitter exponent for the dripline is 0.54 and the manufacturer's coefficient of variation is approximately 3%. There were four driplines in each plot. 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 1.39 gpm/plot, coinciding with an operating pressure of approximately 10 psi. Irrigation water was supplied from an unlined surface reservoir to which groundwater was pumped for temporary storage. The surface reservoir adds two major issues to the study, the introduction of biological activity and varying water temperatures.

Pioneer hybrid 3162 seed corn was used in 1999 -2002. This hybrid is a full season hybrid for the region with an approximately 118 day comparative relative maturity requirement. In 2003, the corn planting was purposely delayed until mid-May to attempt an examination of germination potential of the different depths. Heavy rains following planting negated this study and the results are excluded from discussion. This late-planting date resulted in a much later first irrigation for this study than normal. Pest (weeds and insects) control was accomplished with standard practices for the region. Nitrogen fertilizer was applied to the study area with approximately 125 lbs N/acre early preplant and 75 lbs N/acre through the SDI system in late June each year. A starter fertilizer application at planting banded an additional 30 lbs N/acre and 45 lbs P_20_5/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.

Irrigation was scheduled using a climatic water budget each year and all dripline treatments received the same amount of water within a given year. Daily or bi-daily irrigations were scheduled when the calculated soil water depletion exceeded approximately 1 inch. Irrigation amounts ranged from 0.25 to 0.5 inches for each event depending on availability of pumping capacity for the given event. 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.

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

Pressure and flow measurements were made at the beginning of the study and also at the end of each irrigation season using the municipal grade flowmeters for an approximately 20 minute period and recording the pressure at the inlet and tail end of the plots. High quality 0-30 psi (4-inch face) pressure gauges with approximate accuracy of +/- 1% of full scale were used in 1999-2002 and 0-30 psi pressure transducers with +/- 0.5% of full scale were used in 2003. Flowrates were normalized to 10 psi through use of the emitter exponent to allow comparisons between years and small pressure variations between events.

In 2003, thermocouples were installed in each plot right next to the dripline (closer than 0.25 inch) at a distance of 100 ft from the water inlet for the plot. Additionally, three thermocouples were installed in three plots in the soil surface layer (0-3/4 inch). The water inlet temperature was measured for two plots by installing a thermocouple directly in the inlet pipe immediately prior to entering the plot. During these 2003 temperature tests, large irrigation amounts were used (2-4 inches for each event) to examine the duration of temperature effects.

Corn production data collected during the growing season included irrigation and precipitation amounts, weather data, yield components (yield, harvest plant population, ears/plant, kernels/ear, mass/100 kernels), and periodic soil water content. Weather data were collected with an automated weather station approximately 0.25 mile from the research site. Values calculated after final data collection included seasonal water use and water use efficiency.

RESULTS AND DISCUSSION

Weather Conditions

Briefly, the weather conditions can be specified as wetter than normal in 1999 and excessively dry in 2000-2002. Precipitation during the cropping season was 16.98, 6.21, 9.26 and 9.90 inches for the respective years, 1999-2002. Calculated evapotranspiration was slightly below normal in 1999 (21.64 inches) and above normal at 27.48, 26.28, and 27.68 inches for the years 2000-2002, respectively. This resulted in irrigation requirements of 10.50, 18.00, 19.00, and 19.65 inches for the four respective years, 1999-2002. The SDI system was not used to enhance germination in any year although some additional residual soil water in the surface layers for the shallower dripline depths may have existed in the spring of 1999 shortly following the late spring installation. The crop year 2002 was very dry at planting and it is possible the shallower depths could have benefited in crop germination if they had been irrigated. However, this was not part of the experimental protocol, so no irrigation was performed at this time.

Tillage and Rodent Management Aspects

Although tillage and rodent management was not specifically examined in the study, it should be noted that there were no instances of dripline damage due to tillage or rodents at any point in time. Shallow cultivation for weeds during the corn season was accomplished even for the 8-inch depth. This may have been enhanced by the controlled-traffic bed management scheme used in this study area (Figure 1.). Deep tillage schemes would definitely be affected by dripline depths less than 12 inches. There are thoughts by some researchers that deeper dripline depths (greater than 1 ft) may reduce rodent activity.

Corn Yield and Yield Components

Corn yields were very high in all four years ranging from 249 to 291 bushels/acre (Table 1 and Figure 2.) In any given year there were no significant differences in yield attributable to differences in dripline depth. However, when averaged over the 4 years there was a significant difference with the 24-inch depth resulting in slightly lower yields (Table 1 and Figure 2.) In general, there were no significant effects on the yield components with the exception of a higher number of kernels/ear for the 8 inch depth in 1999 (Table 1.) and a slightly higher ears/plant for the 16-inch depth for the 4-year average. The higher kernels/ear for the 8-inch depth in 1999 may possibly reflect more favorable soil water conditions early in the season that were caused by higher residual soil water conditions in the surface layers following SDI system installation. Corn grain yield levels were very high in all cases and very similar, so there is very little reason to select one dripline depth over another on the basis of grain yield.

Table 1. Yield component and water use data from a dripline depth study for corn, 1999-2002.

Dripline depth inches	Yield bu/acre	Plants/acre	Ears/Plant	Kernels/ear	100 Kernel wt. g	Water use inches	WUE lb/acre-in
Year 1999							
8	290.9	30710	1.00	691	34.79	33.93	480
12	270.6	29621	1.02	647	35.17	33.79	449
16	278.3	30710	1.00	628	36.76	33.41	467
20	275.3	31363	1.00	624	35.81	33.71	458
24	272.8	30274	1.01	642	35.39	33.03	462
Mean	277.6	30536	1.01	646	35.58	33.57	463
LSD 0.05	NS	NS	NS	44	NS	NS	NS
Year 2000							
8	252.6	26354	1.00	642	37.92	29.55	479
12	256.1	27225	1.00	629	38.02	28.56	503
16	265.5	26354	1.05	635	38.45	28.56	521
20	248.7	26789	1.01	622	37.61	27.71	503
24	253.7	27443	1.00	619	38.02	28.00	508
Mean	255.3	26833	1.01	629	38.00	28.48	503
LSD 0.05	NS	NS	NS	NS	NS	NS	NS
Year 2001							
8	268.8	35284	0.96	585	34.58	32.52	464
12	270.0	33977	1.01	594	33.76	32.47	466
16	274.6	35719	1.00	572	34.40	31.98	481
20	277.9	34412	1.00	570	36.05	31.56	493
24	269.0	34848	0.98	582	34.61	31.62	477
Mean	272.0	34848	0.99	580	34.68	32.03	476
LSD 0.05	NS	NS	NS	NS	NS	NS	NS
Year 2002							
8	277.2	34413	0.99	519	39.96	31.91	487
12	264.1	33106	0.99	529	39.11	31.49	470
16	286.0	34194	0.99	547	39.21	32.04	500
20	263.0	34195	0.99	485	41.22	30.61	482
24	254.3	33324	0.98	507	39.39	30.79	463
Mean	268.9	33846	0.99	518	39.78	31.37	480
LSD 0.05	NS	NS	NS	NS	NS	NS	NS
All Years							
8	272.4	31690	0.99	609	36.81	31.98	478
12	265.2	30982	1.00	600	36.51	31.58	471
16	276.1	31744	1.01	595	37.21	31.50	492
20	266.2	31690	1.00	575	37.67	30.90	484
24	262.4	31472	0.99	587	36.85	30.86	478
Mean	268.5	31516	1.00	593	37.01	31.36	481
LSD 0.05	9.0	NS	0.02	NS	NS	0.66	NS

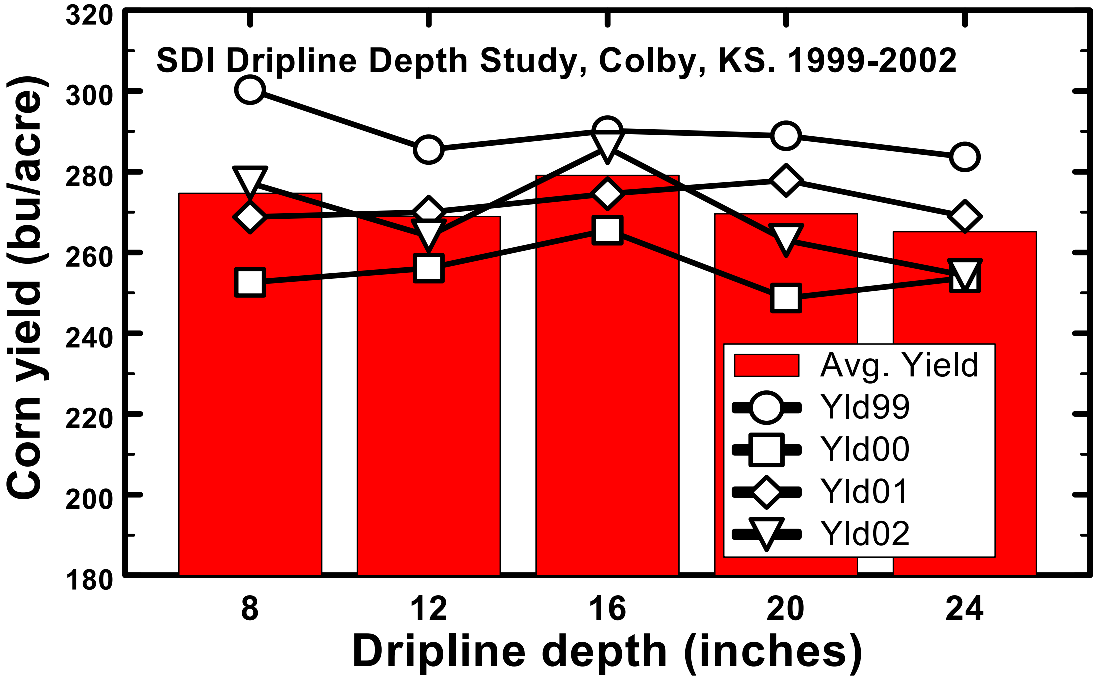

Figure 2. Field corn grain yields as affected by dripline depth, Colby, Kansas, 1999-2002.

Water use and Water Use Efficiency

Water use for the 8-ft soil profile was not affected in any given year but when averaged over the four years was slightly less for the 20 and 24-inch dripline depths (Table 1). There were no significant differences in water use efficiency (grain yield divided by water use) in any year. The fact that no appreciable differences exist suggests that all treatments received adequate water and that dripline depth in the range of 8-24 inches is not a major design issue in terms of water use and water use efficiency.

Soil Water in the Top Three Feet

Visual observations of the various treatments throughout the irrigation seasons indicated that the 8 and 12 inch dripline depths had more wetting at or near the soil surface. This might be an advantage in germinating crops, but has little or no advantage once the crop is germinated. Damp soil surfaces can result in higher evaporative losses and perhaps more weed growth. Visual observations indicated that there were slightly higher flushes of late-season grasses for the 8-inch dripline depth, but the small weed pressure increase was not considered to affect the corn crop. Soil water measurements in the top 3 ft are shown for 2002 in Figure 3. The graph shows a few instances where soil water is noticeably higher for the shallower dripline depths in the top foot of the soil profile but the deeper dripline depths show slightly higher soil water in the second and third foot of the soil profile. Under the full irrigation scheme used in this study, none of the soil water differences would be considered of critical importance, with the exception of the possible germination enhancement by shallower dripline depths that was previously discussed.

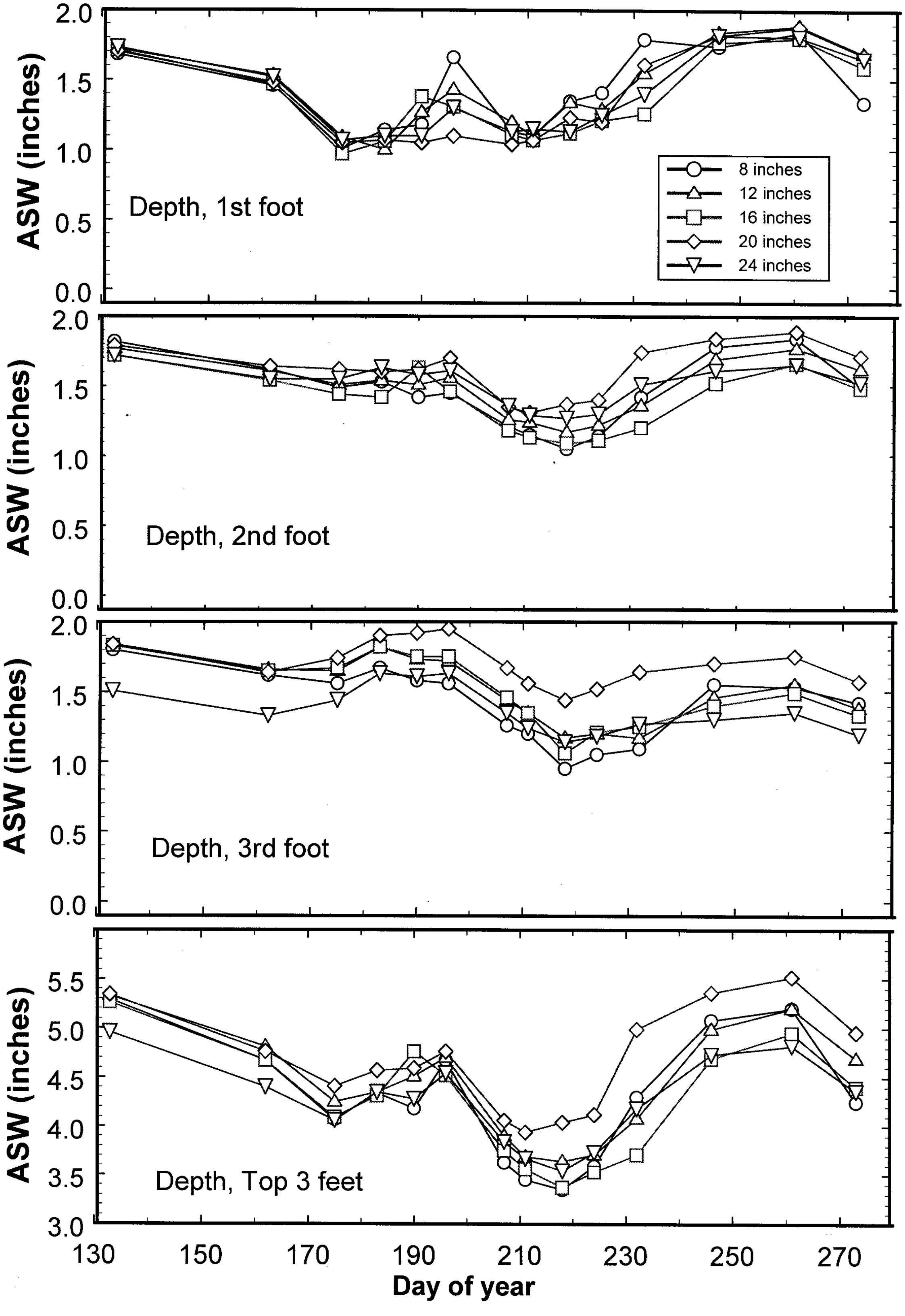

Figure 3. Soil water conditions in the top 3 feet as affected by dripline depth in the dry year of 2002.

Long-Term Flow Measurements and Soil/Water Interface Temperatures.
As previously discussed the water source for this SDI system is an unlined surface reservoir. It was hypothesized that there might be an interaction between dripline depth and emitter clogging because there might be differences in water temperature at the dripline depth. Both biological and chemical clogging hazards are temperature dependent and can be higher with warmer temperatures.

Flowrates did vary appreciably over the course of the five seasons reflecting decreases caused by the silt and biological loads experienced by the driplines (Figure 4). During the course of each season, dripline flowrates would decrease. Acid and chlorine were injected periodically every 2-3 weeks for a period of 1 hour (approximately 50 ppm chlorine and acid to adjust to pH of 4), but dripline flushing during 1999-2001 was restricted to the spring and fall. During 2002, it became more apparent that clogging was becoming more difficult to manage with just acid and chlorine, so one additional flushing was added mid-season. By the end of 2002, dripline flowrates were 10-25% lower than the initial flowrate. There was no clear pattern in terms of flowrate decreases as affected by dripline depth (Figure 4.). Some of the differences that did exist were more related to the random nature of a particular plot being affected by clogging rather than a specific dripline depth treatment. In 2003, additional flushing events were added (approximately monthly) along with more aggressive acid and chlorine treatments (about 2 hours for each event followed by leaving the system off overnight and then flushing again). This stricter maintenance regimen helped recover much of the flow that had been lost during the previous seasons and the treatment average (4 plots) flowrates were within approximately 8% of the initial flowrates at the close of the season.

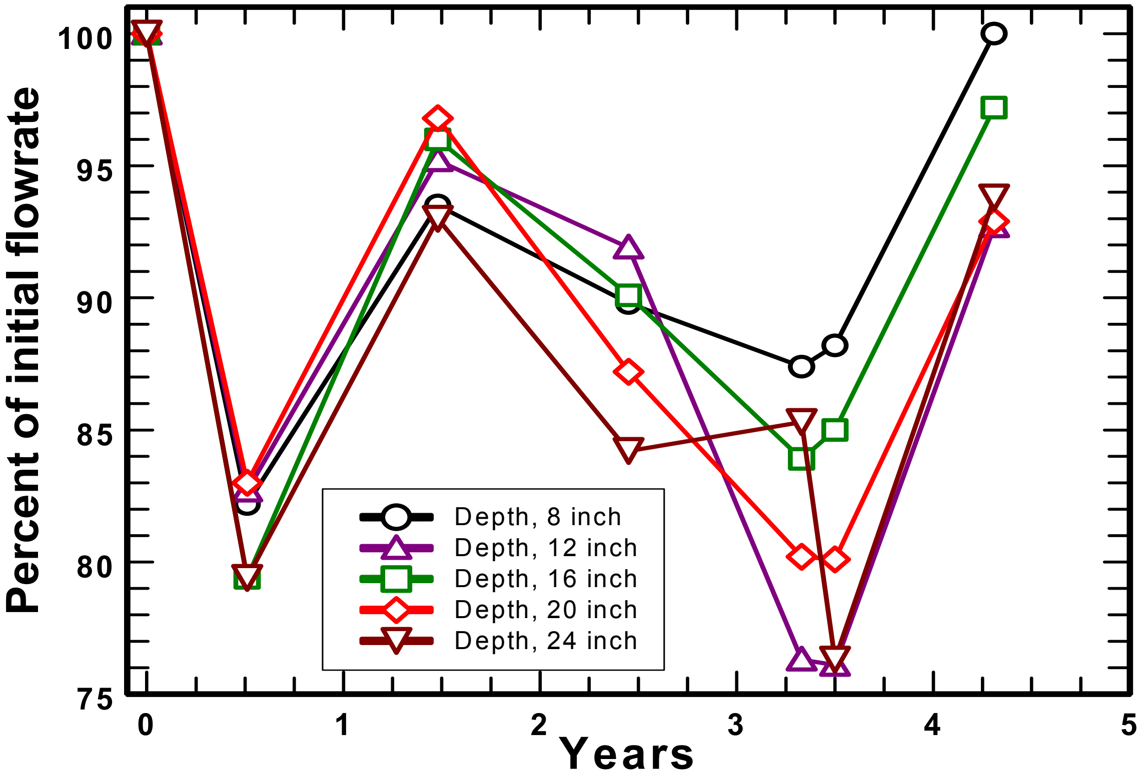

Figure 4. Dripline flowrate as percentage of initial flowrate for the 5 different depths, 1999-2003.

In 2003, temperatures were measured at the soil/water interface at the dripline at a point 100 feet from the water inlet. The first measurements were made in early July just prior to the first irrigation of the corn. The corn was approximately 18 inches tall at this point and did not fully shade the soil surface. Soil temperatures near the surface and also at the different dripline depths were higher at this point in time than they were at any time during the rest of the season. This is because the solar radiation load to the soil surface was still high due to less shading and because no large increment of water at the dripline had been added at this point. Temperatures prior to the first irrigation were varying diurnally for the 8-inch depth from about 75-80 °F and less variable at the deeper depths in the range of 75 °F (Figure 5.). This compared with soil surface temperatures varying diurnally from 75 to 105 °F. During the first irrigation event, the temperatures varied with the water inlet temperature falling about 5 degrees during the initial portion of the event while the water temperature fell approximately 10 °F and then slowly rising back to about 74°F as the water temperature at the inlet increased to about 73 °F. Much of the diurnal variance for the 8-inch dripline depth disappeared following this irrigation event suggesting the large temperature buffering capacity of the wetted soil.

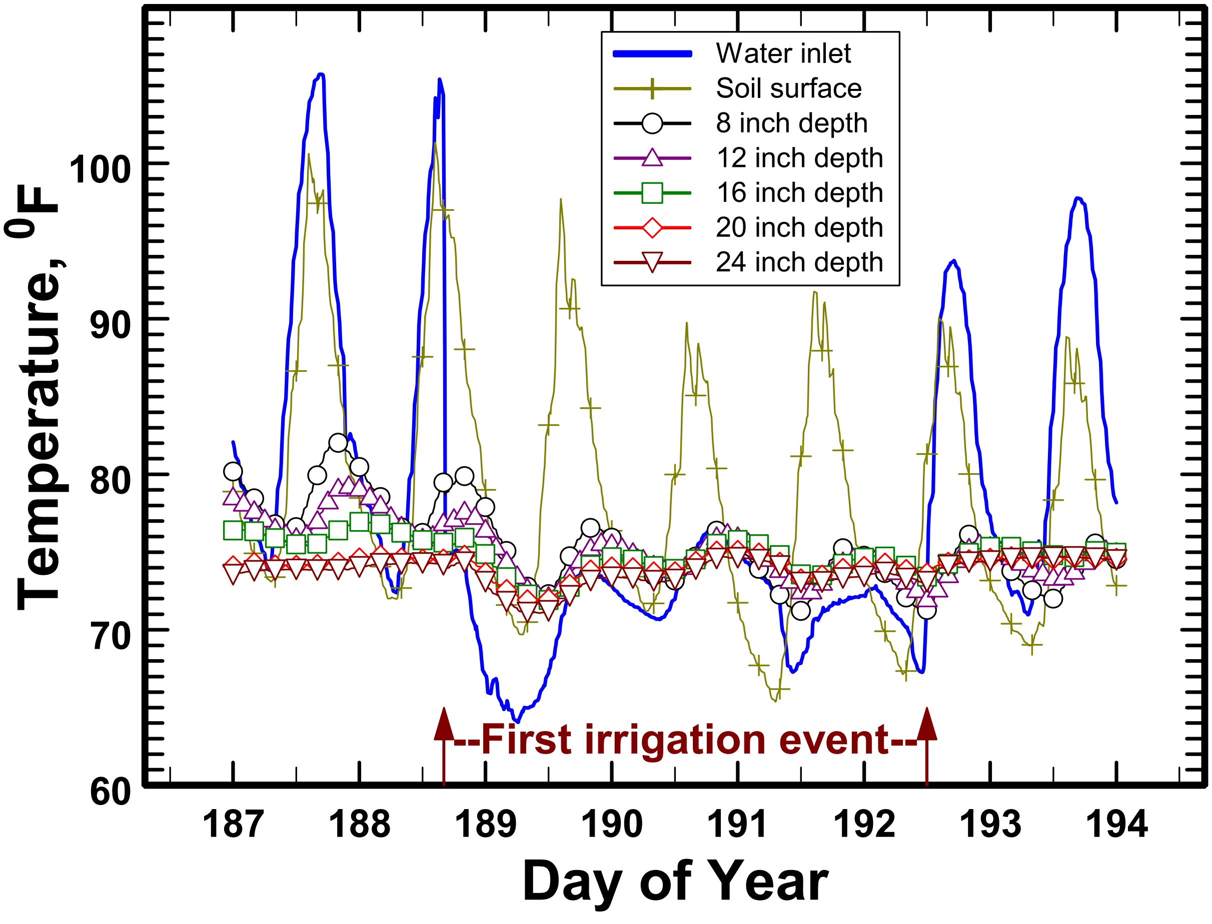

Figure 5. Temperatures at the water inlet, near the soil surface and near the dripline for the 5 dripline depths prior to corn canopy closure and the first irrigation in 2003.

Later in the season (August), temperatures at all of the various dripline depths ranged from approximately 72-73 °F with even cold irrigation water (approximately 62 °F) only decreasing the dripline temperature 1-2 degrees (Figure 6). No appreciable temperature differences were attributable to dripline depth. This suggests that dripline depths of 8-24 inches would greatly moderate temperature variations that would occur for driplines placed on the soil surface. These relatively stable temperatures may be helpful in reducing biological and particularly chemical clogging hazards.

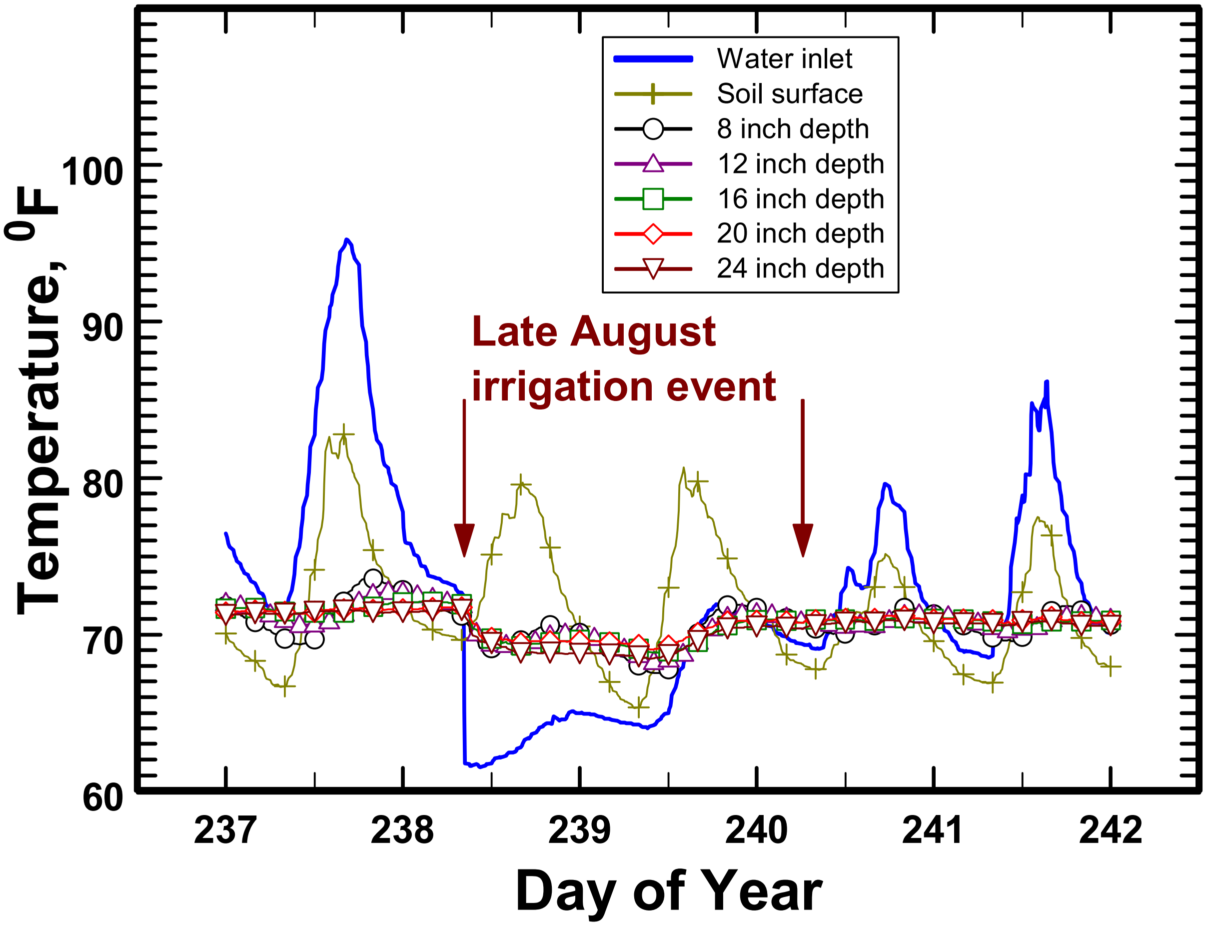

Figure 6. Temperatures at the water inlet, near the soil surface and near the dripline for the 5 dripilne depths near the end of the corn irrigation season in 2003.

SUMMARY AND CONCLUSIONS

Corn production was not strongly affected by dripline depths ranging from 8-24 inches in this study where crop germination was not a factor. A slight tendency existed for corn yields to be reduced for the deepest dripline depth (24 inches) which might be related to early season growth or water and nutrient availability. The deep, well drained silt loam soil with good water holding capacity is conducive to deep rooting of field corn and this may be part of the reason there was no strong effect of dripline depth on corn production. Water use and water use efficiency for the 8-ft soil profile also were not strongly affected.

The shallower 8 and 12-inch dripline depths resulted in slightly higher amounts of soil water at the row location in the top foot of the soil profile. This may be advantageous in years where irrigation is needed for germination, but may also cause larger soil evaporation losses during the cropping season.

Flowrates varied throughout the 5 seasons indicating some clogging problems that were occurring due to the pumping of water from a reservoir. More aggressive maintenance during the 2003 season remediated much of the clogging problems. There was no apparent effect of dripline depth on clogging in this study.

Dripline depths of 8-24 inches resulted in temperatures at the soil/dripline interface in the 72-77 °F range for the whole irrigation season. The greatest amount of temperature variation occurred for the 8-inch depth, but it was only 4-6 degrees during the period preceding canopy closure and the first irrigation. After canopy closure and the start of the irrigation season, temperatures at the dripline were generally about 72-73 °F.   These temperatures may have helped reduce biological and chemical plugging hazards.

The results indicate that there is little effect of dripline depths ranging from 8-24 inches for corn production on the deep silt loams of western Kansas provided there is adequate water for establishment of the crop. Other factors not specifically examined in the study such as producer preferences, tillage schemes, rodent management, need for surface wetting for germination, and installation draft requirements and cost might be better criteria for the dripline depth decision.

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

Long-Term Salinity Buildup on Drip/Micro Irrigated Trees in California

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Executive Summary

The Irrigation Training and Research Center (ITRC) of Cal Poly State University, San Luis Obispo, CA, hypothesized that there is salinity accumulation in the root zone of tree crops that have been irrigated with drip or micro-spray irrigation systems, located in arid and semi-arid regions. Therefore, a study was conducted by ITRC during the summer of 2002 to examine the long-term impact of drip and micro irrigation on salinity accumulation in orchards, focusing on the salinity concentration pattern across a soil profile. The project also provided information to support recommendations on the most effective and efficient leaching techniques.

During the study, two rows of soil cores were collected in ten orchards that had been irrigated with drip or micro-sprayers. Eight of the ten fields were located in the semi-arid climate of the west side of the San Joaquin Valley, CA; the other two were located in Coachella Valley, CA. Fields were selected that had a known irrigation history, without a high water table. Soil samples were collected to a depth of 2.4 m and then tested for ECe. Graphs of soil salinity concentrations for soil profiles 2.4 m deep across two tree rows were developed from these data.

Key points from the salinity accumulation study include:

- In drip-irrigated orchards, there is a significant amount of salt accumulation on the edges of the wetted areas along tree rows.
- Deep percolation with drip still leaves substantial amounts of salt in the soil.
- Orchards with micro irrigation systems accumulate salt in the middle of the tree rows, which is on the edges of the wetted patterns.
- Soil texture effects salt accumulation to a certain extent. There was more salt accumulation in heavier soils compared to sandy soils.

The results from the study suggest that salinity accumulation is a serious concern when an orchard that has been irrigated with drip/micro is removed and a new crop is planted. Many of the fields studied had salinity concentrations on the edges of wetted areas that could be detrimental to a new crop if the salts were not leached prior to planting.

The finding of this study prompted ITRC to conduct a reclamation leaching study. The reclamation leaching study was completed to quantify the leaching water required to remove salts from the effective root zone of trees. This experiment tested a new reclamation leaching technique – multiple lines of low-flow drip tape used to apply water to the area of salinity accumulation along a tree row. The reduction in salinity with a given depth of deep percolation is predictable. The new leaching procedure uses about 1/3 – ½ of the volume of water normally needed for reclamation irrigation.

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Background

Under optimum management conditions, crop yields remain at potential levels until a specific threshold electrical conductivity of the soil water solution is reached. When salinity increases beyond this threshold, crop yields are presumed to decrease linearly in proportion to the increase in salinity.

Salinity build-up becomes particularly important when trees are removed and the field is replanted. When replanted (with new trees or possibly with a less salt tolerant crop), the salt that has accumulated in the soil may inhibit crop growth and reduce tree vigor.

Procedures to Determine Soil Salinity

During the study, two rows of soil cores crossing 2 tree rows each, with samples in a core row taken 0.3 – 0.6 m apart horizontally, were collected in ten orchards that had been irrigated with drip or micro-sprayers. Soil samples were collected to a depth of 2.4 m and then tested for ECe. Graphs of soil salinity concentrations for soil profiles 2.4 m deep across two tree rows were developed from these data.

Site descriptions. Eight of the ten fields studied were located along the west side of the San Joaquin Valley, CA. The fields have the following characteristics that are pertinent to the study:

- There is little annual rainfall (about 15-17 cm), so salts are not leached out of the root zone from winter precipitation.
- Some fields are irrigated with water from the California Aqueduct and other fields are irrigated with deep well water.
- Some orchards have been irrigated with drip or micro-sprayers for over 20 years.
- There is a concern that leaching large quantities of salts from the root zone would have a negative impact on regional water quality.

Fields were selected that had a known irrigation history and known water quality. Therefore, the total amount of water applied to an orchard and the salt load distributed by the irrigation water could be considered when deriving conclusions.

In addition to the eight fields studied in the west side of the San Joaquin Valley, soil samples were also collected from two fields in Coachella Valley, CA. Therefore, the salinity patterns in soils having a different climate and a different soil type could be compared to the results from the San Joaquin Valley.

Soil Sampling. A direct-push type, hydraulically powered soil sampler was used to collect soil cores. The soil sampler was a model 9800E manufactured by Concord Environmental Equipment, located in Hawley, MN. This machine included an engine used to power a hydraulic cylinder, which is used in conjunction with a hydraulic percussion hammer to force the sampling barrel into the soil.

To develop a grid for each soil profile, 2.4 m deep soil cores were removed across two tree rows. One tube was used for retrieving soil to a depth of 1.2 m; a separate tube was used for retrieving a soil core to 2.4 m below the soil surface. A new clear plastic tube was used for each core that was removed.

Nine individual soil samples were collected from each 2.4 m core at increments of 0.3 m, starting at the surface and ending at a depth of 2.4 m. Approximately 300 grams of soil were collected for each sample to be tested.

Each soil sample was sealed in a plastic bag and labeled according to the specific location where it was taken. Just prior to bagging, the approximate soil moisture content for each soil sample was determined using the "feel method" and recorded.

Figure 1. Soil core sampler in the field.

A row of soil cores was removed perpendicular to the tree rows. The first soil core was taken close to the midpoint between two trees, in line with the tree row. The last core in the row was removed two tree rows over near the midpoint between two trees, in line with the tree row. The horizontal distance between soil cores varied between 0.3 m and 0.8 m. Core spacing was 0.3 m in areas wetted by the irrigation system. Between the wetted zones, soil cores were typically spaced 0.6 m. Two rows of soil cores, in different locations, were taken in each field. The two locations were not necessarily located along the same tree rows as illustrated in Figure 2.

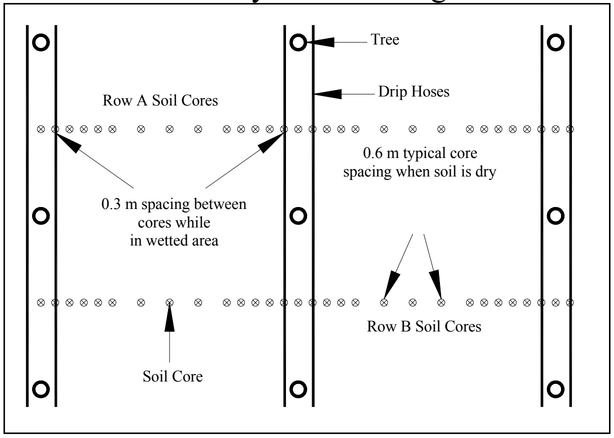

Figure 2. Plan view of typical soil core locations.

Results of Salinity Measurements

In this paper soil salinity results from a few cases are shown. They are typical of what were found. It can be seen that the salinity is more concentrated in drip systems than with micro-spray systems. This is hardly surprising because the same amount of applied salt is spread out over more soil area – resulting in the same amount of total salt, but less pockets of concentrated salt.

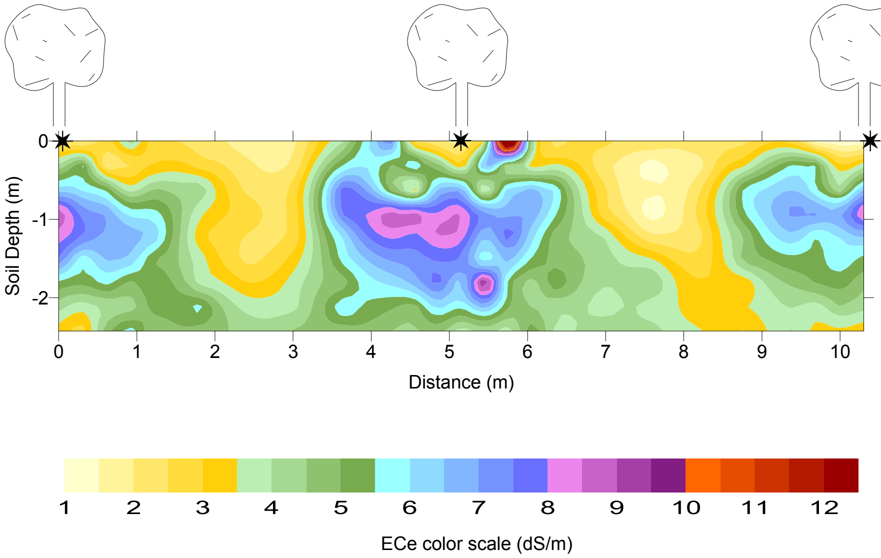

Figure 3. Field 5 (#4100) soil salinity concentration pattern (Location A). One drip hose per row, 3 emitters/tree. 5.2 m x 5.2 m tree spacing. Pistachios planted 1982. Predominant soil texture: loam. Weighted ECw = 0.46 dS/m. Average ECe = 4.5 dS/m

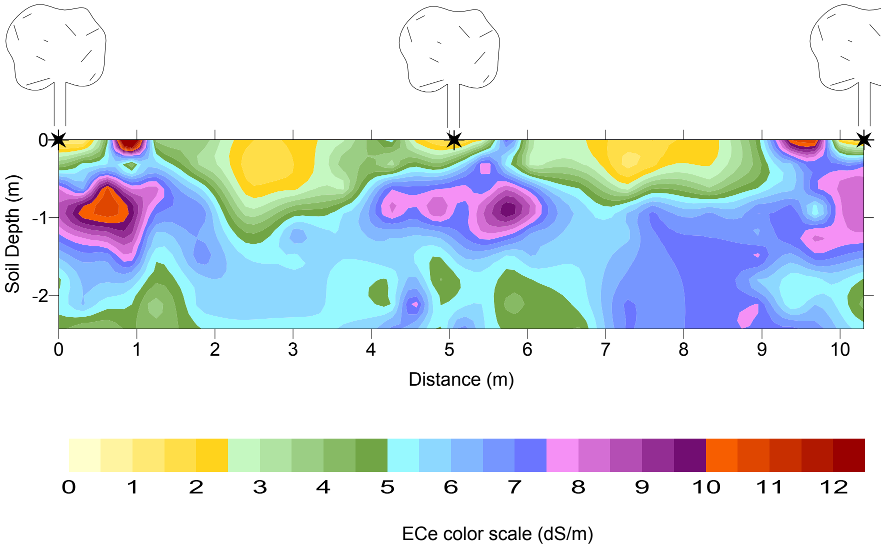

Figure 4. Field 5 (#4100) soil salinity concentration pattern (Location B) Same soil as Location A in Fig. 3. Drip. Average ECe = 5.4 dS/m

A comparison of Figures 3 and 4 show that soil salinity patterns are quite varied – even with the same irrigation management, emitter spacing, and soil type. This was typical of what was seen. This definitely shows the limitations of various 3-D soil salinity models in predicting patterns of salinity accumulation.

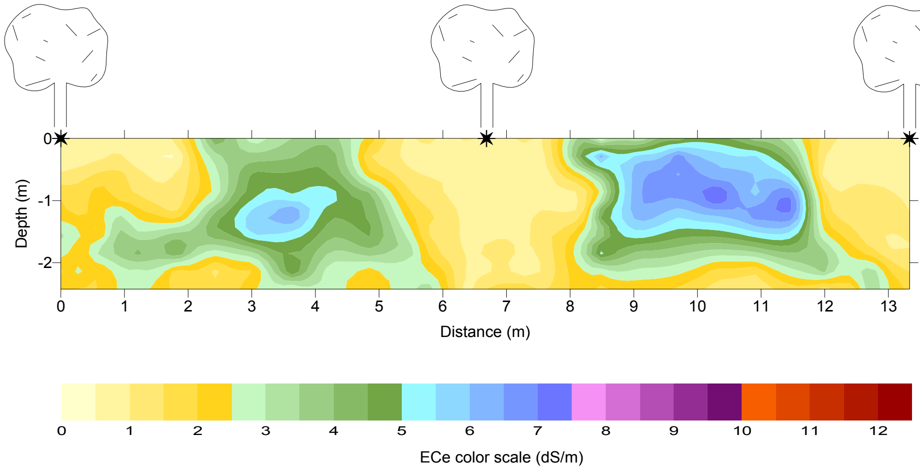

Figure 5. Field 6 (#4830) soil salinity concentration pattern (Location A). One microsprayer/tree. 6.7 m x 4.6 m tree spacing. Pistachios planted in the late 1960s. Loamy sand. Weighted average ECw = 0.44 dS/m. Average ECe = 3.0 dS/m.

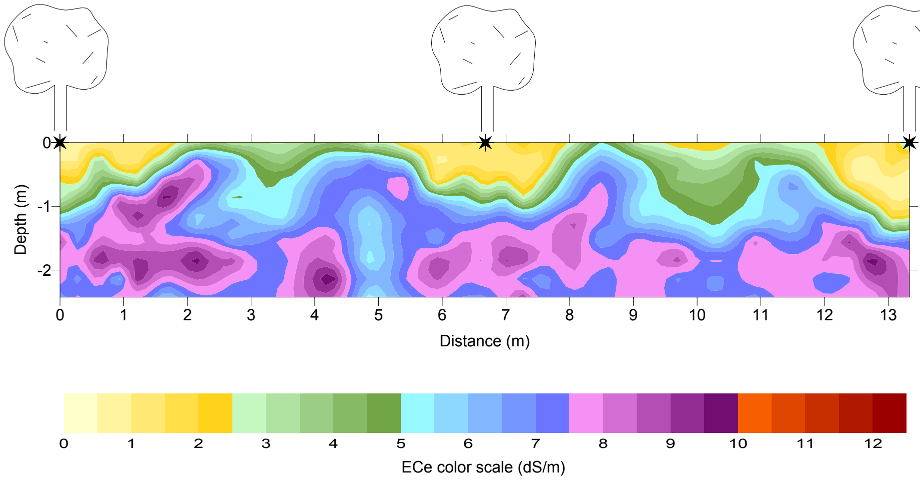

Figure 6. Field 6 (#4830) soil salinity concentration pattern (Location B)
Not as sandy as Location A. Average ECe =5.9 dS/m

Conclusions from the Salinity Accumulation Study

Key points from the salinity accumulation study include:

- In drip irrigated orchards, there is usually a significant amount of salt accumulation on the edges of the wetted areas along tree rows. Additionally, we found that deep percolation with drip still leaves substantial amounts of salt in the soil.
- Orchards irrigated with micro-sprayers seem to accumulate salt between the tree rows, which is on the edges of the wetted patterns.

- Some of the salt applied through irrigation water is being leached from the root zone.
- Soil texture effects salt accumulation to a certain extent. There was more salt accumulation in heavier soils compared to sandy soils.

The results from the study suggest that salinity accumulation can be a serious concern when an orchard that has been irrigated with drip/micro is removed and a new crop is planted. Many of the fields studied had salinity concentrations on the edges of wetted areas that could be fatal to a new crop if the salts were not leached prior to planting.

Introduction – Soil Salinity Reclamation Leaching

ITRC conducted a reclamation leaching experiment, in a pistachio orchard south of Huron, CA, during the winter of 2002-2003. The study was conducted to quantify the leaching water required to remove salts from the effective root zone of trees. This experiment tested a new reclamation leaching technique – multiple lines of low-flow drip tape were used to apply water to the area of salinity accumulation along a tree row.

The pistachio orchard was planted in 1982. The trees are drip irrigated with two drip hoses per tree row. Historically, the field where the leaching study was conducted has been irrigated with both surface water and well water. The historical weighted average EC of the irrigation water (ECw) was 0.70 dS/m. The water applied during the reclamation leaching experiment had an ECw of 0.51 dS/m.

Figure 7 and Figure 8 illustrate the pre-leaching salt distribution pattern in an 2.4 m (8-foot) deep soil profile. There is salt accumulation on the edges of wetted patterns along the tree rows. The area between the tree rows is unaffected by drip irrigation and has virtually no salinity buildup from irrigation – as expected because the wetted area from the drip system did not extend to that area.

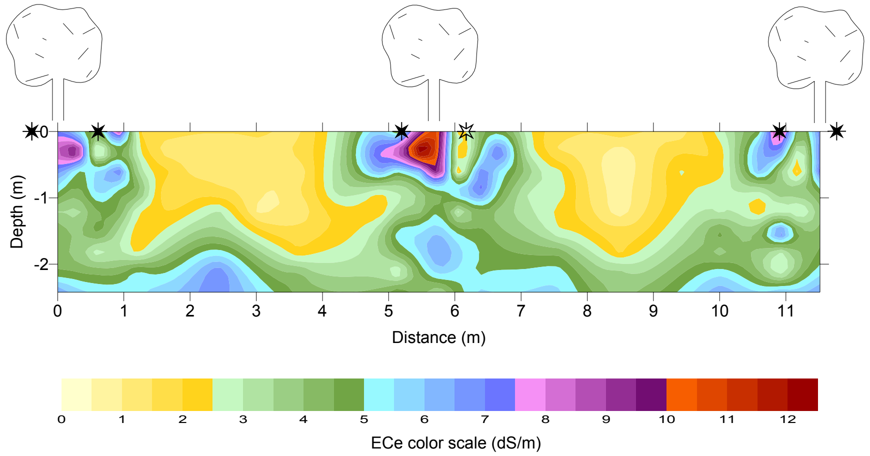

Figure 7. Typical soil salinity concentration profile in the field where the reclamation leaching study was conducted.

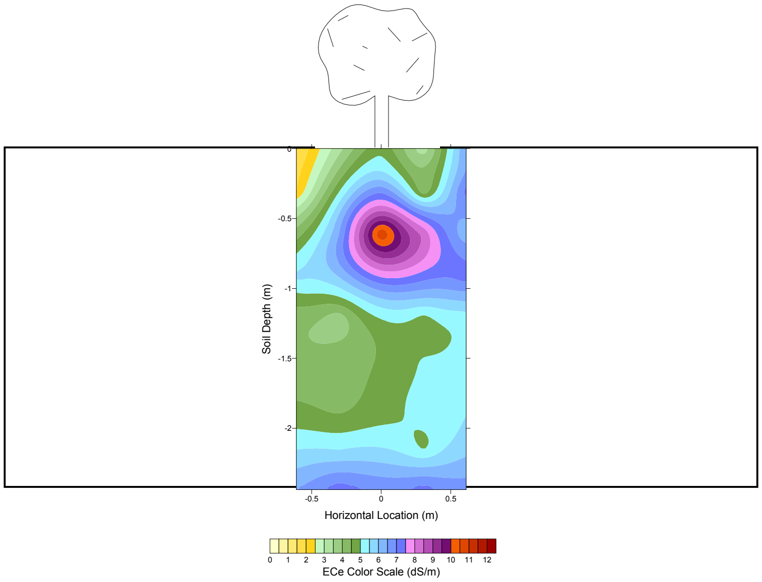

Figure 8 High salinity concentration along the tree row prior to leaching
Average ECe of 6 locations along the same tree row

Leaching Procedure

Six lines of low-flow drip tape were placed along one row of trees (30 trees total) and used to apply the leaching water. Three lines of drip tape were placed on either side of the tree. The spacing between the drip lines was .305 m (1 ft.). The emitter spacing was also .305 m along the tapes. The nominal flow of the drip tape was 1.64 LPH per meter (0.22 gpm/100 ft). The actual average application rate during leaching was approximately .5 cm/hr (0.2 inches/hour).

Figure 9. Low-flow drip tapes, spaced .3 m (1 ft.) apart, were used to apply reclamation leaching water in a pistachio orchard south of Huron, CA.

The practice of leaching using multiple lines of drip tape allows water to be applied where there is salt accumulation along the tree row, as opposed to putting water on the entire area of the field. Since reclamation leaching requires a relatively large depth of water, this technique offers the potential for significant water savings for reclamation leaching.

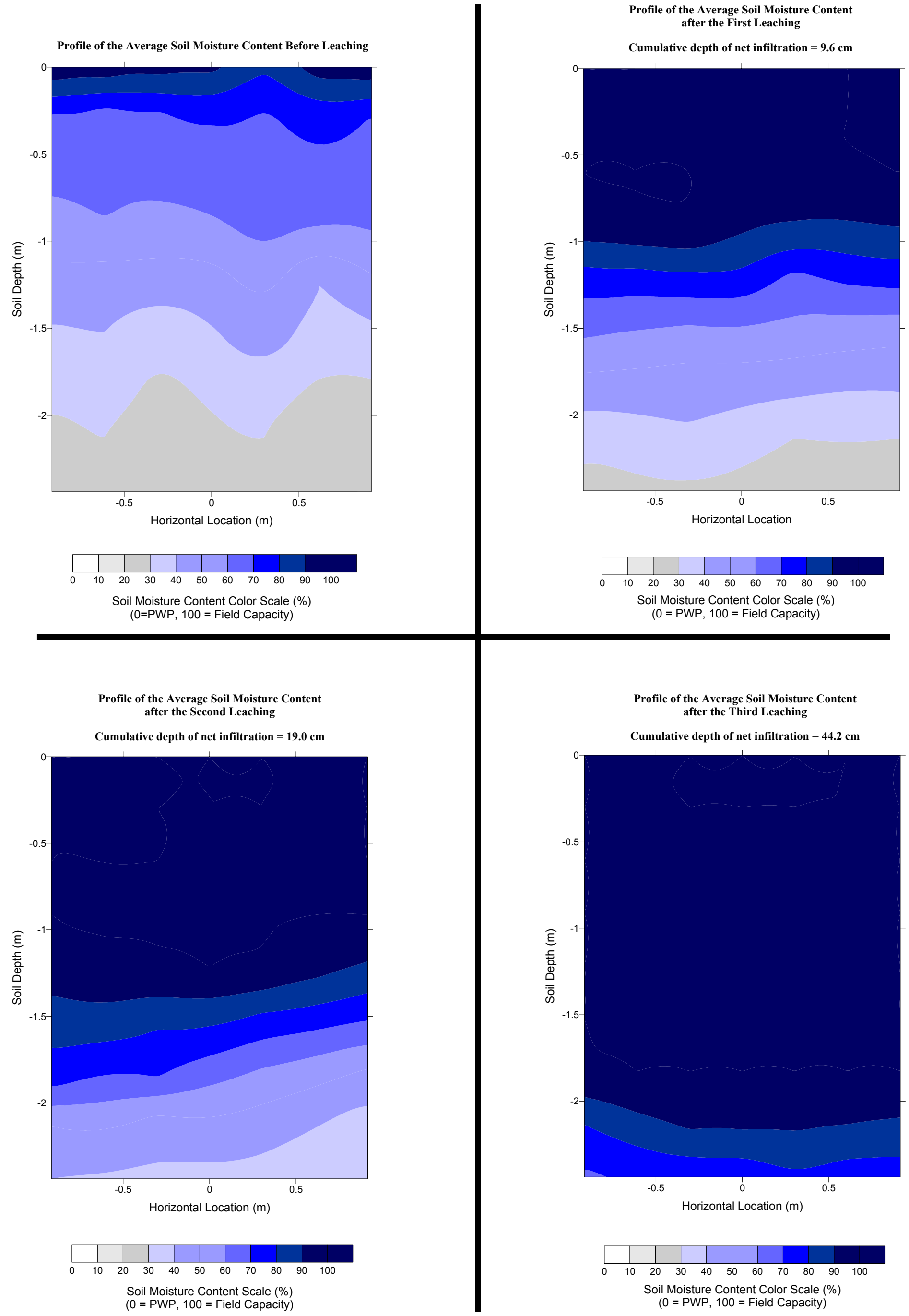

Figure 10. Profiles of the average soil moisture content after consecutive leaching applications.

Figure 10 illustrates increasing soil moisture contents down through the 2.4 m (8-foot) soil zone as increasing depths of leaching water were applied. The surface soil layer had a significantly greater depth of water that percolated through it compared to the soil layer 2.4 m deep – this is because the soil moisture contents of intermediate soil zones had to be increased to field capacity.

During the experiment, leaching water was applied four times. Soil samples were collected at six different locations along the tree row after each leaching. Evapotranspiration (specifically evaporation since the trees were dormant and there was no weeds in the area of consideration during the experiment) and precipitation were considered when determining the net depth of water infiltrated. After four leaching applications, there was approximately 56 cm (22 inches) of net infiltration over the 1.5 m (6-foot) width that the drip tapes spanned.

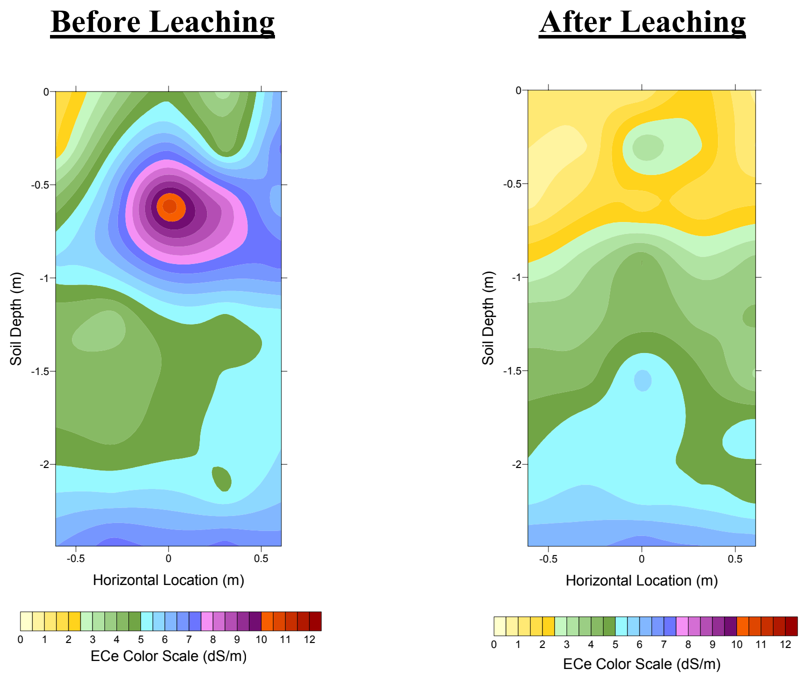

Figure 11. A comparison of the average ECe along the tree row before leaching and after 56 cm (22 inches) of net leaching water infiltration using low-flow drip tape.

Leaching Study Conclusions

A salt reduction/equivalent leaching depth relationship was developed (see Table 1 and Figure 12). An equivalent leaching depth was defined as the depth of net leaching water that percolated through a soil zone, divided by the depth of a soil zone (each having the same units). The depth of irrigation water applied for leaching must be greater than the leaching water because some of the applied water goes to soil moisture storage and evapotranspiration during reclamation.

$$\text{Equivalent leaching depth} = \frac{\text{net leaching depth that percolated past a soil zone}}{\text{soil zone depth}}$$

For example, if 3 m of water deep percolated (leached) past a soil depth of 2 m, the equivalent leaching depth would equal (3m/2m) = 1.5. To fill the root zone to field capacity and get 1 meter of net leaching water may require 1.25 meters or so of water application.

Table 1. Approximate salinity reductions for various equivalent leaching depths using multiple lines of low-flow drip tape (silt loam).

Equivalent leaching depth	Approximate fraction of original salt concentration		
0.2	0.80	to	0.60
0.4	0.57	to	0.38
0.6	0.43	to	0.28
0.8	0.36	to	0.23
1.0	0.30	to	0.20

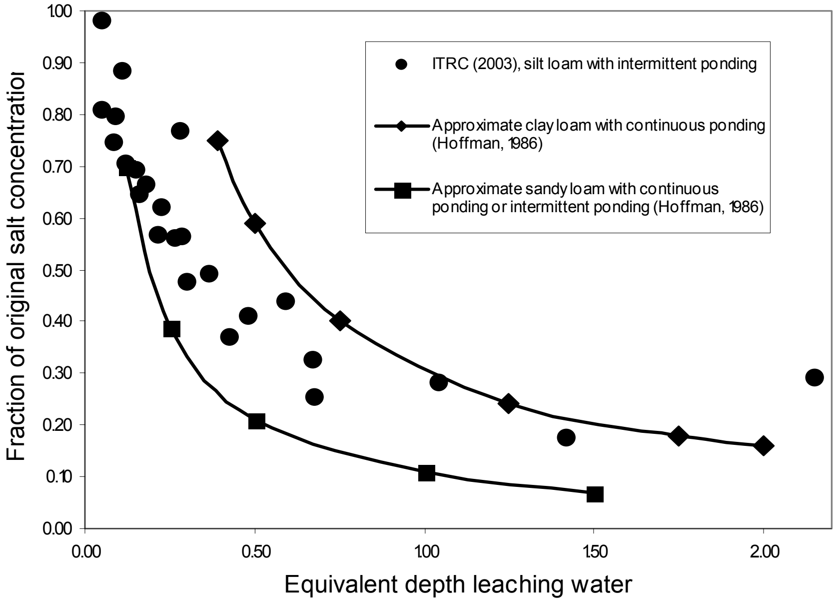

Figure 12. Salt reduction/equivalent leaching depth relationship developed by applying leaching water using multiple lines of low-flow drip tape.

The relatively high application rate of 0.5 cm/hr (0.2 in/hr) in this experiment caused surface water ponding. Therefore, it is reasonable to find the curve for silt loam between the clay loam with continuous ponding and the intermittent ponding curves developed by Hoffman (1986). If the emitters had lower discharge rates, we hypothesize that the efficiency of salt removal would have been greater.

Summary

In summary, there is salt accumulation along the tree rows of many orchards irrigated with drip/micro irrigation systems. Salinity build-up becomes particularly important when trees are removed and the field is replanted. The most effective and efficient reclamation leaching practices for tree crops irrigated with drip/micro include:

i. Apply leaching water only to the areas with salt accumulation – typically along the tree row with drip
ii. Use low application rates for maximum effectiveness of salt removal
iii. Multiple lines of low-flow drip tape can be used to achieve (i) and (ii)
iv. Consider the point of diminishing return for reclamation leaching: we found quantities of leaching water greater than 0.8 equivalent depths result in insignificant salt reduction (for a typical silt loam soil using intermittent leaching)
v. Use intermittent applications of reclamation leaching water, which minimize the effects of bypass flow

Acknowledgements

Funding for this study was provided by Cal Poly State University, using funds of the California Statue University Agricultural Research Initiative and the California Dept. of Water Resources. Participating growers included Bob Viets (West Hills Farms, Coalinga); Gary Robinson (Gold Coast Pistachio, Huron); Dennis Elam (Paramount Farming Co., Lost Hills); Cort Blackburn (Blackburn Farming Co., Firebaugh); Cleo Ornelas (De Bonne Ranch Mgmt, Coachella); Ole Anderson (HMS Ranch Mgmt, Coachella).

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Drip Irrigation in Salt Affected Soil

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Introduction

Excessive soil salinity can reduce crop yields. Thus, salinity control of irrigated land is necessary to prevent yield reductions where saline water is used for irrigation or where saline shallow water tables exist. Salinity control consists of applying sufficient water, called a leaching fraction, to flush salts out of the root zone. The leaching fraction is defined as the percent of the applied water that percolates below the root zone. A leaching fraction of 20 percent means that 20 percent of the applied water percolates below the root zone.

Soil salinity is normally characterized by the electrical conductivity of a saturated extract (ECe). The ECe is determined by collecting soil samples from a field, drying and grinding the soil, saturating the soil with distilled water, and then extracting the solution from the soil. The electrical conductivity (EC) of the extracted solution is measured and is called the EC of the saturated extract or ECe. The higher the amount of salts in a soil, the higher the ECe.

The effect of leaching on soil salinity depends on the amount of leaching water and its flow pattern and the salinity of the irrigation water. Under drip irrigation, water flows from the drip line in a somewhat radial pattern that depends on soil type and existing soil moisture content. Soil moisture content is the highest near the drip line and decreases with distance from the drip line.

Patterns of Salt Under Drip Irrigation

Under surface drip, salt patterns around a drip line reflect the water flow patterns. Low soil salinity occurs near the emitter (Figure 1). Zones of low salinity also extend downward beneath the drip lines, the result of leaching directly below the drip lines. Salinity increases with depth and distance from the emitter. Midway between the drip lines, soil salinity near the soil surface is very high because little or no leaching occurs at that location. The salinity values near the emitter reflect the salinity of the irrigation.

Salt patterns under subsurface drip irrigation differ slightly because of upward flow of water above the drip line. Figure 2 shows a salt pattern under subsurface drip irrigation where the drip line is buried about 5 inches deep. In the vicinity of the drip tape, low soil salinity occurs. Salinity increases with lateral distance from the drip tape, with high salinity under the furrow. Very high soil salinity occurs above the drip tape. Salts carried by water flowing upward from the drip tape cause this high salinity. No leaching occurs above the drip line during the drip irrigations.

The salinity of the low salt zone depends largely on the salinity of the irrigation water. However, the extent of the zone of relatively low salt soil depends on the leaching fraction. Figure 3 shows salt patterns under surface drip irrigation for leaching fractions of 5 and 25 percent (Hoffman et al., 1985). The larger the leaching fraction, the larger the zone of low soil salinity, and the smaller the zone of high soil salinity. As with surface drip irrigation, the zone of low salinity soil also increases as the leaching fraction increases for subsurface drip irrigation (Figure 4).

If no leaching around the drip line occurs, then soil salinity can increase in the vicinity of the drip line as shown in Figure 4 for April. Soil salinity was highest near the drip line and decreased with horizontal distance and with depth. The opposite in salt distribution around the drip line occurred when leaching occurred as shown in Figure 4 for July.

In many areas of California, excessive levels of soil salinity are caused by upward flow of shallow saline ground water. For furrow and sprinkler irrigation, soil salinity near the soil surface is controlled by the salinity of the irrigation water, while soil salinity at the deeper depths is controlled by the salinity of the shallow ground water. Under drip irrigation, however, the salinity in the near vicinity of the drip line is controlled by the salinity of the irrigation water, the amount of leaching, and the flow pattern around the drip line.

Figures 6 and 7 show salt patterns around the drip line for different depths to the water table and irrigation water salinity. Soil salinity in Fig. 6 (Site DI) was less than about 2 dS/m for all depths and distances from the drip line. The EC of the irrigation water was 0.34 dS/m. These ECe's were less than the threshold ECe 2.5 dS/m for tomatoes. At this location, the EC of the shallow ground water ranged from 8 to 11 dS/m. However, the depth to the water table generally was about 6 feet, and thus, little upward flow of shallow ground water into the root zone apparently did not occur. (Note: The threshold ECe value is the maximum average root zone ECe at which no yield reduction should occur (Maas, 1990). The actual root zone salinity under drip irrigation at these sites is unknown because of spatially varying patterns of soil salinity, soil moisture, and probably root density around drip lines. The threshold value is provided as a reference only to indicate a potential for yield reduction.) The salt pattern in Fig. 6 for Site BR shows much higher levels of soil salinity with the smallest values near the drip line, where the root density is likely to be the highest. The EC of the irrigation water was 0.34 dS/m. Near the drip line, ECe value were between 3 and 4 dS/m, but values as high as 7 to 10 dS/m occurred elsewhere in the soil profile, caused by upward flow of saline, shallow ground water.

Soil salinity was the highest near the drip line for Site DE in 2000 (Fig. 7). At this location, the irrigation water EC was about 1.1 dS/m. However, a severe spring rainstorm caused ponding of water at this location, which leached the salts out of the top 1 of soil. The following year the pattern, the ECe were the least near the drip line and increased with depth and horizontal distance from the drip line (Fig. 7). The higher values of 2001 near the drip line compared with the values of Site BR (Fig. 6) near the drip line appear to reflect the differences in the irrigation water electrical conductivity.

Effect of Soil Salinity on Tomato Yield under Drip Irrigation

Several studies have shown a potential for producing processing tomatoes, a moderately salt sensitive crop, under saline conditions. Hand-harvested tomato yields ranged from 129.1 Mg/ha to 140.5 Mg/ha in 1991 and from 110.7 Mg/ha to 145 Mg/ha in 1993 under saline, shallow ground water conditions (Ayars et al., 2001). Machine-harvested yields of 1993 ranged from 71.7 Mg/ha to 112.0 Mg/h. Depth to the shallow ground water was less than 2 m and its salinity was about 5 dS/m. Soil salinity ranged from about 4 dS/m to 10 dS/m for depths less than 1 m. About 10% of the water requirement of tomatoes was supplied by upward flow of the shallow ground water.

Surface drip irrigation was used to irrigate processing tomatoes under saline conditions (Pasternak et al., 1986). Treatments consisted of different levels of irrigation water salinity with electrical conductivity of 1.2 dS/m, 4.5 dS/m, and 7.5 dS/m. Results showed a yield reduction of about 10% to 12% for the 4.5 dS/m water compared to the 1.2 dS/m irrigation water, while yields of the 7.5 dS/m were reduced by about 60%.

Drip irrigation of processing tomatoes was compared with sprinkler irrigation in the salt-affected soil along the west side of the San Joaquin Valley (Hanson and May. 2003). Tomato yields under drip irrigation were 5 to 10 tons per acre more than under sprinkler irrigation. Levels of soil salinity are shown in Figures 6 and 7, where ECe near the drip line ranged from values less than the threshold ECe of tomatoes to values greater than the threshold value. However, no trend in yield was found among the three sites suggesting that soil salinity under drip irrigation had a smaller effect than would be expected under low-frequency irrigation. This study also showed that maximum yields under drip irrigation occurred for water applications of about 100 percent of the potential crop evapotranspiration.

Discussion and Conclusions

High irrigation frequency drip irrigation has a potential for affecting the relationship between crop yield and root zone soil salinity in several ways. First, relatively high levels of soil moisture content around the drip line occur throughout the irrigation season because of the high frequency irrigation and the wetting pattern for a properly managed drip system. Second, soil salinity is the least in the zone of maximum soil moisture content. Third, high frequency irrigation prevents salt accumulation near the drip line if sufficient leaching occurs. Fourth, root density is the highest near the drip line where the soil moisture content is maximum and the soil salinity is minimum.

The objective of leaching is to control the average soil salinity in the root zone such that no crop yield reductions occur. Under drip irrigation, the average root zone salinity is difficult to estimate because of spatially varying levels of soil salinity, soil moisture content, and root density. However, soil conditions near the drip line are more likely to control yield response to soil salinity than those elsewhere in the soil profile. Under drip irrigation, the higher the leaching fraction, the larger the zone of relatively low salt soil near the drip line. The levels of soil salinity near the drip line will largely reflect the salinity of the irrigation water.

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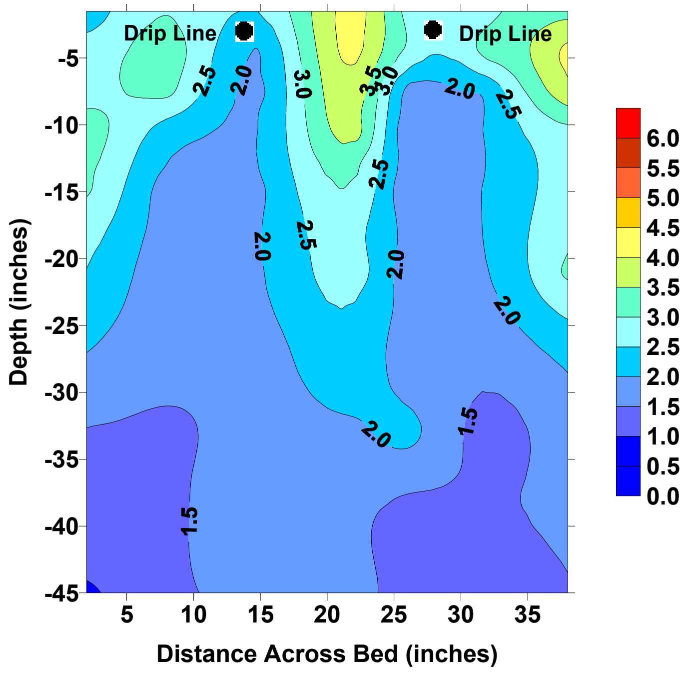


Figure 1. Pattern of ECe for surface drip irrigation of strawberries. The contour lines are lines of constant ECe.

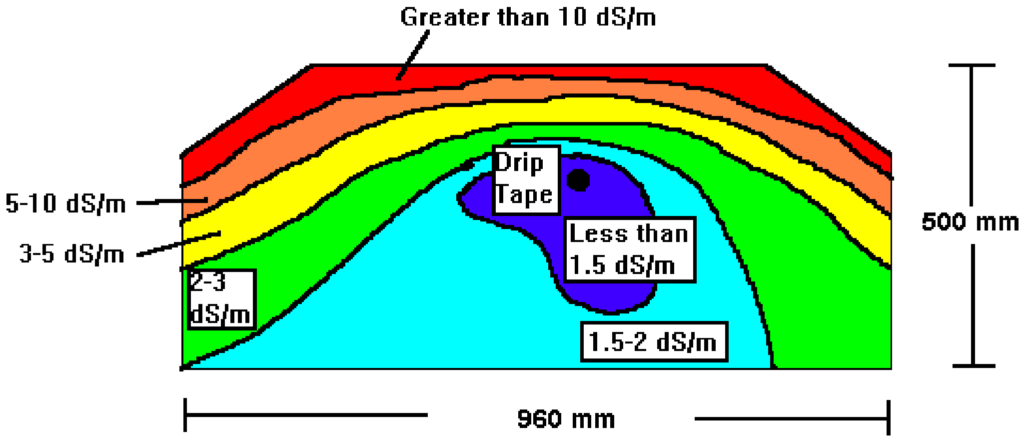


Figure 2. Pattern of ECe for subsurface drip irrigation of lettuce.

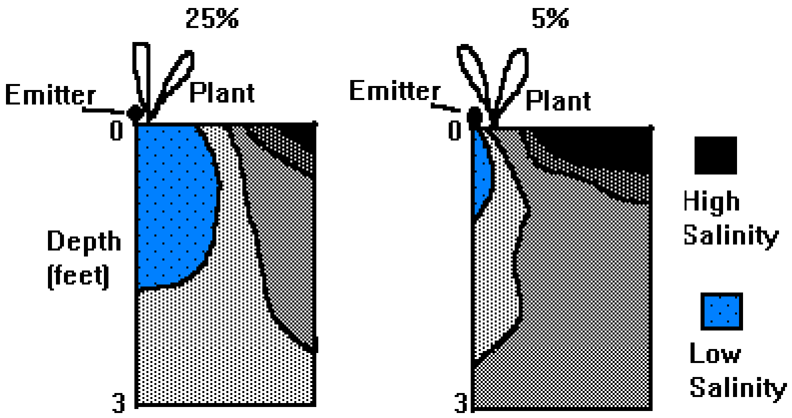


Figure 3. Patterns of salinity for different leaching fractions under surface drip irrigation.

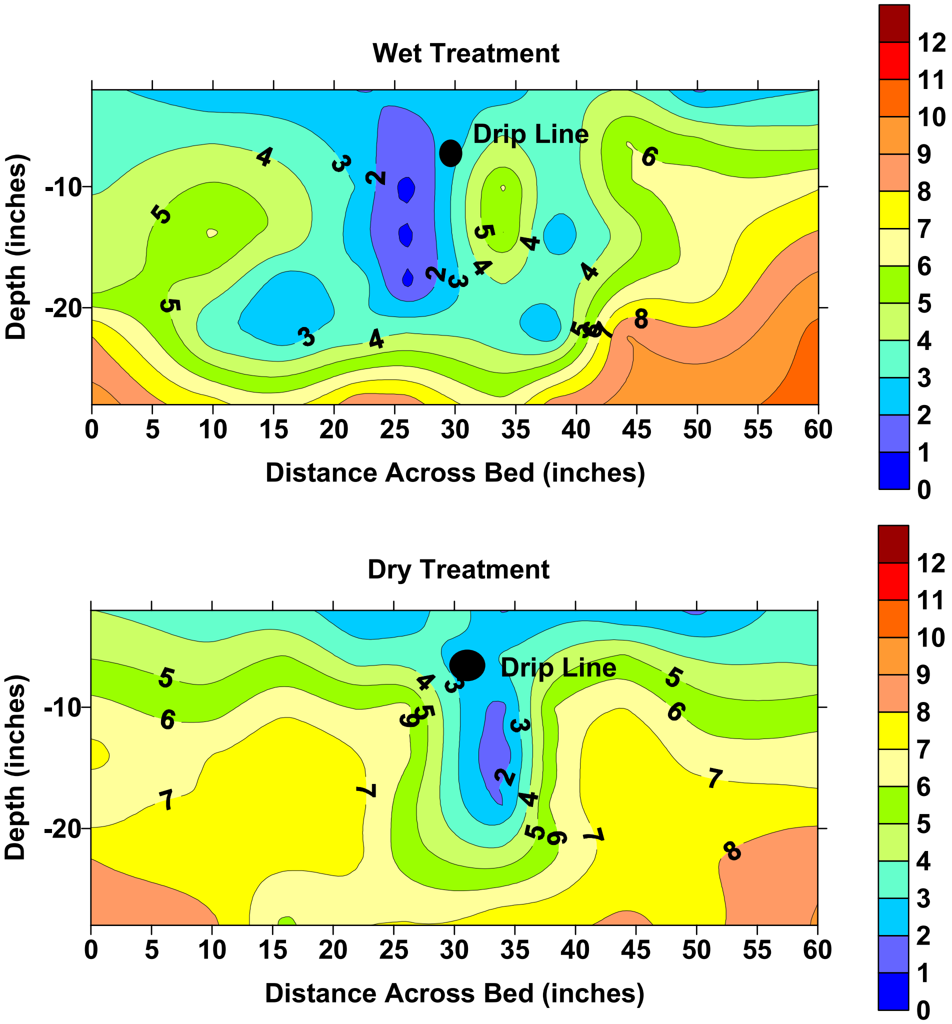


Figure 4. Patterns of ECe for different amount of applied water under subsurface drip irrigation.

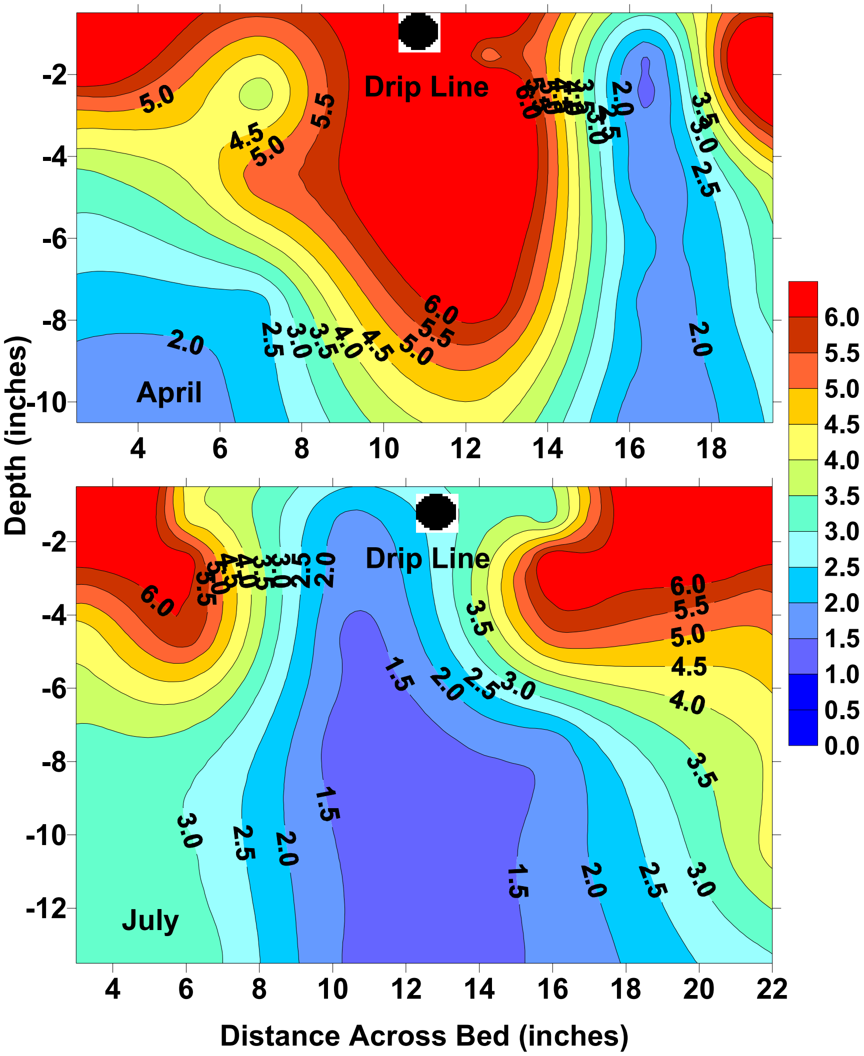


Figure 5. Patterns of ECe under surface drip irrigation for conditions of no leaching and adequate leaching.

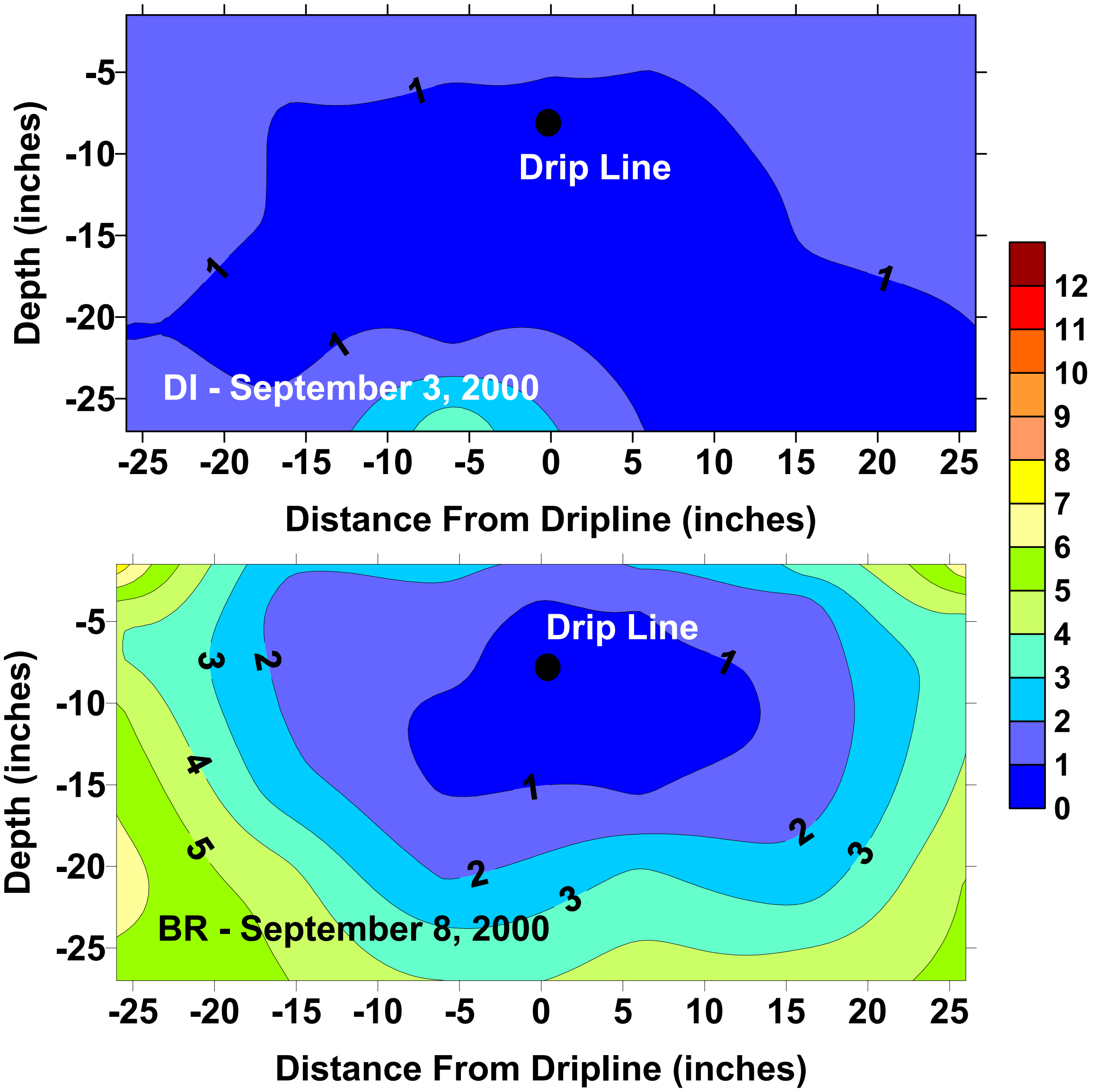


Figure 6. Patterns of ECe under subsurface drip irrigation for shallow, saline water table conditions.

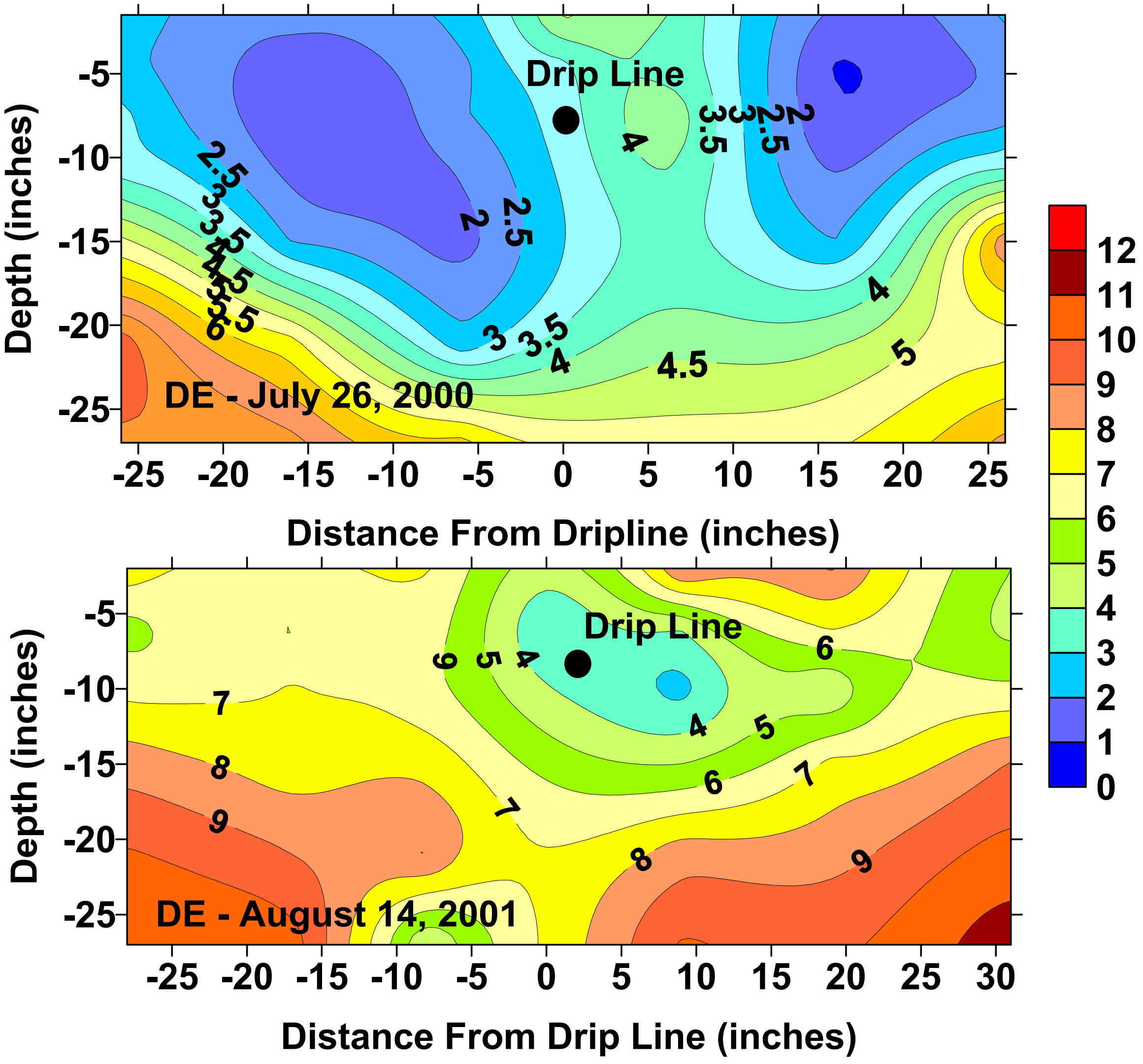


Figure 7. Patterns of ECe under subsurface drip irrigation for shallow, saline water table conditions.

Micro flood, a new way of applying water

Colin Austin

In August 2003 a group comprising specialists from the department of agriculture, water experts, irrigation engineers and pipe manufactures assembled in the Kouebokkeveld some 300 kilometres north of Cape Town, South Africa, to view a new irrigation technology.

To all appearances it looks like conventional flood irrigation but was apparently achieving the impossible of successfully flood irrigating soil which is essentially blown sand, from relatively small pipes, without loosing water past the root zone. Could this possibly be the most significant development in flood irrigation since the Sumerians 6,000 years ago?

At first sight the system called Micro Flood looks deceptively simple, nothing more than plastics pipes, bought from the local store, feeding water into small areas in sequence by squeezing a flexible pipe shut by the weight of water.

Could such a simple, even crude, looking system have the potential to bring great increases in agricultural productivity in many areas where hunger is endemic through more efficient use of water resources? Here is the story.

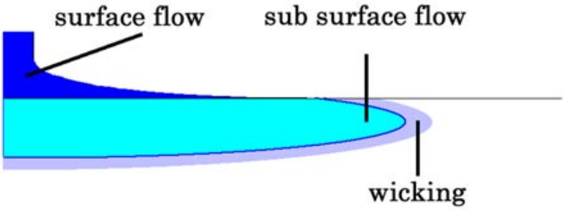
World Vision, an international relief and development agency is constantly searching for long term solutions to hunger. Because provision of relief food is not a long term solution, World Vision sought help to provide farmers with a more efficient way of using limited supplies of water for irrigation.

In areas of limited or unreliable water, increasing irrigation efficiency is not some academic interest, it should be thought of in terms of how many more people can be fed from a finite water resource.

Much of the world's water is used by flood irrigation in the less affluent countries which may not have electricity for pumps let alone for computers and moisture sensors. A totally new technology was required that still had to be highly efficient, but be gravity fed and should not require sophisticated electronics.

Advances in technology come from some new understanding. Flood irrigation may appear to be a very simple process yet developing a better understanding of this deceptively simple process has lead to the development of the Micro flood technology.

Imagine a simple garden hose pouring water onto the ground. Immediately under the hose the water will build up forming a puddle, the puddle will steadily get bigger with water flowing over the surface. If we were to poke a screw driver into the ground we would see the hole would immediately fill with water to the top of the hole.



Types of flow

Initially water flows over the surface. Pressures in the soil build up giving subsurface flow ahead of the surface flow.

Later wicking wets the soil even further ahead of the main flow front.

At some distance from the hose the water stops flowing over the surface but if we were to push our screw driver into the ground the hole would again fill with water but this time not quite to the top.

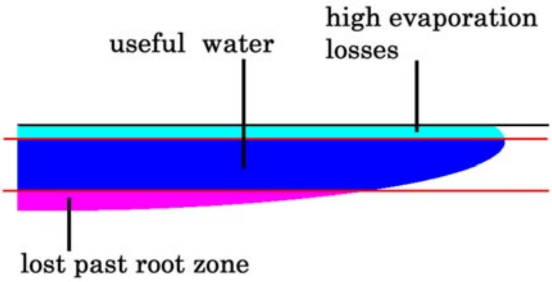
If we were to make another hole further away the hole would still fill with water but this time would not come quite so close to the surface.

If we made a series of such holes we can see that there is a water line at some angle to the surface. If we did this in a sandy soil the angle would be very steep, may be 30 degrees to the surface while in a clay soil the angle may only be 5 degrees. This flow is subsurface flow resulting from hydraulic pressure.

Now if we make further holes away from the hose we would not see any liquid water in the hole, but the soil would still look damp. If we were to repeat this experiment a number of times on a lawn over a hot dry period we would see a ring of green extending beyond the area where we can actually see water.

There is still water movement but this is caused largely by surface tension but there are other mechanisms at work such as osmosis, subsurface evaporation and condensation and even the plant extracting water from the soil from wet areas in the day time and then returning water by different root systems at night.

Now if we were to dig a trench out from our hose we would see the wetted profile. Under the hose the soil may be wetted to quite some depth, well beyond the root zone. This water that passes the root zone is wasted so the region near the hose or source is not very water efficient. It can also aggravate salinity.

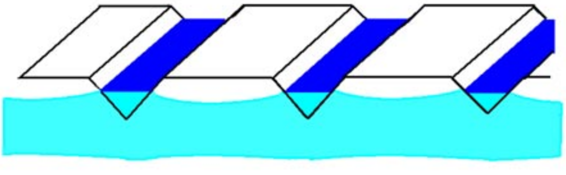


Shallow water near the surface is largely lost by evaporation; deeper water is lost past the root zone.

Useful water lies in between; the aim is to get water into this useful zone.

Further away the water will have thoroughly wetted down to, but not passing beyond the root zone, so we are making good use of the water in this region.

Even further away water will have only reached just below the surface and will not be properly wetting the root zone. This water will quickly evaporate away so this region where we have only shallow penetration is also not efficient.

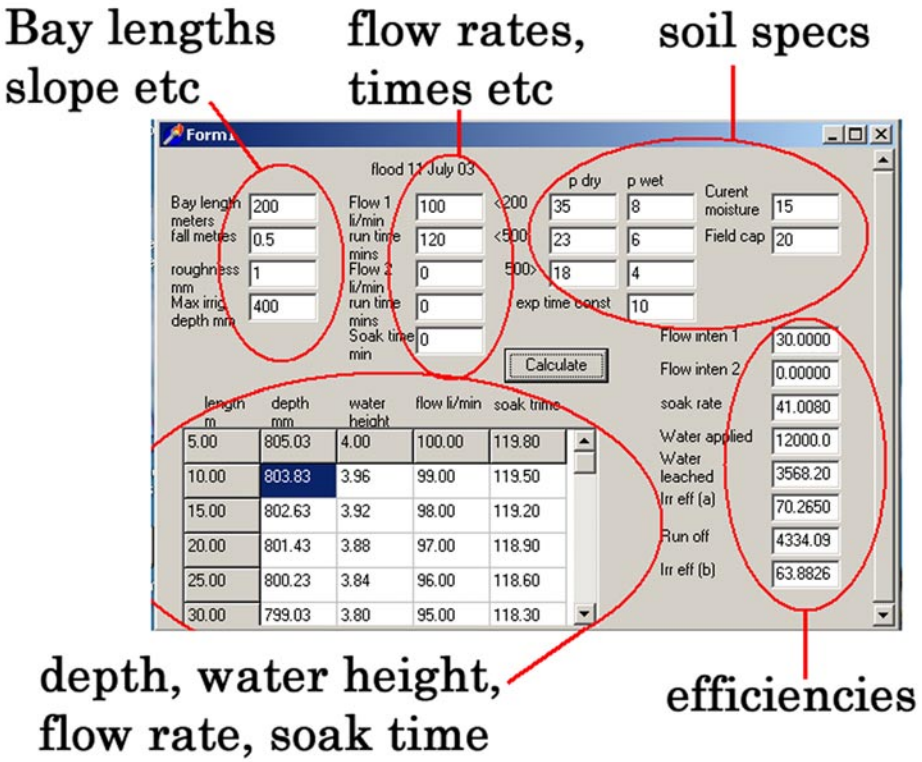


Subsurface flow in furrows cuts evaporation losses and give high efficiencies

Furrows are much more efficient as the wetted surface area is dramatically reduced while the subsurface flow wets the soil between the furrows.

Computer software has been developed to calculate the wetted profile.

Sample print out



Bay lengths slope etc

flow rates, times etc

soil specs

depth, water height, flow rate, soak time

efficiencies

flood 11 July 03

Bay length meters: 200
fall metres: 0.5
roughness mm: 1
Max irrig depth mm: 400

Flow 1 li/min: 100
run time mins: 120
Flow 2 li/min: 0
run time mins: 0
Soak time min: 0

	p dry	p wet
<200	35	8
<500	23	6
500>	18	4

exp time const: 10
Curent moisture: 15
Field cap: 20

Flow inten 1: 30.0000
Flow inten 2: 0.00000
soak rate: 41.0080
Water applied: 12000.0
Water leached: 3568.20
Irr eff (a): 70.2650
Run off: 4334.09
Irr eff (b): 63.8826

length m	depth mm	water height	flow li/min	soak time
5.00	805.03	4.00	100.00	119.80
10.00	803.83	3.96	99.00	119.50
15.00	802.63	3.92	98.00	119.20
20.00	801.43	3.88	97.00	118.90
25.00	800.23	3.84	96.00	118.60
30.00	799.03	3.80	95.00	118.30

Water soaking into the ground can be calculated from the permeability of the soil. Permeability can however depend quite significantly on how much water there is in the soil, a dry clay for example is extremely permeable, it may even crack so water just runs straight through, but as water soaks into the pores the clay swells and seals. To describe this we can use two different set of data, one wet and one dry, for each of the various levels. We also need a time constant, to describe how rapidly the soil changes its permeability.

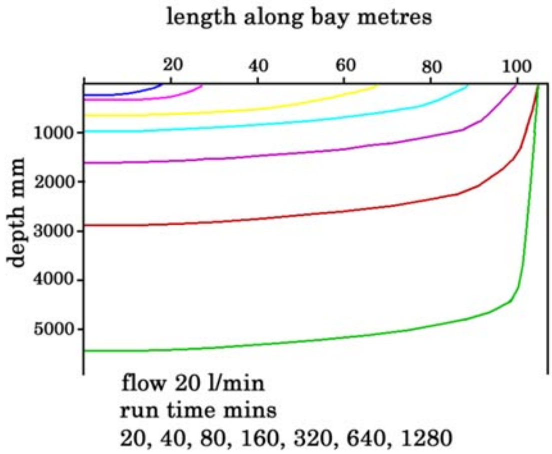
Soil characteristics have a major effect on how well flood irrigation works. Expanding clays with a large difference in permeability's between a deep wetted layer and the shallower laminates give better water movement across the surface, in some cases they are so impervious that it may be difficult to ensure adequate water penetration. Uniform soils with higher permeability's allow excess water to pass the root zone.

It is interesting to vary the flow rate throughout filling. The current software has three stages, in the first two the flow rate and time can be varied, the third stage is a soak period to analyze how the water sitting above the ground is redistributed after the flow into the bay has stopped.

What do we get? The water distribution or wetted profile is the key.
A summary shows how much water has been applied, how much water has been lost by soaking beyond a specified root zone depth and how much water has been lost by run off.

Analyzing results

Sample results are shown for a typical 200 metre long bay with 0.5 metres fall. The soil type is a typical expanding clay loam, with significant difference in permeability at different depths between the wet and dry states.

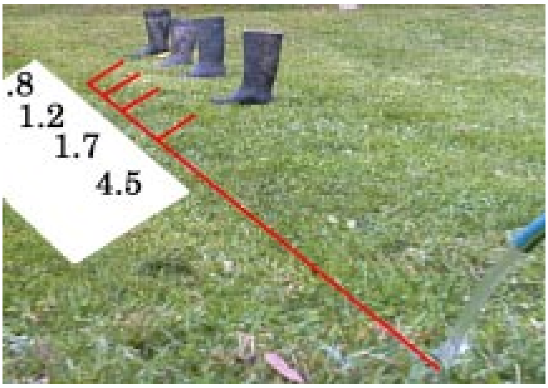


Results showing the effect of increasing run time. At first the water moves further down the field but eventually stops when the soak rate equals the rate at which water is applied.

The maximum flow length is 105 metres regardless of how long water is applied.

We see that if we fix the flow rate and scan the run time that the water will progressively move further down the block until a maximum flow length is reached.

Length metre	Flow rate Litre/min/metre	Distribution efficiency
200	150	7.2%
200	200	53%
200	320	65%
20	20	75%
20	40	95%



Simple hose experiment

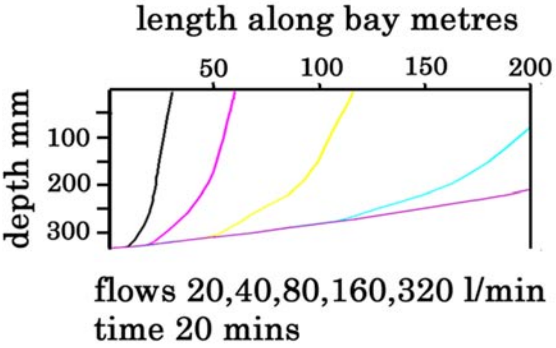
Numbers show how far the water has travelled every 5 minutes.

First 5 mins = 4.5 metres
Second 5 mins = 1.7 metres
Third 5 mins = 1.2 metres
Forth 5 mins = .8 metres

As the wetted area increases the rate of water loss by infiltration into the soil increases, the speed of the flow front reduces and eventually stops. After that all the water is lost to infiltration. The area around the hose is very wet deep into the ground while the edge of the wetted area is only wet on the surface.

This very simple practical test of running water over the surface and measuring flow front velocity, although crude is very informative. We can also measure how far the water has infiltrated into the ground at points along the flow path. We can then use the computer simulation to classify the soil characteristics. This gives us reliable information for later design work.

The next experiment is to look at the effect of varying flow rate, keeping the run time fixed.



Increasing flow rate does not affect the start but gives a better water distribution with more water at the end.

If the bay were only 20 metres long there would be a good water distribution throughout.

We see that when we keep the run time fixed that the depth at the start of the bay always remains the same regardless of flow rate. As the wetted area increases the rate of water loss by infiltration into the soil increases, the speed of the flow front reduces and may not reach the end of the bay.

If the flow rate is high enough the water will easily reach the end of the bay however for the water to properly soak into the ground the flow must be maintained after it has reached the end of the field giving significant run off.

We could immediately improve efficiency flooding the bay using a very high flow rate then dropping to a lower flow rate close to the infiltration rate (which is shown on the computer print out) to avoid run off, but get good wetting at the end of the bay.

High flow rates versus short bays

To achieve this high efficiency very high flow rates are required which means very large delivery channels coupled with sophisticated control to switch from high to low flow. The maximum flow rate shown in the graph is 320 litres per minute which gives an application rate of 96 mm per hour, which is some ten times the application rate commonly used in flood irrigation.

How practical is this? Well if we have plenty of money and can build large channels and are prepared to install proper flow control the answer is very practical. But what about poor countries? They may not have the money for large dams and channels but they also need to be harnessing the many relatively small flows, from streams, springs and aquifers which may be available locally.

However if we look closer at the simulation results we can see some very interesting numbers. At the almost absurdly high flow rate of 320 litres per minute the depth at the end of the 200 metre bay is 210 mm which is still only 65% of the depth at the start of the bay, (323 mm).

In the early sections of the bay, even at the lowest flow rate of 20 litres per minute, which is only 6.25% of the maximum flow rate, the penetration depth at the 20 metre is 251 mm which is 75% of the depth at the start of the bay. While at just 40 litres per minute, still very modest and only 12.5 of the maximum flow, the penetration depth is 323 mm which is 97% of the depth at the start of the bay.

To summarize;- reducing the length of the block gives a high efficiency with a uniform spread of water along the block, even using very low flow rates.

To reduce bay lengths while still using conventional channels would be absurd, we would simply waste more water in the channels than we would gain by efficiency on the block.

This highlights the classic dilemma in designing a flood irrigation bay, finding that compromise between losing water in channels and losing water in the bay itself. The net result is that most bays around the world are far too long to be really efficient.

Open channels are really the only practical way of delivering the high flows to flood irrigating large areas; it simply costs too much money for the massive pipes to achieve the required flow rates. However we simply don't need these massive flow rates if we are only irrigating short bays. It therefore becomes economic to use pipes and as the pressure is very low these can be simple low cost flexible pipe or fluming.

What we need is a cheap and simple valve system to split an irrigation bay up into a number of short sections so that each section can be irrigated in turn.

This gives high efficiency even with low flows so we can take advantage of all the small water sources which cannot be effectively used by flood irrigation.

The solution is the tilt valve, a remarkably simple yet sophisticated device. Basically it is a pipe which is gradually filled with water which squeezes the flexible delivery plastics pipe shut.

However it is not quite that simple. If the pipe was simply progressively filled with water there would be a slow shut off with the flow rate gradually reducing. This is exactly the opposite of what is required. The valve should stay fully open until it is time to close and then snap shut.

This is achieved by a having two chambers, the first chamber to fill actually holds the valve open, after a period the second chamber fills sufficiently to overbalance the valve, the water from the first chamber then flows into the second chamber giving an abrupt shutting action.
The next problem is that in a large scheme there may be many valves, how do we arrange the sequence in which they open and shut?

This is achieved by a system of risers, which directs water into the first valve, when this valves shuts the water is deflects over the riser to the next valve.

When the tilt valve is open the riser deflects water into this micro block, when the valve shuts water flows over the riser so water is directed to the next micro block.

It is more efficient to run the water down the block in small furrows as this is far more efficient hydraulically but also uses the highly efficient subsurface flow to distribute water sideways, without evaporation losses

Note this block is blown sand, impossible to irrigate with conventional flood.

A system of flow balancing has been developed in which a computer program calculates emitter sizes to compensate for pressure drops.

Design and installation

The first and highly critical step is to measure the characteristics of the soil. This is done in a special test in which water is flowed down a small channel or furrow and the velocities and penetration depth measured.

Different soils will lead to totally different designs. Virtually any soil can be irrigated with the Micro Flood technology but the final designs may be totally different. A sandy porous soil will require short run lengths and irrigation times and preferably high flow rates, while a soil with a lower layer of expanding clay will allow much longer run lengths and lower flows.

The computer simulation is then used to determine the size of the micro blocks, considering the soil characteristics in conjunction with the available flow rate. High flows allow large blocks to be used while sandy soils require smaller blocks.

Next further software is used to design the hydraulics of the system establishing pipe and emitter sizes, flow rate and required heads.

Scheduling

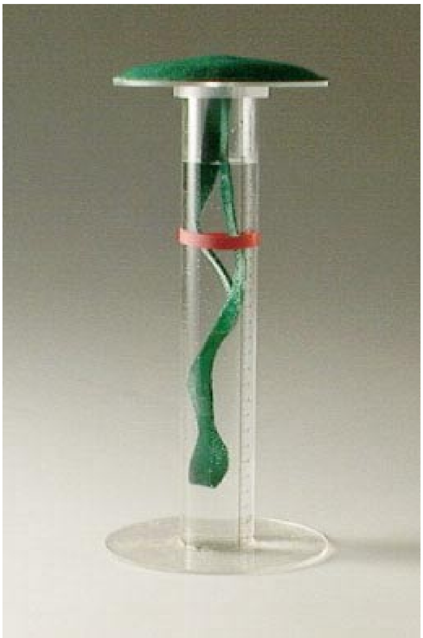
Any irrigation system, however good its potential is, is only as good as its management, so scheduling is essential to ensure efficient use of water.

Affluent farmers can afford the latest soil moisture monitoring equipments to help them schedule correctly but what about the many farmers who cannot afford such luxuries? Another way had to be found. The easiest way of measuring soil moisture is to apply a known amount of water then see how far the water soaks into the ground. This can be done using simple hand tools like an auger or even a spade.

Traditional flood irrigation usually applies large volumes of water, about 50 mm, which are only applied every 5 to 10 days. Plants grow much better if they have smaller but more regular watering. Micro Flood applies these smaller but more regular irrigations, to give higher productivity. Systems are generally designed to apply a fixed amount of water, say 5 mm at each irrigation depending on the water holding capacity of the soil.

The still leaves the farmer with the job of deciding when to irrigate.

Evaporation meter



A simple evaporation meter which works just like a plant has been developed. The water stored in the tube represents the water in the soil, the wick representing the trunk or stalk and the top represents the leaves.

This can be used just like a conventional evaporation pan but can also be fitted under one of the flood-emitters so it is filled at every irrigation.

A rubber band can be placed around the tube to act as a marker. When the water level drops to the marker it is time to re-irrigate. This gives a constant evaporation between irrigations. The irrigation depth is checked after irrigation by digging a hole or using an auger and the position of the band adjusted to change the evaporation between irrigations.

Flood irrigation and bad PR

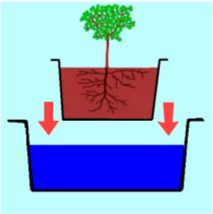
Flood is still by far the largest user of water using some 95% of all irrigation water around the world, because it is simple and cheap but is widely thought of as grossly inefficient. The reality is that most flood irrigation systems are inefficient. This inefficiency is not an intrinsic feature of flood; it is just the way it has been implemented.

Micro Flood can be more effective than the much more expensive alternatives. Sprinklers wet the entire surface area so there are significant evaporation losses, some during application and the rest by evaporation from the upper layers of the soil.

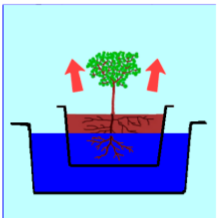
By contrast furrows results in much of the water going straight to the useful zone by subsurface flow.

Drip can apply very small quantities of water; however the water distribution is generally very poor with little patches of wet soil.

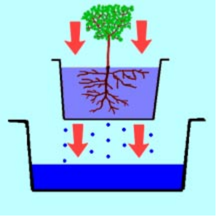
The key issue is how much growth we get from a given amount of water. Micro Flood has the natural breathing action of Flood and drain systems, one of the most productive systems of irrigation, widely used in hydroponics It provides a natural breathing action, replacing stale air containing carbon dioxide and ethylene, which act as growth inhibitors, with fresh oxygen.



A plant in a pot is immersed in water, often containing nutrients



The water soaks into the soil expelling all the stale air.



As the water drains it sucks fresh air in behind giving ideal growing conditions.

Conclusions

So what does all this mean? It means that the worlds malnourished have a highly efficient irrigation system which is still low cost and gravity fed.

It means that high flow rates, associated with conventional flood irrigation are no longer required.

It means that many water sources, which were too small for effective flood irrigation can now be used and the traditional large open channels can be replaced with small diameter low cost pipes, saving significant quantities of water.

It means that any soil, even sandy highly permeable sandy soils can be irrigated.

It means increasing food production by some 40%.

In simple terms this means we can feed more people from our finite water resources.

It can be truly said that this is the most significant advance in flood irrigation since the Sumerians 6,000 years ago.

A Study of Operating Efficiencies Comparing Aluminum Pipe Systems

to Certa-Set PVC Irrigation Piping

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Fresno, California April, 2003

INTRODUCTION

In the design of all irrigation systems, consideration must be given to the system efficiency. The efficiency is defined as the ratio of water pumped to the water effectively applied to the crop. In determining a best estimate of efficiency, consideration must be given to the following losses:

1. Field runoff.
2. Aerial evaporation and drift.
3. Application pattern losses to seepage below the root zone.
4. Leakage from system components while in operation.
    - Sprinkler bearings
    - Pipe couplers
    - Air vents and valves
    - Pipeline imperfections
5. Drainage from system components when not operating thus requiring a refilling of the system on each start up.
6. Differential application from sprinklers caused by variation in operating pressure along the mainline and laterals.

For convenience, this paper will group items 1, 2, and 3 and term them as “application losses.” Items 4, 5, and 6 will be grouped and termed “operational losses.”

Over the years, application losses, in particular pattern losses, have been the subject of a major amount of study with special coefficients proposed and worked into design calculations. By contrast, there is very little data in the literature on studies of operational losses. This is partly accounted for by the fact that the dominant system utilized portable aluminum pipe with no alternatives that might give improved performance. In addition, the effect of varying system operating pressure has also been largely ignored and accepted as a consequence of limited system component options. The availability of pressure-compensated sprinkler components are an exception. This pressure variation is manifested as lower pressures at the distal end of the laterals as a result of frictional headloss. Recognition of this pressure variation has been enshrined in the following rule that presumably represents good design practice.

- Limiting frictional headloss to not over 20% will limit application rate variation to not over 10%.

If the system operation focuses on the health of the "driest plant," then excess water is being applied to all sprinklers operating at higher pressures. In addition to wasting water, the surplus applied can have a negative impact on the crop. As we develop ever more refined designs, in an attempt to save water and energy, the impact of these accepted "rules of thumb" should be investigated. The availability of the "Certa-Set PVC Irrigation Pipe" by Certainteed Corp. when compared to standard portable aluminum pipe provides one such opportunity. This study then determines the operational losses for a commonly used configuration of portable solid set system using both aluminum and PVC piping components. The study addresses only the determination of operational losses and does not address any other factors involved in a system selection decision such as first cost, probability, application losses, system maintenance, corrosion, etc.

The study was funded by the Certainteed Corp. The work was conducted during the period from January through March, 2003.

RESULTS: PORTABLE ALUMINUM PIPE SYSTEM

Shown in Table #1 are the results from six test runs with an aluminum pipe system. The system consisted of 1200 ft. of 8 in. mainline with five 3 in. by 1140 ft. laterals attached at the distal end. The sprinklers were spaced 30 ft. X 50 ft. The runs simulate irrigation events with gross applications ranging from 1.2 to 1.7 inches. The net volume shown in Table #1is calculated knowing the pressure at the end of the laterals, the number of sprinklers operating, and the net runtime when the sprinklers have reached the correct operating pressure. The gross volume is determined from the 8-in. mainline flow meter and the net runtime. The operating efficiency is the ratio of net to gross volume. The resulting average operating efficiency is 86.3%. These results show the losses to be 13.7% from the combined effects of leakage when the system is operating, drainage when it is shut down and variations in sprinkler operating pressure.

RESULTS: CERTA-SET PVC IRRIGATION PIPING

Shown in Table #2 are the results from six test runs with the Certa-Set irrigation pipe system. In this case the runs simulate irrigation events with gross applications ranging from 0.4 to 1.7 inches. The PVC pipe system was laid out in a manner identical to the aluminum pipe system except the sprinkler pipe spacing was 40 ft. X 40 ft. In this case, the average operating efficiency was 94.8% which shows the losses to be 5.2%. After the initial filling of the system, it stayed full between runs even during a weekend shut down. This suggests that the water loss is limited to the variations in sprinkler operating pressure. It follows then that this value could be minimized by reducing the headloss in the laterals or the use of pressure-compensated sprinkler components.

For the conditions as defined by this study, direct comparison of an aluminum pipe system versus the Certa-Set PVC irrigation piping system, operational losses have been reduced on average from 13.7% to 5.2% or by 62 %.

Table #1 – Portable Aluminum Pipe System

Test	Average Pressure	Average Sprinkler Flow Rate	Run Time	Net Volume	Gross Volume	Op. Efficiency	Gross App.
(#)	**(psi)**	**(gpm)**	**(min)**	**(gallons)**	**(gallons)**	**(%)**	**(in.)**
1 (1)	53.6	2.44	450	208,449	244,078	85.4	1.47
2 (2)	53.9	2.45	534	246,865	283,764	87.0	1.74
3 (3)	55.0	2.47	514	233,659	271,187	86.2	1.70
4 (4)	54.1	2.45	500	231,620	264,345	87.6	1.64
5 (5)	54.0	2.45	360	167,512	195,660	85.6	1.18
6 (6)	53.2	2.43	397	179,872	209,541	85.8	1.29
Total			**45.9 hrs.**	**1,267,977**	**1,468,575**		**9.02 in.**
Average	**54.0**	**2.45**				**86.3**	**1.503 in.**

(1) system drained overnight
(2) system flooded at start of test
(3) system drained overnight (mainline end plug removed)
(4) system drained overnight
(5) system drained overnight
(6) system drained overnight

Table #2 – Certa-Set PVC Irrigation Piping

Test	Average Pressure	Average Sprinkler Flow Rate	Run Time	Net Volume	Gross Volume	Op. Efficiency	Gross App.
(#)	**(psi)**	**(gpm)**	**(min)**	**(gallons)**	**(gallons)**	**(%)**	**(in.)**
1	52.0	3.19	125	55,045	58,323	94.4	0.39
2	56.0	3.31	189	90,112	97,032	92.9	0.63
3	54.5	3.27	369	162,696	171,712	94.7	1.21
4	53.5	3.23	469	212,082	219,478	96.6	1.52
5	53.7	3.24	500	233,428	248,282	94.0	1.63
6	55.3	3.29	500	236,880	249,520	94.9	1.65
Total			**35.9 hrs.**	**990,243**	**1,044,247**		**7.03 in.**
Average	**54.2**	**3.26**				**94.8**	**1.17 in.**

(1) system observed to be flooded at the beginning of each test.

SITE INSTRUMENTATION PROCEDURE

The site was on the California State University, Fresno Farm Laboratory, field 13 with a gross area of approximately 25 acres. The mainline and lateral layout was meant to be typical of commercial systems. The area was not cropped. Observations on the flooded condition of the PVC plastic pipe system suggested that the field topography was generally flat. Figure #1 and Figure #2 show the aluminum pipe and the PVC piping systems in operation, respectively. Water was supplied to the system using a portable diesel-powered pump as shown in Figure #3. The pump drew water from a standpipe on the edge of a large reservoir. The flow meter is a McCrometer 8 in. saddle meter model M0300. The flow meter calibration was checked against the master meter in the CIT laboratory.

Table #3 - 8 in. Portable Flow Meter Accuracy Test

Run No.	Flow Rate Read (1)	Test Run Time	Laboratory Flow Meter Volume	Laboratory Flow Meter Flow Rate	8-in. Portable Meter Volume	8-in. Portable Meter Flow Rate	Error (2)
	(gpm)	(min)	(gallons)	(gpm)	(gallons)	(gpm)	%
1	400	5	2025	405	1955	391	-3.5
2	485	5	2385	477	2444	489	+2.5
3	690	5	3410	682	3585	717	+5.1
4	970	5	4870	974	4887	977	+0.35

(1) Instantaneous Reading

(2) All tests run between 460 and 545 gpm suggesting that the 8 in. portable meter was overstating the flow rate by 2 to 3%. The 8-in. portable meter installation was the same for both the aluminum and plastic pipe systems.

The portable aluminum pipe system was rented from a local vendor and thought to be representative of commercial offerings. The Certa-set PVC irrigation pipe system was supplied by Golden State Irrigation Services. All components in both systems were taken from existing supplies of used equipment except for the Certa-Set sled coupling which was new.

The system operating pressure was measured on a riser at the high end of the lateral as shown in Figure #4. The pressure tap was designed to recommend good practice standards. The same tap was used for the sprinkler calibration tests. The gauge is an Ascroft test gauge with a 4½” face and a Grade 3A with an accuracy of ¼” of full scale. It was checked before and after test sequences and found to agree with a dead weight tester to within ¼ psi. During the test run the pressure was recorded and a Dickson Model PW4 Recorder. These chart records were confirmed by periodic reading of the pressure gauge and stop watch manual records of run times.

The sprinkler flow rates shown in Tables #1 and #2 are the results of laboratory calibrations using representative sprinklers. The sprinkler flow rate versus pressure calibrations of four sprinklers were analyzed by a curve fit routine and gave the following results.

- Aluminum Pipe System (½-inch impact sprinklers – full circle, 7/64-in. nozzle)
  $q = 0.286\,(P)^{0.538}$, gpm   P, pressure, psi
  $R^2 = 0.973$

- Certa-Set PVC Irrigation Pipe System Sprinkler (Nelson model Red WR15, Wind Fighter)
  $q = 0.446\,(P)^{0.498}$, gpm   P, pressure, psi
  $R^2 = 0.998$

The net volume shown in Tables #1 and #2 are calculated by the following expression:

Net volume = (average sprinkler flow rate) (run time) (no. of operating sprinklers)

Note: The number of operating sprinklers was 190 and 145 for the aluminum pipe system and the PVC pipe system respectively corrected for plugged sprinklers.

The gross volume shown in Tables #1 and #2 were taken directly from the flow meter readings. The operating efficiency is calculated by dividing the net by the gross volume. The gross application is calculated using the following formula:

$$\text{i (gross application)} = \left[\frac{q\,(96.3)}{S_1 \times S_2}\right] \text{(run time, hrs.), in.}$$

S_1 and S_2 are the sprinkler spacings. They were 30 ft. by 50 ft. for the aluminum pipe system and 40 ft. by 40 ft. for the PVC irrigation piping system.

Figure 1 Portable aluminum pipe solid set system in operation.

Figure 2 Certa-Set PVC irrigation piping portable solid set system in operation.

Figure 3 Portable pumping plant. Note the water meter is visible in the 8 inch mainline just outside of the security fence.

Figure 4 Pressure gauge mounted on a riser at the end of the lateral.

Figure 5 Recording pressure gauge located on the second from the end sprinkler.

PRECISION PIVOT IRRIGATION CONTROLS TO OPTIMIZE WATER APPLICATION

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ABSTRACT

A precision control system that enables a center pivot irrigation system (CP) to precisely supply water in optimal rates relative to the needs of individual areas within fields was developed through a collaboration between the Farmscan group (Perth, Western Australia) and the University of Georgia Precision Farming team at the National Environmentally Sound Production Agriculture Laboratory (NESPAL) in Tifton, GA. The control system, referred to as Variable-Rate Irrigation (VRI), varies application rate by cycling sprinklers on and off and by varying the CP travel speed. Desktop PC software is used to define application maps which are loaded into the VRI controller. The VRI system uses GPS to determine pivot position/angle of the CP mainline. Results from VRI system performance testing indicate good correlation between target and actual application rates and also shows that sprinkler cycling on/off does not alter the CP uniformity. By applying irrigation water in this precise manner, water application to the field is optimized. In many cases, substantial water savings can be realized.

INTRODUCTION

Agricultural water use is a major portion of total water consumed in many critical regions of Georgia. Georgia has over 9500 center pivot systems, watering about 1.1 million acres (Harrison and Tyson, 2001). Many fields irrigated by these systems have highly variable soils as well as non-cropped areas. Current irrigation systems are not capable of varying the water application rate to meet the needs of plants on different soil types nor capable of stopping application in non-cropped inclusions. This limitation results in over-applying or under-applying irrigation water. In addition, five years of drought and a lawsuit over Georgia water use by Florida and Alabama have prompted a renewed interest in water conservation methods by the general public, which is becoming increasingly insistent that agriculture do its part to conserve water.

The NESPAL Precision Ag Team has developed a prototype method for differentially applying irrigation water to match the precise needs of individual sub-field zones. Research projects dealing with spatially-variable irrigation water application have been ongoing for a number of years (Sadler et al., 2000; Heerman et al., 1999; Jordan et al., 1999; King and Kincaid, 1996; Evans and Harting, 1999). In each case, the research team used a different method for accomplishing the variable water application. However, most of these systems remain in the research phase.

Recognizing that water is the major yield determiner in nearly all agricultural settings, the authors' original interest lay in varying application rates from a precision crop production viewpoint. However, it readily became apparent that a method for varying irrigation across a field could also lead to substantial water savings.

The method is referred to as Variable-Rate Irrigation (VRI). This system easily retrofits onto existing center pivot irrigation systems.

The major components of the NESPAL VRI system are shown in Figure 1. The process for using the VRI system is as follows:
1. Pivot information is entered into the desktop software;
2. Desired application rates are defined in the desktop software;
3. A control map is transferred from desktop PC to the Canlink3000 controller via data card;
4. The controller determines pivot angle via GPS;
5. Based on the control map, the controller optimizes pivot speed and/or cycles sprinklers (and/or end gun) to set application rate.

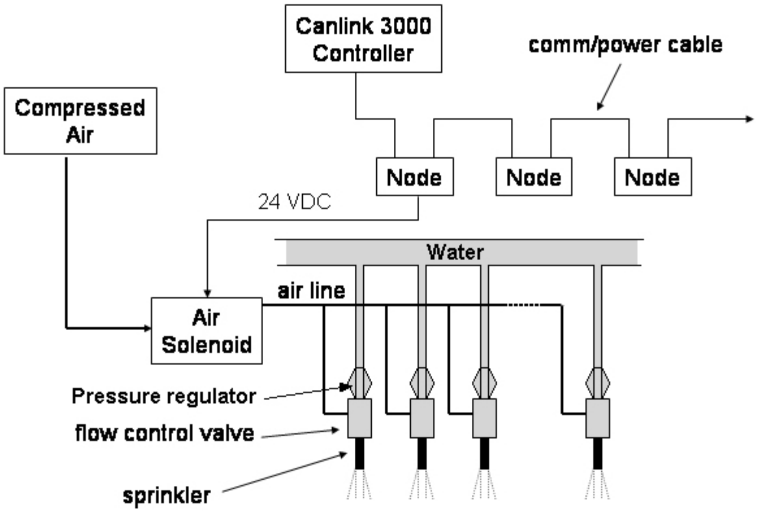
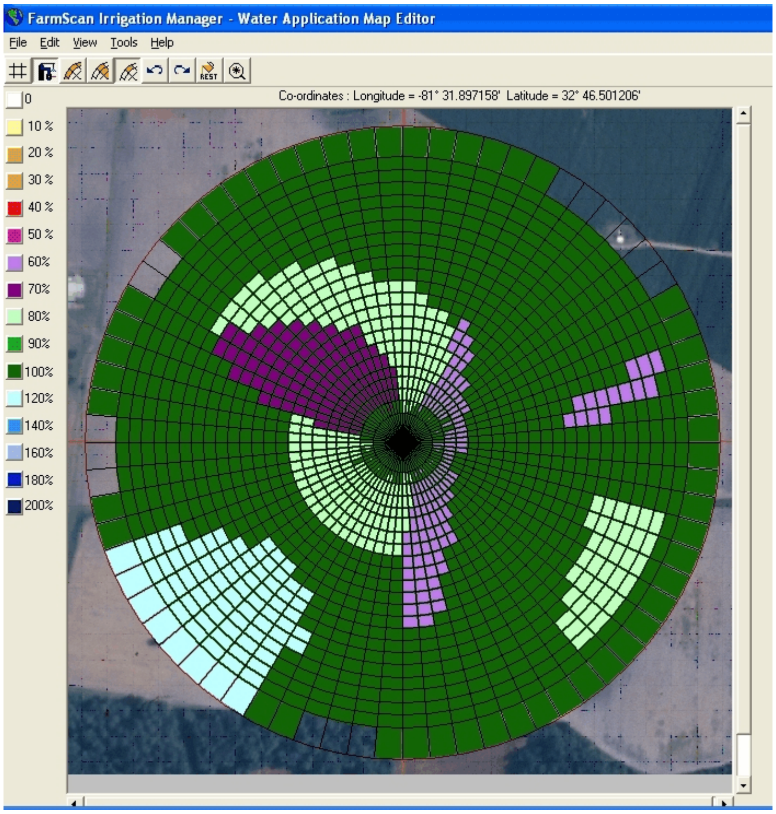


Figure 1. Layout of variable rate control system.

MATERIALS AND METHODS

The Farmscan Irrigation Manager^{TM} software (Figure 2) provides for development of application maps. The software allows multiple pivots to be defined and allows each pivot to have multiple application maps defined. The software allows a pivot to be divided into wedges from 2 to 10 degrees "wide" with up to 48 control zones radially along the wedge/pivot. The number and size of the control zones are determined by features/anomalies in the field to be managed and by the installation of valve control hardware. Once a pivot and its irrigation control zones have been defined, a pie-shaped grid is displayed (divided into sections corresponding to the defined control zones). Using a legend of application rates (0 to 200%) the user selects a rate from the legend with the mouse and then "marks" each control zone of the map with an application rate. The resultant map (Figure 2) is then copied to a memory card and uploaded to the master controller.



Co-ordinates : Longitude = -81° 31.897158' Latitude = 32° 46.501206'

Figure 2. Software for creating application maps.

At the present time, the water application map is a static map created with the aid of the farmer's knowledge of the field, aerial images of soil and/or crops, soil maps, yield maps, etc. The user must account for the control map possibly having higher resolution than can be practically accomplished with the actual sprinkler arrangement on the pivot.

The VRI control system was installed on a NESPAL research pivot during February, 2001. Fifteen sprinkler banks or groups were configured to contain 2, 3, or 4 sprinklers so as to provide approximately 50 ft zones, each controlled by an addressable "node." The node circuitry was placed in four weather-proof enclosures located on two of the wheeled support structures for the pivot. Flow uniformity was maintained by installing 15 psi pressure regulators at each sprinkler. The sprinkler banks were configured in small segments to provide fine control resolution. The banks could be combined if coarser control was desired. The relatively small banks also allowed for system testing with multiple control zones and associated hardware (air lines, solenoids, nodes, etc.).

To verify the variable-rate functionality and that the pivot's sprinkler uniformity was not adversely impacted by the addition of VRI controls, a series of application tests, each repeated three times, were performed on the NESPAL pivot. The first test involved operating the pivot with VRI engaged but all sprinklers at 100% cycle time for 100% application rate. In effect, this test produced a baseline uniformity of the pivot. The second test instructed the VRI control system to operate all sprinklers at 50% cycle time to produce 50% application rate. The third test consisted of setting various target application cycle times and rates along the pivot.

Catch cups (3.58 in diameter plastic drinking cups) were attached to wooden dowel rods via a plastic ring. The cup/rod assemblies were placed at 5 ft intervals radially along the mainline, beginning 30 ft from the pivot's center point (Figure 3). The cups rested on the rods approximately 18 in above the soil surface. The catch cups were deep enough to prevent most water drops from splashing out of the container. The pivot was operated at 11% speed timer setting, corresponding to an end tower travel speed of approximately 22 in/min. During the three repetitions, the pivot was operated twice in the "forward" direction and once on the "reverse" direction. During the uniformity testing, speed control was not engaged to keep the pivot travel speed constant. As the system passed completely over catch cups, the collected water was measured in a graduated cylinder. This test is similar but does not fully conform to the ASAE Standard S436.1 (ASAE, 1998) for testing uniformity of center pivot irrigation systems.

Figure 3. Catch cups underneath center pivot.

The VRI control system has since been installed on four farmer-owned CP systems in Georgia (Table 1). To determine actual water use (and potential water savings), a test was conducted on two of these CP systems (TS and LP). An application control map was developed for each system which was used to estimate water use for one complete pass of the irrigation system. The two systems were operated with VRI engaged for one complete pass (circle) while actual water use was being monitored by a Polysonic DCT-7088 ultrasonic flow meter mounted on the mainline (Figure 4). The water used while irrigating without VRI engaged was determined by measuring the normal flow rate with the Polysonic meter and then multiplying that rate by the time the CP would normally take to complete one pass.

RESULTS AND DISCUSSION

The results of the 100% and 50% application rate tests are shown in Figure 5. The 100% data provided a “normal” or baseline application amount to which other application rates could be compared. The amount of irrigation water collected in each cup was used to determine coefficients of uniformity (CU) by the Christiansen Method and the Heermann and Hein Method (ASAE, 1998). For the 100% test, the Christiansen CU was 89% and the Heerman and Hein CU was 87%. The 50% test produced a Christiansen CU of 89% and a Heerman and Hein CU of 88%. These CU’s indicate a uniform application for both rates.

The mean application for the 100% test was 61.2 ml with standard deviation (SD) of 5.9 and a coefficient of variation (CV) of 0.096. The 61.2 ml value became the baseline for further comparisons. The mean application for the 50% test was 28.4 ml with SD of 4.2 and CV of 0.148. This mean differed from the expected mean (30.6) by 7.1%. A single sample t-test was used to compare the 50% data to the assumed expected/known rate of 30.6 (50% of 61.2), and indicated a significant difference between the 50% mean and the known rate. This could be attributed to application losses that often occur in center pivot irrigation systems and which have a greater effect at lower irrigation rates.

Figure 4. Ultrasonic flow meter.

Table 1. Farmer-owned center pivot systems with VRI controls installed.

Pivot	Towers	Mainline Length (ft)	End Gun	Total Acres	Flow Rate (gpm)	Pressure (psi)	Sprinkler Type	Control Zones
LP	3	569	Yes	32	275	25	Spray on drop	13
TS	3	609	Yes	37	750	55	Impact	16
JB	5	995	Yes	88	1000	43	Spray on top	23
DS	7	1408	Yes	162	1200	40	Impact	8*

* Only the last span, overhang, and end gun were controlled by VRI system.

The results of the variable rate testing are shown in Figure 6. All of sub-section 1 and most of sub-section 2 were located within the first span of the pivot. The uniformity of application from sprinklers in this span is usually poor and unavoidable due to nozzle size limitations. By design, irrigation sprinklers are sized and spaced to overlap adjacent sprinklers to improve uniformity. Sections 3, 4 and 5 were large enough to allow calculation of CU values and were each quite uniform (86%, 94%, 95%).

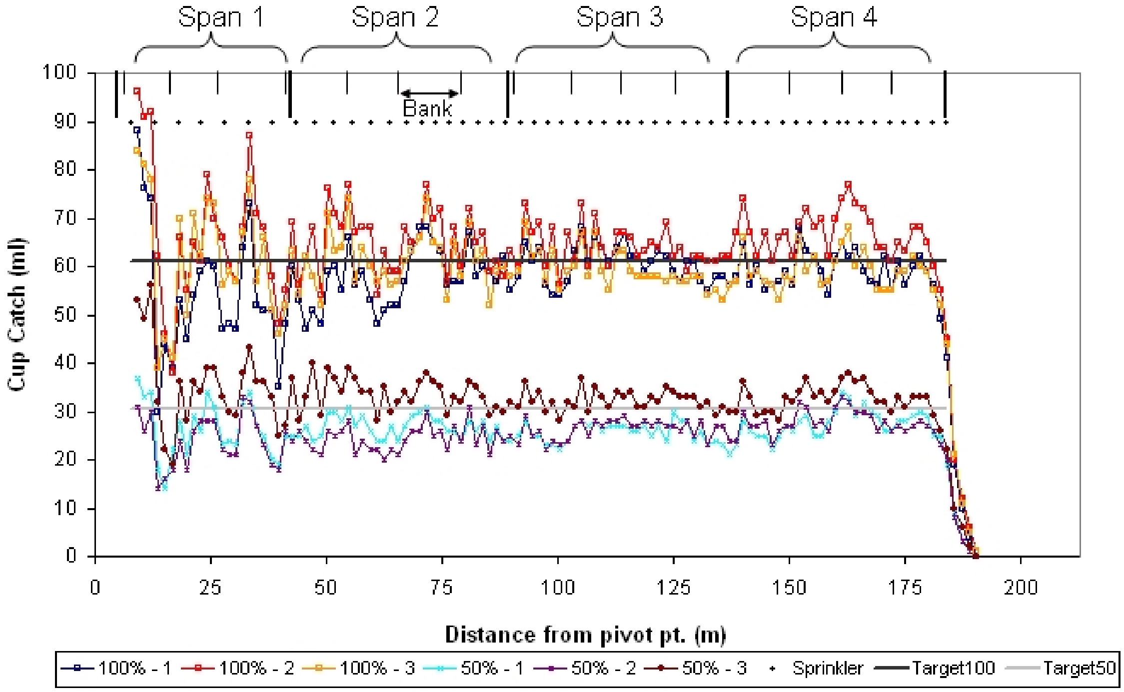


Figure 5. Results of the NESPAL pivot 100% and 50% tests.

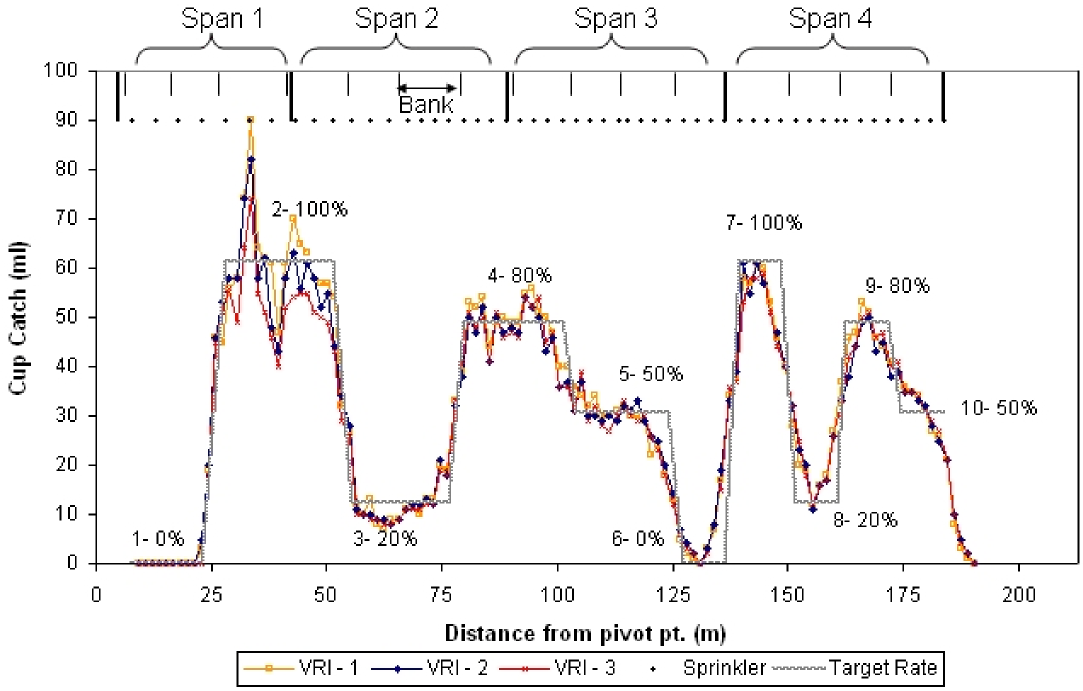


Figure 6. Results of the NESPAL pivot variable rate tests.

Results from the actual water use study with the two farmer-owned CP systems are shown in Table 2. The two pivots were operated at higher than normal travel speeds to reduce the time personnel had to remain on site during the testing. With VRI controls, the LP pivot used considerably less water in one pass. However, the TS pivot used slightly more water under VRI controls.

Table 2. Results of actual water use testing.

Pivot	Measured non-VRI water use	Measured VRI water use	Calculated VRI water use	Percent Timer Setting	Time for one pass
TS	188,800 gal	195,300 gal	197,600 gal	90 %	4.4 hours
LP	68,400 gal	43,800 gal	52,900 gal	100 %	4 hours

SUMMARY AND CONCLUSIONS

The results of the application tests indicated that the NESPAL pivot's application was uniform in non-VRI mode. Similarly, when all sprinklers were set to 50%, the application was again uniform, showing that the VRI system's cycling of sprinklers on/off to vary application rate did not alter the uniformity. Normal irrigation losses likely prevented the system from more closely matching the target application (50% of normal). The third series of tests mimicked a variable-rate scenario and the VRI system was able to achieve target application amounts fairly well, especially at higher rates. However, these tests measured variations in application only along the pivot mainline.

The results from the actual water use study indicated substantial water savings in one field while no change in water use in the other field. This is common with many precision agriculture tools. Each field is a unique situation that has its own variability to be addressed.

The installed VRI systems will be tested further for circumferential variations, reliability and usability. The authors plan to continue to document actual water savings and crop yields realized from use of VRI controls. New sensors that could interface with the VRI controller and provide real-time soil water information will also be investigated.

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Center Pivot Evaluation and Design (CPED) Lite program

Dale F. Heermann and Thomas L. Spofford[1]

INTRODUCTION

The USDA, Environmental Quality Incentive Program (EQIP) administered by the Natural Resource Conservation Service (NRCS) provides cost sharing on the installation and upgrading of irrigation systems for improving water quality or the conservation of water under irrigation. Center pivots are frequently the system of choice. There is a need to assure that installed systems will provide the desired improvement in irrigation performance. A similar need exists for any user of center pivot systems to assure that an installed or modified system will perform as designed. The NRCS has written a new Conservation Practice Standard, 442 - Irrigation System, Sprinkler. The irrigation industry, along with University and Agricultural Research Service (ARS) researchers met with the NRCS technical staff to discuss the standard and an appropriate evaluation technique for approving the design. The industry suggested that the ARS Center Pivot Evaluation and Design (CPED) program be used for the design evaluation. Discussion among the Industry representatives and the University and Government technical specialists resulted in the design of a streamlined version of CPED, CPEDlite. The use of this model would result in a mutually accredited tool to evaluate system performance for use by the NRCS field office personnel and contract EQIP Technical Service Providers (TSP’s). The objective of this paper is to present the CPEDlite program that is currently being tested and made ready for evaluation of new and upgraded field center pivot systems.

EVALUATION OBJECTIVES

The selection or development of an evaluation standard and procedures should focus on the need for the evaluation. The USDA, Environmental Quality Incentive Program (EQIP) administered by the Natural Resource Conservation Service (NRCS) requires an evaluation procedure that is repeatable and can be easily accomplished by the NRCS field office personnel and TSP’s. For USDA’s EQIP, proposed and installed systems must provide improvement in irrigation performance and water conservation. Irrigation scheduling is of primary importance for optimizing the use of water. Efficient scheduling requires knowing the amount of water applied per irrigation. Selecting the appropriate depth for scheduling (Duke et.al. 1992) requires knowing or determining the uniformity of water application to minimize over and under application.

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When evaluating existing systems, the major factors that can change a systems performance are a change in nozzle size due to wear, changes in pumping plant efficiency, water supply changes (particularly with ground water decline), system leaks and changes in roughness of the supply and lateral pipe lines. Evaluations should be performed when new systems are installed or when existing systems are modified with new sprinkler packages, to assure they operate as designed.

CURRENT EVALUATION PROCEDURES

The most common procedure for evaluating the uniformity of center pivot irrigation systems is to measure the application depth with catch cans. ASAE S346.1, (1999) and National Engineering Handbook, (1983) are the most commonly used standards in the US, and internationally for evaluating the uniformity of center pivot irrigation systems. The ASAE standard recommends two radial lines of catch cans with the outer end of the rows not more than 50 m apart. The NRSC recommends a single line of catch cans. Both standards recommend calculating the uniformity with the Heermann and Hein (1968) modified equation for the Christiansen (1942) uniformity coefficient. The NRCS includes other measures and performance parameters in their procedure.

The ASAE recommendation to run evaluations at night is often not practical. The requirement for low wind velocity at the time of evaluation is also difficult to satisfy, particularly when attempting to evaluate a number of systems. A wind tunnel study (Livingston et. al. 1985) showed that the divergence from 2.5 to 6.2 m/s wind speeds resulted in decreased catches of 5 - 25%. Losses of this magnitude can easily lead to the conclusion that a center pivot system is very inefficient. Evaporation from the catch cans before they are measured also introduces an error in the technique. Both the ASAE and NRCS standards were developed when impact sprinklers were typically used on moving systems. The current ASAE standard is modified for systems equipped with spray nozzles having significantly smaller pattern radii. The newer spray sprinkler heads often are installed on drop tubes having a wetted diameter of six m or less. The 3 to 4.6 m catch can spacing is not adequate for this small wetting pattern. A typical 380 m system would require more than 400 catch cans for the double row test to satisfy the ASAE standard. This results in evaluation of systems with the newer type sprinkler heads being extremely time consuming and resource intensive. A procedure or process that would provide the needed evaluation information with minimal sampling and use of human resources is an attractive alternative.

EVALUATION REQUIREMENTS

The current standards provide a single estimate of the CU at the time of the test. They require documenting the test and climatic conditions that should be considered when comparing tests between systems. The test however does not provide an insight to the performance of the system as it moves around the circle that is irrigated. The effect of topography and water supply characteristics should also be evaluated.

Field catch can data are an excellent way of observing the operating status under field conditions. One major problem is the inability to repeat the test and obtain identical evaluations in terms of depths caught and the resulting calculated uniformity.

ALTERNATIVE EVALUATION PROCEDURE

Computer simulation of the center pivot sprinkler performance was first presented by Heermann and Hein (1968). A user friendly simulation program Center Pivot Evaluation and Design (CPED), an enhancement of this work, is currently being used by the NRCS to evaluate center pivot systems. The required inputs and options for the model were presented by Heermann (1990). Simulation programs for evaluating different characteristics of center pivot systems have been written by Edling (1979), James (1984), and Bremond and Molle (1995). The distinct advantage of computer simulation over field tests is that a large number of design options and operating conditions can be compared with limited time and resources. The evaluation is also repeatable.

Suggested Protocol for Alternative Procedure

Manufacturers and distributors of center pivot and/or sprinkler heads use computer models to design the vast majority of new or renozzled center pivot systems. Most system designs will provide a uniform irrigation if nozzles and sprinklers are installed according to the design, and operated within their intended flow and pressure. The manufacturer's computer design inventory provides the majority of the inputs needed to run a simulation to obtain the potential uniformity of the system. The major manufacturers and distributors of center pivot sprinkler packages have written programs that will output their design packages to the CPED data file format and significantly reduce potential errors and the time of entering the center pivot design for evaluation.

The model documents the uniformity of the system as designed, however a key element to verify performance would be to go to the field and perform a physical and visual inventory of the system. The size and length of all pipes, sprinkler model, nozzle sizes, pressure regulators, and location of each outlet should be compared with the design chart and inventory. The elevation of the pivot and each tower is needed to accurately solve for the pressure distribution on the system. It is desirable to use pump and drawdown curves but the model can be run with constant pressure or discharge. An approximation of the pipe roughness is needed to run the simulation. With the system operating, pressure and discharge measurements should be taken along the lateral line and compared with the calculated pressures and discharges. A word of caution when running CPEDlite for pressure regulated systems. The current version of CPEDlite does not change the pressure as a function of line pressure with pressure regulators. For these systems it is recommended that the pivot pressure be specified. Pressure-regulated systems may lead to difficulties in matching a regression fit of pump curve data.

Model output includes the hydraulic operating pressures on the system, the sprinkler discharge, the application depth at requested positions and the coefficient of uniformity

(Christiansen). Differences between measured and computed pressures and discharges suggest that the system may not be performing as desired.

Potential causes of simulation errors are wear, age, or from initial input due to measurement or entry errors of the components. Factors that can change with age include the pipe roughness factor, pump characteristic curve, and nozzle size. Pressure regulators may have a hysteresis effect and could lead to differences between simulated and measured pressure. Age also can change the performance of flow control devices. Measurement is always a potential source of error. This could include measured pressures, discharges, distances and elevation, recognizing accuracy is ± 5% with most standard measuring devices for flow and pressure.

SIMULATION EVALUATION OF CENTER PIVOT SYSTEMS

The simulation model in this paper is based on the first model presented by Heermann and Hein (1968) which was verified with field data. Their simulation model required input of the sprinkler location, discharge, pattern radius and an assumed stationary pattern shape of either triangular or elliptical. The application depth versus distance along a radial line from the pivot was determined and application rates at a specified distance from the pivot were determined. The hours per revolution were input and each tower was assumed to move at a constant speed for the complete circle. Kincaid, Heermann and Kruse (1969) used the model to calculate potential runoff for different system capacities and infiltration rates. Kincaid and Heermann (1970) added the calculation of the flow resistance and verified with measured pressure distribution along the center pivot lateral. Chu and Moe (1972) studied the hydraulics of a center pivot system and developed a quick approximation for determining the pressure loss from the pivot to the outer end of the lateral as a constant (0.543) times the loss that would occur if the entire discharge flowed the total length of the lateral.

The model was adapted by Beccard and Heermann (1981) to include the effect of topographic differences in the resulting application depths along radii of the center pivot on non level fields. The model included the pump and well characteristics and calculated the hydraulic equilibrium point as the system moved to different positions on a rough terrain. The model was exercised to determine the uniformity changes when converting from high pressure to low pressure on rough terrain. Edling (1979), James (1982), James (1984), and James and Blair (1984) also used simulation models to study the performance of center pivot systems on variable topography and with different pressures.

The current simulation model has been expanded to include donut shaped stationary patterns which represent many of the low pressure spray heads.

EXAMPLE OF SIMULATION EVALUATION

The uniformity of application depths can be calculated by inventorying the sprinkler head models, nozzles sizes and distance from the pivot. The pump curve and drawdown, or pivot pressure, or pivot flow is also needed. Figure 1 illustrates a model simulation with nozzles installed as designed. The dashed line represents the distribution if the sprinkler heads were reversed between 2 towers at the time of installation. Note that the change reduced the CU by 3 percent.

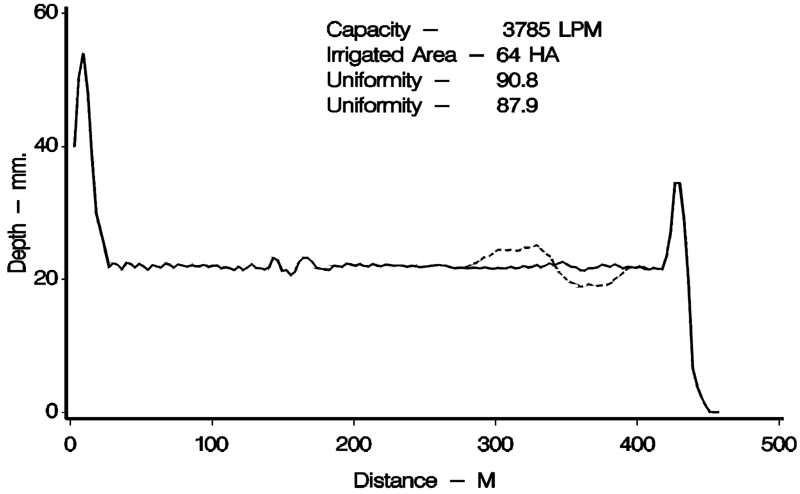


Figure 1 Typical center pivot as designed (CU = 90.8) and with 10 sprinkler heads incorrectly installed shown as a dashed line (CU = 87.9)

CPEDlite versus the full CPED model differs primarily in the selection of variable system parameters. The System file that contains system basics is identical for each simulation model. The System file consists of:

- Pump curve information, constant discharge or constant head with discharge estimate
- Total dynamic lift if using a pump curve.
- Length, inside diameter, resistance coefficient from pump to pivot hub
- Pipe diameter, distances and resistance coefficient along the lateral pipe.
- Pivot pad elevation, nozzle height and reference for specified pressures
- Number of towers, tower location from pivot and elevation relative to the pad
- Booster pump pressure increase, number of sprinklers beyond booster including big gun

- Distance, sprinkler brand, model # , size (64th in.)of each sprinkler on the system, sprinkler application shape (donut, triangular, or elliptical
- Pressure control (specified pressure) on pressure controlled sprinklers.
- Start and stop angle for each part circle sprinkler.

Full description and detail of these elements are presented in the CPED users manual

Once the System File is complete, the simulation can be run after addition of a few more specific parameters. As previously stated CPEDlite limits the entries that can be changed.

1. Hours/Rev - The time needed to complete one revolution of the Pivot. This directly determines how much water is applied. (Both)

2. Sprinkler Number - All, Can not be changed. (CPEDlite)

3. Starting Distance for depth simulation (ft.). Is set to 12% of the total length, Cannot be changed. (CPEDlite)

4. Stopping Distance for depth simulation (ft.).Set to the end of the hardware but exclude the big gun, Cannot be changed. (CPEDlite)

5. Distance Increment - The distance between the simulated catch cans (ft.).Set to 1 foot, Cannot be changed. (CPEDlite)

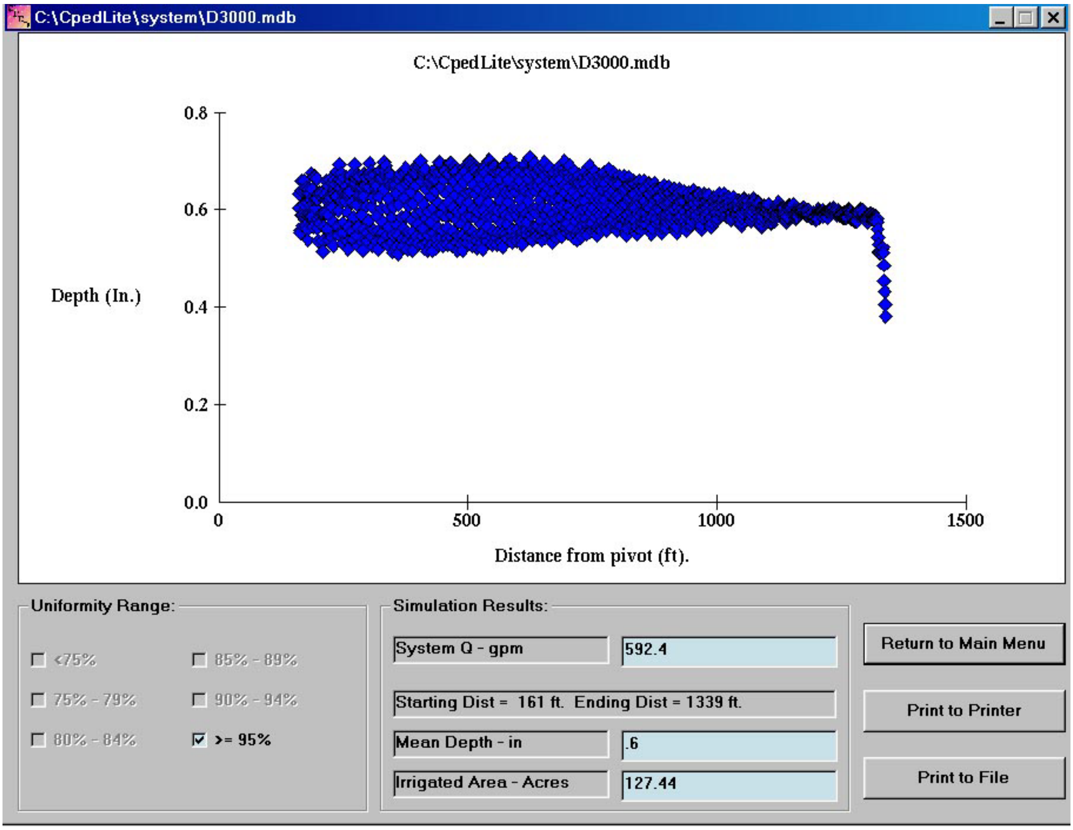
6. The Minimum Depth for Uniformity (in.) Set to 0, Cannot be changed. (CPEDlite)

Once these parameters are entered, start the simulation.

RESULTS

As the simulation runs, depths vs distance are plotted on the monitor. On completion the uniformity range (in 5% increments), system Q, starting and ending evaluation distances, mean depth and irrigated area are displayed. An example monitor display is shown in Figure 4. The uniformity is in the > 95% uniformity range. The resulting depths have a large difference between the consecutive simulated points. The system has a 10 foot spacing of spray sprinklers. The large variation in depth is typical of what can be expected with the spray sprinklers with pattern radii varying from 10 to 16 ft. The variation decreases as the distance from the pivot increases with the larger pattern radii.

The CPEDlite is constrained on run time options to assure that repeatable results will be obtained for the same system. Industry, Government and University personnel determined that it would be appropriate for CPEDlite to report CU in 5 percent increments to assure repeatable results. The actual CU for the example system is 95.2%. If the spacing interval was changed from one to ten ft. the CU would increase to 97.7%. Spacing intervals from one to ten ft. by one foot increment were simulated with starting distances between 160 and 169 feet. The lowest CU (93.3%) resulted with a starting distance of 164 feet and a spacing interval of five feet (Figure 5). A CU of 98.1% was simulated with a starting distance of 161 feet and ten foot spacing (Figure 6). Thus, a 4.8 % point change resulted with changes in the starting distance and spacing interval. It should be noted that the data points shown in Figure 5 and 6 are subsets of the entire data set in Figure 4 where application depths were simulated at one foot intervals. Figure 5 represents the envelope of the points in Figure 4 and thus reduces the CU. Whereas, Figure 6 is a set from the middle of the data in Figure 4 and thus a higher CU. The five percent increments in reported CU is nearly equivalent to the range in CU for a single system simulated.



Uniformity Range:

☐ <75%
☐ 75% - 79%
☐ 80% - 84%
☐ 85% - 89%
☐ 90% - 94%
☑ >= 95%

Simulation Results:

System Q - gpm: 592.4
Starting Dist = 161 ft. Ending Dist = 1339 ft.
Mean Depth - in: .6
Irrigated Area - Acres: 127.44

Figure 4. Example Monitor output from CPEDlite for D3000 system.

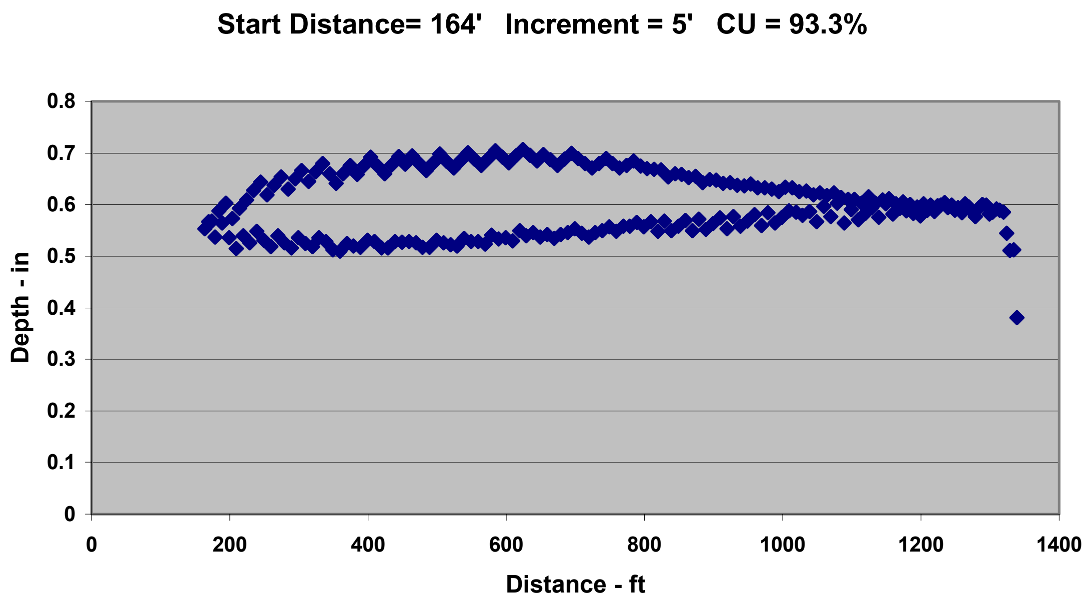

Start Distance= 164'   Increment = 5'   CU = 93.3%

Figure 5. Simulation of D3000 with depth measurements at 5 foot intervals.

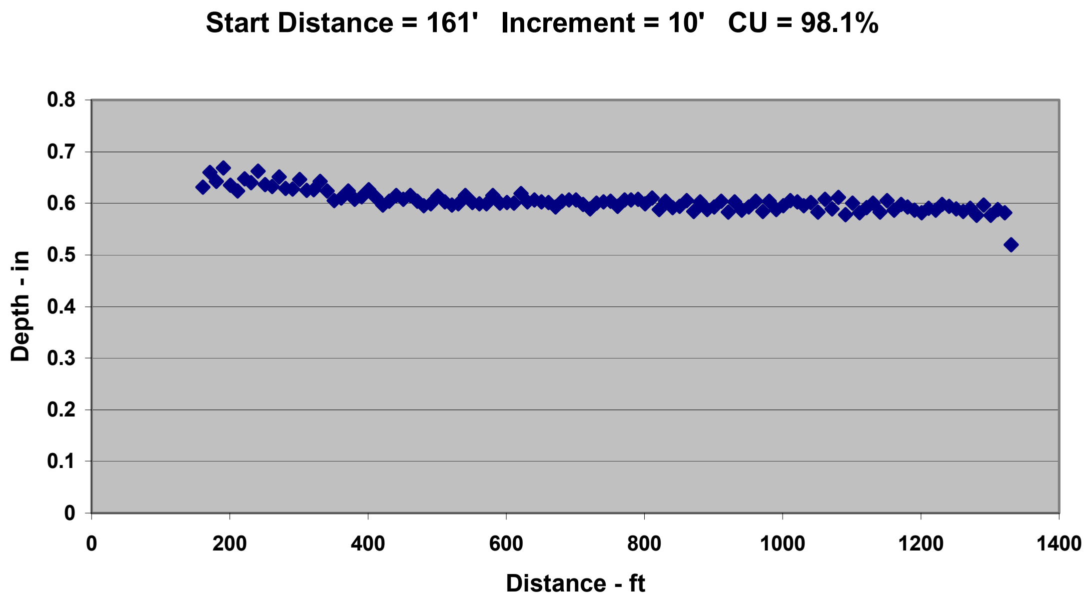

Start Distance = 161'   Increment = 10'   CU = 98.1%

Figure 6. Simulation of D3000 with depth measurements at 10 foot intervals.

The simple example and comparisons demonstrates the validity of reporting the uniformity in 5% uniformity bands. It also points out the potential problem of measuring with catch cans when a four to five percent difference in CU is possible with different starting distances and simulated catch can spacings.

Other information that can be printed or saved in a file for each sprinkler is:

1. The line pressure - psi
2. The nozzle pressure - psi
3. The discharge - gpm
4. The pattern radius - ft

DISCUSSION OF EVALUATION PROCEDURES

Evaluations of center pivot simulations were compared against catch can spacing (Heermann and Spofford, 1998). Catch can data had significantly more variation than the simulated but approximately the same average depths. The sprinklers were spray nozzles with deep grooved pads producing distinct streams and large drop sizes. The catch can test was repeated on the same system by replacing the pads with smooth pads. The catch can CU increased by 10% when changing from the deep grooved pads to the smooth pads. The distinct streams are not measured correctly with small (10-20 cm) catch cans.

The particular objective for evaluating a center pivot system should be considered when selecting the evaluation procedure. If the objective is to consider modifications to improve the uniformity, there is a distinct advantage in using the simulation model procedure. Once the distribution uniformities are calculated with the existing system, it is quite simple to propose changes and simulate the improvements.

Disadvantages of catch cans

Wind
Night Testing
Evaporation
Difficulty in catching streams from grooved pads
Small pattern radii – large number of cans
Extreme care to set cans level and at proper distance
Labor intensive

Advantages of catch cans

Provides real field data from actual conditions
Simple to install
More readily accepted by user or system owner
Does not need a computer

Disadvantages of Simulation

Difficult to obtain pump curves
Difficult to obtain elevation data.
Requires labor to verify field installation
Need drawdown water level
Must have understanding of running models
May need additional measurements if simulation disagrees with field data
Need to know pattern shapes for application devices

Advantages of Simulation

- Less labor intensive to obtain field pressure and discharge data
- Wind is not a problem
- Provides a complete hydraulic analysis for comparison with field data
- Measurement errors of catch cans eliminated
- Modification of design can easily be evaluated
- Used to analyze for potential problems
- Aids in identifying pump problems
- Allows analysis of changing drawdown
- Successive runs with water table changes
- Can be used to recommend design changes
- Analyze effects of elevation changes for a particular field
- Analyze effect of big-gun operation

CONCLUSION

Simulation models can effectively be used in the evaluation of center pivot systems. The advantage of a simulation procedure is the speed of evaluation of an existing system and system modifications. The simulation model can also be used to determine the distribution over the entire field as the topography varies and big gun sprinklers are turned on and off. It also can be an effective tool for diagnosing distribution problems of a center pivot system. Procedures need to be developed to effectively use the simulation for detecting and interpreting the cause of differences between the field measured and simulated system pressure and discharge.

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Irrigation Strategies For Optimizing Yield and Water Use Efficiency

Donald. F. Wanjura and Dan R. Upchurch [1]

Abstract

Subsurface drip irrigation (SDI) can apply precise quantities of water uniformly along the row and enhance the efficiency of water use. The Biologically Identified Optimal Temperature Interactive Console (BIOTIC) irrigation timing protocol was used to control irrigation timing using two strategies for establishing different water levels in a cotton SDI study in 2002. Daily irrigation decisions for treatments in both strategies were determined by the different time threshold (TT) values required to generate irrigation signals. The TT were specific accumulations of stress time which were periods when canopy temperature exceeded 28°C during the daytime. One strategy maintained different constant rates of irrigation (CTT) and a second strategy varied irrigation (VTT) during four growth stages in proportion to each stage's yield sensitivity to water stress. The purpose of the study was to compare the yield and water use efficiency (WUE) of the two irrigation strategies. Three water levels were established with each strategy. Cumulative irrigations in the CTT strategy were 398, 313, and 201 mm for the 2.5 hr TT, 5.5 hr TT, and 7.5 hr TT treatments, respectively. The VTT strategy had cumulative irrigations of 152, 262, and 318 mm for the LW, MW, and HW treatments. Lint yield increased with irrigation and total water for both irrigation strategies in a positive curvilinear manner. The 5.5 hr TT treatment in the CTT strategy and the MW treatment in the VTT strategy produced the best combination of high yield and high WUE. Irrigation and total water WUE values from both irrigation strategies had a common negative linear relationship with applied water, except for the 7.5 hr TT treatment which had lower WUE values. The performance of the CTT or VTT strategies in scheduling irrigation was inconsistent across water levels based on the criteria of yield and irrigation WUE.

Introduction

Crop yield and water use efficiency are factors which usually change in opposite directions to water application. Since these factors do not maximize at the same levels of water input a choice is made on which factor receives priority. If water supply is ample yield is emphasized as long as its incremental increase from additional water remains positive. Frequently water supply is limited and irrigation level is determined by the availability of water. Irrigated area in the U.S. in 1996 was around 20 Mha and annual applications were 500 mm, ERS (1997). Irrigated area had remained constant in recent years, but irrigation application declined from 650 mm in earlier years.

Lamm, et al., 1994 irrigated corn in level basins at 0.75, 1.0, and 1.25 times ET using daily deficits of 0, 1, and 2 mm/day after tasseling. Irrigations were applied when soil water depletion was approximately 65 mm. Yields were related linearly to irrigation and water use with a reduction in irrigation or water use reflected by yield reductions. Water use efficiencies (WUE) were similar whether planned soil water depletion was used or not. The influence of low energy precision application (LEPA) sprinkler irrigation and subsurface drip irrigation (SDI) systems on WUE of cotton was studied by Bordovsky and Lyle (1998) with application rates of 2.5, 5.0, and 7.6 mm/day. Cotton yields and water use efficiencies were significantly higher for SDI than LEPA. A three

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year SDI study with cotton examined the effect of different irrigation levels, row spacing, and planting patterns on WUE, Enciso-Medina, et al., (2002). The average WUE of the ultra-narrow row spacing (0.25 m or 0.26 m) for the three years was 12 % and 21% higher than the 0.76 and 1.02 m spacings, respectively.

The use of SDI is increasing on the southern high plains due to the diminishing supply of water from the Ogallala aquifer which is the primary water supply. The advantage of SDI over other irrigation methods is the reduction of water loss from evaporation. A disadvantage is the high initial cost to purchase the equipment and install the system. SDI can be used with a wide range of water supplies and the quantities applied can be precisely controlled. The capability of SDI to apply precise quantities of irrigation with a wide spectrum of application frequencies may make it possible to produce high yields with improvements in water use efficiency. The trade-offs between amount of irrigation and the efficiency of its use by crops in producing the yield component of total biomass need further study. We have investigated the BIOTIC methodology for timing irrigation and identified operational parameters that produce high yield without applying excessive irrigation (Upchurch , et al., 1996; Wanjura, et al., 1992; Wanjura, et al., 1995).

The objective of this paper is to describe the results from a one year field study where BIOTIC was utilized to vary seasonal irrigation using two strategies for timing irrigation application. One strategy maintained a constant crop water stress during the irrigation season and the other strategy varied irrigation frequency in proportion to the sensitivity of yield to water stress during different growth stages.

Materials and Methods

Two studies were conducted in adjacent blocks in the field of the Plant Stress and Water Conservation Laboratory at Lubbock, TX. The cotton variety Paymaster 2326 BGRR was planted on 13 May 2002 (DOY 133) in north-south rows having a spacing of 1 m. Most seedlings emerged by 20 May and the final seedling population averaged 50,500 plants/acre. One study examined the strategy of using constant time thresholds, (CTT) of 2.5, 5.5, and 7.5 hrs of canopy temperature above 28°C and the other study included three water levels designated as LW, MW, and HW, which utilized a strategy of variable time thresholds (VTT) that were changed during five growth stages. Both studies were watered with subsurface drip irrigation. The CTT study had laterals located under each bed and the VTT study had laterals under alternate furrows. Two 13 mm irrigations were applied through the subsurface drip irrigation system on 14 May and 16 May to ensure adequate moisture for germination.

The drip lateral diameter was 0.875 in ID with 0.23 gph emitters having a 24 in spacing. Each irrigation zone included 8 rows 542 feet long and was individually metered. An Elgal-Agro Controller Ver. 109 (Eldar-Shany, Yad Mordechai, 79145, Israel) was activated by a 5 mv signal from a Campbell Scientific CR 7 data logger that computed stress time values and generated irrigation signals from canopy temperature measured by infrared thermocouples located within plots.

The time-threshold (TT) is an integral part of the BIOTIC protocol for timing irrigation applications. Different TT values apply varying irrigation amounts which cause different soil water levels. The three irrigation treatments in the CTT study were controlled by TT of 2.5, 5.5, and 7.5 hr, which were selected to apply excessive, optimum, and deficient amounts of water. Canopy temperature > 28 °C, air temperature > 28 °C, and net radiation > 200 Wm^{-2} were required for a time interval to be added to the stress time accumulation for determining the occurrence of an irrigation signal. Irrigation signals were dependent on the amount of time above a canopy temperature of 28 °C (referred to as stress time) exceeding the TT for each irrigation treatment.

Irrigation decisions were made daily and a 5 mm irrigation was applied in response to an irrigation signal, which could be over-ridden by recent sufficient amounts of rain. The target amount of water application was 5 mm from either rain or irrigation. Rain events > 5 mm were accumulated and prevented irrigation until their accumulation was reduced to zero at the rate of 5 mm day^{-1}. When the daily accumulation of ST for an irrigation treatment failed to exceed the required TT, only 5 mm was applied after the next irrigation signal regardless, of the number of days between irrigation signals.

Both experiments were randomized complete block designs with four replications in the CTT study and three replications in the VTT study. The studies were sprayed with Ginstar on DOY 270 (27 September) to drop the leaves. Each plot was stripper harvested on DOY 316 to provide an estimate of lint yield.
In addition to monitoring canopy temperature in both studies, air temperature, relative humidity, net radiation, and windspeed were measured at a 2 m height and saved as 15 min averages.

Microclimate measurements and crop development data were collected only in the CTT study. Plant heights were measured weekly beginning on DOY 164 and bi-weekly biomass sampling started on DOY 171.

Results and Discussion

After planting, automated irrigation in each of the studies was delayed until cotton plant canopies had reached sufficient size to measure canopy temperature with infrared thermocouples without viewing the soil below the plants. Early season rain of 115 mm between DOY 155 and DOY 162 provided sufficient moisture for seedlings growth without irrigation, Fig. 1.

Automated irrigation began on DOY 170 in the CTT study and DOY 177 in the VTT study. Plants in both studies had reached the squaring growth stage when irrigation was started. The irrigation signal TT values remained constant for the entire irrigation period for each treatment in the CTT study. The TT values used for the VTT study are given in Table 1 for each growth stage. Lower TT values result in more irrigation during the season because the probability of accumulating sufficient stress time to trigger an irrigation signal is higher for each day.

Water Application

Irrigation after crop emergence was initiated on DOY 170 in the CTT and on DOY 177 in the VTT studies, Fig. 1. Cumulative irrigation was 398, 313, and 201 mm for the 2.5 hr TT, 5.5 hr TT, and 7.5 hr TT treatments, respectively, in the CTT study. In the VTT study total irrigation was 152, 262, and 318 mm for the LW, MW, and HW treatments. Differences in irrigation application rate began on DOY 193 among treatments in both studies. The rate of irrigation application was different and constant for each treatment in both studies for most of the irrigation period following DOY 193. Cumulative irrigation was nearly equal between the MW and HW water levels in the VTT study through DOY 220.

Total rain during the growing season was 177 mm with 83% received by DOY 192. Total water applications in the CTT study were 577, 492, and 380 mm for the 2.5 hr TT, 5.5 hr TT, and 7.5 hr TT treatments, respectively, Fig. 2. In the VTT study total water amounts were 490, 434, and 324 mm, respectively, for the HW, MW, and LW water levels.

The 5.5 hr TT and HW treatments received the same amount of irrigation and total water application. Irrigation signals were determined by a constant TT value in the 5.5 hr TT treatment and a combination of 3.0 hr TT and 5.0 hr TT in the HW treatment. The 5.5 hr TT treatment also started irrigating on DOY 170 compared with DOY 177 for the HW treatment.

Yield and Water Use Efficiency

The highest lint yield in the CTT study was 1588 kg ha^{-1} from the 2.5 hr TT treatment, but it was not statistically different from the 1555 kg ha^{-1} yield for the 5.5 hr TT treatment, Table 2. The 1018 kg lint ha^{-1} from the 7.5 hr TT was lower than from the other treatments. As a comparison the dryland yield was 307 kg lint ha^{-1}. In the variable time threshold study the lint yields of 1476 kg ha^{-1} and 1453 kg ha^{-1} for the HW and MW treatments, respectively, were similar and different from the LW yield of 1110 kg ha^{-1}.

The relationship of irrigation and total water applied during the season with lint yield and water use efficiency are compared in Fig. 3. Irrigation WUE values from both studies fit a common negative linear relationship with amount of irrigation, except for the 7.5 hr TT treatment. Total water WUE values show a similar relationship with water applied, including the anomaly of the 7.5 hr TT. The WUE values based on total water are lower than those based only on irrigation since rain is included in total water. Rain in proportion to irrigation ranged from 31% for the 2.5 hr TT treatment to 114% for the LW treatment.

Water use efficiency based on either irrigation or total water was negatively related with lint yield in both studies, Fig. 4. The trend lines do not include the 7.5 hr TT treatment since its response deviates from the pattern of the other treatments. The slope of the lint yield-WUE relationship is greater for irrigation than total water, primarily due to the large decrease from irrigation WUE to total water WUE in the LW treatment.

The most water limited treatments, 7.5 hr TT in the CTT strategy and the LW treatment in the VTT strategy, had contrasting responses to quantity of water application. The LW treatment received about 5 cm less irrigation than the 7.5 hr TT treatment but its yield was about 100 kg lint/ha higher, Table 2. The irrigation WUE for the LW treatment was 73 kg lint ha^{-1} cm^{-1} compared to 51 kg lint ha^{-1} cm^{-1} for the 7.5 hr TT treatment. One explanation for the different yield responses to limited water may be in the variation of irrigation applied over time. The 7.5 hr TT treatment received irrigations throughout the season that maintained a relatively constant level of moderately high water stress. The LW treatment received ample irrigation during the squaring growth stage, followed by limited irrigation during boll setting, followed by no irrigation during boll maturation, Table 1.Thus the LW treatment had low water stress up to first bloom, moderate water stress during boll setting, followed by relatively high water stress during crop boll maturation.

Among the treatments receiving high levels of irrigation the 5.5 hr TT treatment had a yield of 1555 kg lint/ha and the HW treatment produced 1476 kg lint/ha. However, the 5.5 hr TT had an irrigation WUE of 50 kg lint ha^{-1} cm^{-1} compared to 46 kg lint ha^{-1} cm^{-1} for the HW treatment. These treatments did not agree with the general trend of decreasing irrigation WUE as yield increases.

In the CTT strategy the 5.5 hr TT treatment produced 98% of the highest yield (2.5 hr TT treatment) with an irrigation WUE that was 98% of the highest irrigation WUE (7.5 hr TT treatment). In the VTT strategy the MW treatment produced 98% of the highest yield (HW) with an irrigation WUE that was 76% of the highest value (LW treatment).

Comparing between the two strategies the 5.5 hr TT treatment and the HW treatment at the high irrigation level received the same amount of irrigation, there were no differences in irrigation WUE, but lint yield of the 5.5 hr TT treatment was higher than the HW treatment yield. The 7.5 hr TT and LW treatments received the least amount of irrigation within their respective studies. Irrigation was higher in the 7.5 hr TT treatment than in the LW treatment with, yield and irrigation WUE being higher in LW treatment than for the 7.5 hr TT treatment. Thus the performance of the CTT or VTT strategies to scheduling irrigation were inconsistent across water levels based on the criteria of yield and irrigation WUE. It is important to emphasize that these are first year results of a planned multi-year study.

Conclusions

Cumulative irrigations in the CTT study were 398, 313, and 201 mm for the 2.5 hr TT, 5.5 hr TT, and 7.5 hr TT treatments, respectively. The VTT study cumulative irrigations were 318, 262, and 152 mm for the HW, MW, and LW treatments. Water use efficiency based on irrigation or total water from both studies fit a common negative linear relationship with amount of irrigation, except for the 7.5 hr TT treatment. The most water limited treatments, 7.5 hr TT in the CTT study and the LW treatment in the VTT study, had contrasting yield (1018 kg lint/ha versus 1110 kg lint/ha) and irrigation WUE (51 kg lint ha^{-1} cm^{-1} versus 73 kg lint ha^{-1} cm^{-1}) responses to quantity of irrigation applied (201 mm versus 152 mm). Among the high irrigation treatments the 5.5 hr TT treatment had a yield of 1555 kg lint/ha and the HW treatment produced 1476 kg lint/ha. However, the 5.5 hr TT treatment had an irrigation WUE of 50 kg lint ha^{-1} cm^{-1} compared with 46 kg lint ha^{-1} cm^{-1} for the HW treatment. The performance of the CTT or VTT strategies to scheduling irrigation was inconsistent across water levels based on the criteria of yield and irrigation WUE.

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Table 1 Time thresholds used to control irrigation during five growth stages in the three water levels of the variable time threshold study, 2002

Growth Stage ID	Growth Stage Description	Crop Water Level		
		LW	MW	HW
		- - - Time Threshold, hours - - -		
GS 1	Emergence to First Square [1]	NI	NI	NI
GS 2	First Square to First Bloom DOY 177 – DOY 190 [2]	3	3	3
GS 3	First Bloom plus 2 weeks DOY 191- DOY 204	7	5	3
GS 4	Peak Bloom plus 3 weeks DOY 205 – DOY 233	7	5	3
GS 5	Boll Maturity (80 % open bolls) DOY 234 [3]	NI	7	5

[1] Rain between DOY155 - DOY162 was 115 mm when seedling leaf area was too small to measure canopy temperature without also viewing some bare soil.

[2] Automated irrigation was delayed beyond first square because infrared thermometers were viewing some bare soil through the canopy on DOY 171 and 113 mm of rain fell between DOY155 - DOY162, which allocated 5 mm of rain per day for seedling use.

[3] Final irrigations were applied on DOY 231, DOY 250, and DOY 255 to the LW, MW, and HW crop soil water levels, respectively.

Table 2 Yield, water application, and water use efficiency for time-threshold irrigation and water use efficiency studies, 2002

Time Threshold Treatments	Lint yield, kg ha $^{-1}$	Total Irrigation cm	Total Water cm	Water Use Efficiency Irrigation, kg lint ha $^{-1}$ cm $^{-1}$	Water Use Efficiency Total Water, kg lint ha $^{-1}$ cm $^{-1}$
Constant Time Threshold Study					
2.5 hr	1588 a [1]	39.8	57.7	39.9	27.5
5.5 hr	1555 a	31.3	49.2	49.7	31.6
7.5 hr	1018 b	20.1	38.0	50.6	26.8
Variable Time Threshold Study					
LW	1110 b	15.2	32.4	73.0	34.3
MW	1453 a	26.2	43.4	55.5	33.5
HW	1476 a	31.8	49.0	46.4	30.1
Dryland	307	- - -	17.7	- - -	17.3

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1 Lint yields followed by a common letter are statistically similar at the 0.01 probability level according to Duncan's Multiple Range Test.

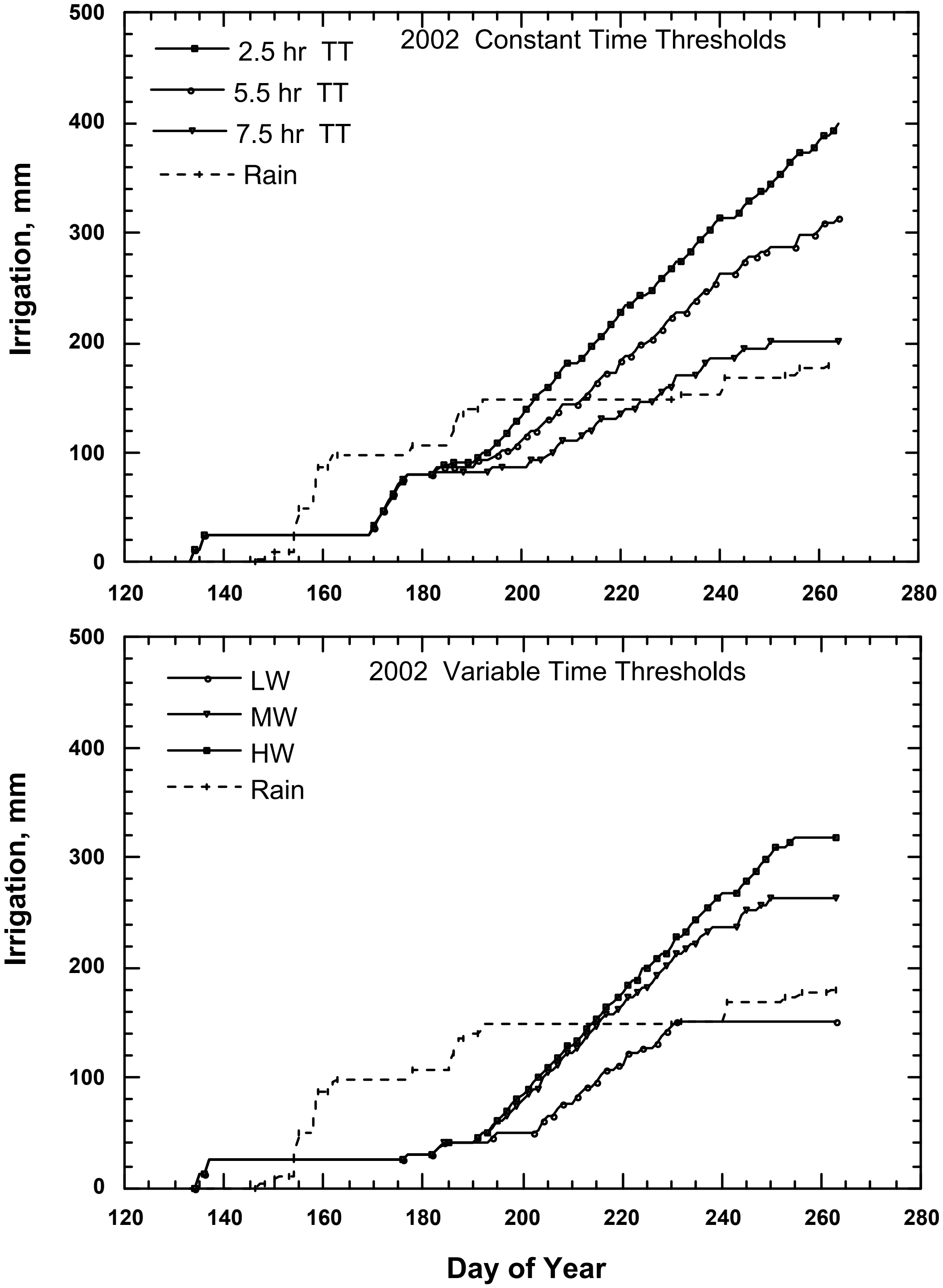

Fig. 1 Cumulative irrigation for constant and variable time threshold studies, 2002

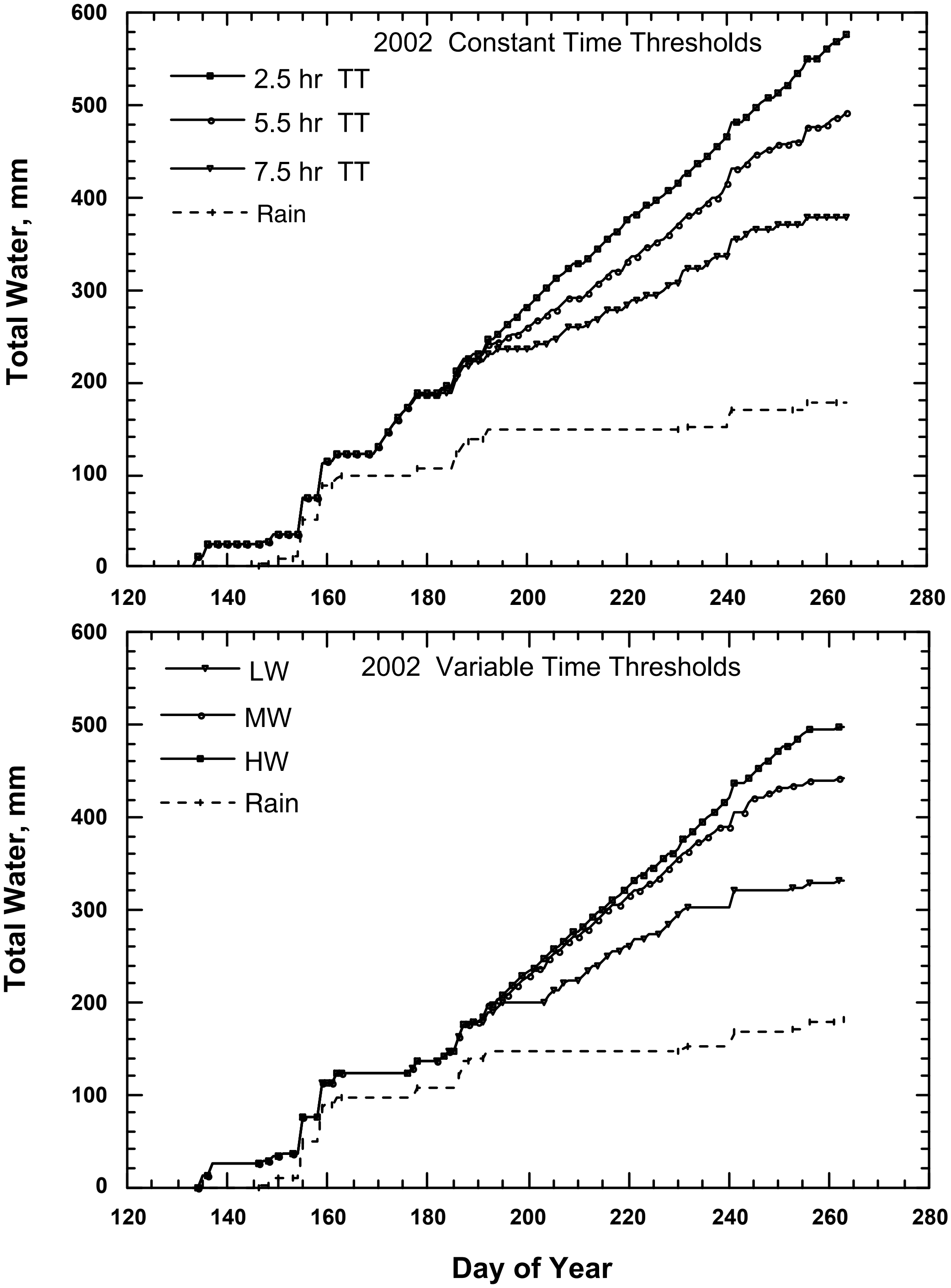

Fig. 2 Total water application for constant and variable time threshold studies, 2002.

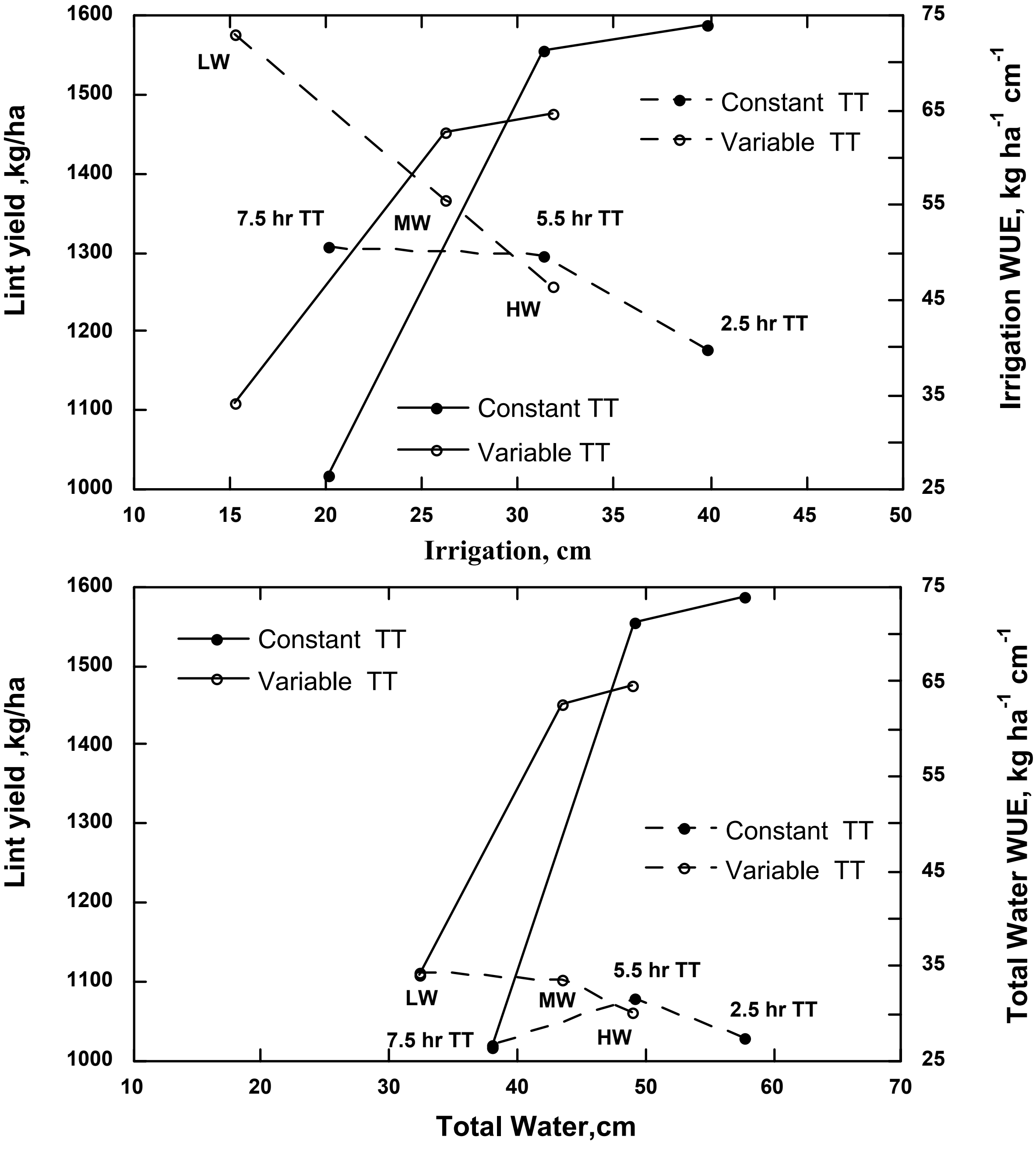

Fig. 3 Relationship of irrigation and total water with lint yield and water use efficiency for constant time threshold and variable time threshold strategies, 2002

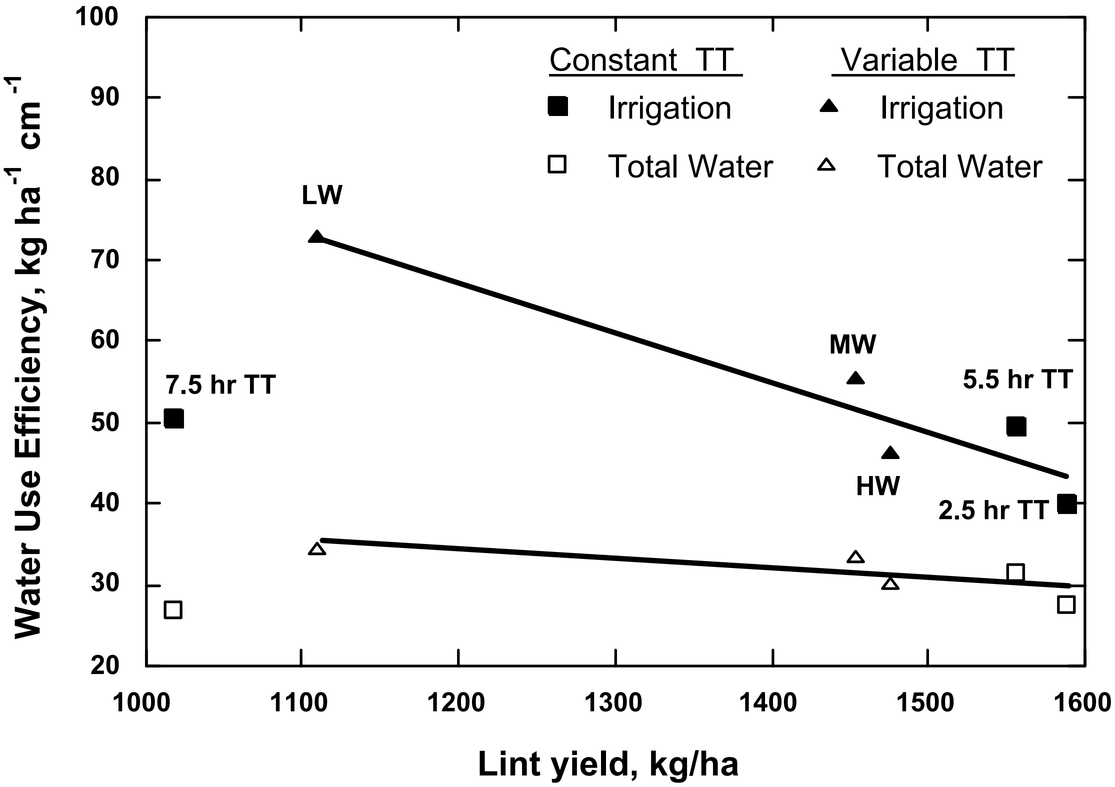

Fig. 4 Lint yield relationship with water use efficiency for constant time threshold and variable time threshold strategies, 2002.

SITE-SPECIFIC IRRIGATION OF COTTON ON THE TEXAS HIGH PLAINS

James P. Bordovsky and Robert J. Lascano[*]

Abstract

Cotton production might benefit from planned-variable distribution of irrigation as a function of soil water holding capacity (SWHC) and topography leading to better utilization of both rain and irrigation in water short regions of the Texas High Plains. Spans 5, 6, 7 and 8 of an 8-tower LEPA center pivot system were modified to deliver variable-rate (VR) irrigation within areas no larger than 400 m^2. Applicators were modified to provide relative flow rates of 2x, 3x, and 4x thus allowing stepwise increases in irrigation discharge of 20% of a base irrigation quantity. A control system opened solenoid valves relative to field location, thereby controlling irrigation quantities at specific sites.

Field experiments were conducted in 2001 and 2002 to evaluate equipment and document potential advantages of VR irrigation of cotton over standard practices. Alternating strips of cotton, 20 to 22 rows wide, were irrigated by either VR or uniform-rate (UR) irrigation. In 2001, the VR irrigation strategy attempted to level lint yields by reducing irrigation in areas of high SWHC and increasing irrigation on areas of low SWHC following uniform pre-plant irrigations. Management zones were based on soil texture and slope in a 5-ha area. In 2002, irrigation quantities were increased in areas thought to be "more productive". Soil electrical conductivity (EC) was used to determine the management zones on a 6.2-ha test area for site-specific irrigation.

Evaluations of the VR irrigation system following its construction in 2001 and modification in 2002 resulted in actual applicator flow rates within 5% of achievable flow rates. Errors in pivot positioning were documented. Based on preliminary comparisons with given management zone criteria, VR irrigation of cotton produced no significant increase in total lint yield or total irrigation water use efficiency (WUE) over uniform LEPA application in 2001 or increases in WUE in 2002. Using soil EC to establish management zones for VR irrigation resulted in lint yield increases of 2 to 4 % over uniform irrigation, but at the cost of additional water inputs.

Introduction

More than 20,000 center pivot systems irrigate 1.2 million ha of cropland in the Texas High Plains. However, available irrigation capacity is typically far less than peak evapotranspiration (ET) demand for crops grown in this region. Furthermore, irrigated soils are seldom uniform due to differences in texture and depth, and water availability within a field will differ due to topography and its effect on runoff. Crop production could benefit from the planned, non-uniform distribution of irrigation water based on SWHC and topography, leading to better utilization of both rain and irrigation water in this semi-arid environment.

The "multiple manifold" method of dispersing variable quantities of water with irrigation systems has been used at the Texas Agricultural Experiment Station (TAES) at Halfway in small plot research for many years (Bordovsky, et al., 1992). This method uses manifolds with different size nozzles in combinations to create a stepwise range of rates. The USDA/ARS in South Carolina also uses this method (Omary et al., 1997). Other

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VR irrigation systems use pulsing applicators for time proportional volume control (Farmscan Canlink 3000, VRI Controller, Western Australia) and altering the aperture of nozzles with a pin to achieve multiple flow rates (Sadler et al., 2001).

This paper discusses the construction and initial evaluation of a site-specific LEPA irrigation system and presents preliminary evaluations on criteria for managing variable-rate cotton irrigation in the Texas High Plains.

Materials and Methods

Spans 6, 7 and 8 of an 8-tower Zimmatic™ center pivot irrigation system were modified to provide VR irrigation during the spring and summer of 2001. The pivot was located at the Helms Research Farm, 2 miles south of the TAES Research and Extension Center at Halfway, TX. The hydraulic and control components of the VR system were evaluated in July and August. Field evaluations comparing VR to UR water application on cotton were conducted with water treatments beginning in August 2001. Management zones in 2001 were based on soil texture and slope down the furrow. An additional VR section (span 5) was installed in 2002. Irrigation management zones were created based on soil electrical conductivity (EC) measured by the Veris 3100 system (Veris Technologies, Salina KS).

Irrigation Equipment

The VR irrigation system conveys water from the pivot lateral through pressure regulators and solenoid valves into three separate 16-m long manifold pipes, which comprise the manifold unit. Three manifold units are positioned under each 49-m long pivot span. Hoses are used to direct water from the manifolds to specially designed LEPA irrigation applicators. In 2001, nozzle sizes for each applicator provided relative flow rates of 1x, 2x, and 3x, which, when opened in various combinations, provided six discrete irrigation amounts ranging from 25 to 150% of the base irrigation (BI) rate. In 2002, LEPA applicators were modified to provide relative flow rates of 2x, 3x, and 4x allowing stepwise increases in flow of 20% of BI. With additional water sources in 2002, the base flow rate for the 54-ha pivot was increased to 2270 L/min with equivalent flow rates in the modified spans ranging from a low of zero to a high of 3180 L/min.

The VR equipment evaluation began in July 2001. Original LEPA application devices were extensively modified to accommodate high water volumes without causing runoff. The final LEPA applicator consisted of a group of four nozzles, three were individually connected to one of the three manifolds of a VR manifold unit, and the fourth connected to the pivot mainline and sized at the BI flow rate. The entire nozzle assembly was inserted into a custom made “sock” with the lower portion of the open-ended sock dragging the ground and dispensing water between pairs of crop rows. All irrigated crops were planted in circular rows. The fourth nozzle was valved so that its flow would be off when the VR system was in use.

Applicator flow rates were determined by volumetric catchments from individual LEPA applicators for each of the manifold units during irrigation events from July through August in 2001, and in June and July in 2002. Water pressure taps were positioned at strategic locations throughout the manifold units to determine pressure losses and help improve water distribution. The two wells supplying water to the VR pivot were equipped with Cycle Stop® (Cycle Stop Valves, Lubbock, TX) pressure regulating valves to stabilize pressure at 200 kPa as changes in pivot flow rates occurred.

An electronic control system was installed to activate solenoid valves at each manifold unit relative to field location, thereby controlling irrigation quantities at specific sites. A SNAP-LCSX-PLUS industrial controller (Opto 22, Temecula, CA), two remote terminal units (SNAP-B3000), software, and related accessories were installed for this purpose. The control system was programmed to provide four control signals to each manifold unit (3 signals for 3 water manifold solenoids and an additional signal for a future chemigation actuator). Programming further allowed changes in solenoid status every 3° around the 360° perimeter of the pivot. Therefore, the largest control area under this VR pivot was < 400 m^2 (16-m manifold unit length by 22-m maximum 3° arc) resulting in more than 2000 potential water/chemical control cells under the 54-ha pivot. A standard incremental encoder (Dynapar™ Series E15, Danaher Controls, Gurnee, IL) was used to provide input signals to the controller to determine pivot location. A Microsoft Excel™ program was written to create coded map files from desired irrigation application maps. The application sequence was then loaded into the VR controller with a laptop computer.

Crop Response to VR Irrigation

2001 growing season. Field experiments were conducted to explore potential advantages of VR irrigation compared to standard uniform LEPA irrigation of cotton on the High Plains. The 2001 experiment was conducted in a 5-ha area irrigated by the VR system. This portion of the field contained the greatest elevation changes and the most notable differences in surface soil texture. The 60° arc was divided into 9 strips with each strip either 20 or 22 rows wide and falling beneath one of the 9 VR manifold units. Alternating strips were irrigated by either VR or UR irrigation. Comparisons of crop responses from these areas were used to evaluate VR irrigation. Figure 1 shows the position of the 5-ha area relative to the pivot and the locations of the nine VR and UR treatment strips in the 2001 experiment.

Past research at Halfway and the AgCares research site at Lamesa had shown variability in cotton lint yield correlated with factors associated with crop water use such as slope, elevation, soil texture, and seasonal irrigation (Bordovsky and Keeling, 2000; Li et al., 2001). At the Helms site, profile elevations and soil texture at 64 locations within the area were used to determine different irrigation zones in the VR strips. Differences in elevation and row direction were used to determine furrow slope at each of 64 referenced sites (Figure 2). Soil texture below 0.4-m depth had not been determined prior to initial VR irrigation on 2 August, therefore, the only textural data used in the initial decision on water placement in VR strips was clay content in the top 0.4 m (Figure 3). The general VR irrigation strategy was to level lint yields by reducing irrigation in areas of high SWHC and adding water to areas of low SWHC. A decision was made to divide the area into three zones. The low-rate zone was irrigated at a rate equal to 75% of the UR in the area where furrow slope was 0% and clay content in the top 0.4 m was > 40%. This zone contained soils with high SWHC and limited risk of rain runoff. The medium-rate zone was irrigated at 100% of UR and included the area of furrow slope from 0.0 to 0.5% and clay content of < 40%. The high-rate zone was irrigated at 125% of the UR where slope was > 0.5%. The high-rate zone had the highest risk of rain losses. Previously defined sampling sites also affected decisions on irrigation boundary positions since yield analysis required representative numbers of sites per zone. Boundaries between zones of different irrigation levels are shown in Figures 1, 2, and 3.

Cotton (Paymaster 2326RR) was planted in the test area on 24 May 2001 and the crop maintained using normal cultural practices. Nutrients were applied based on aggregate soil sampling and pests were treated at recommended thresholds. Irrigation was initiated on 26 May and continued through 30 August. Due to the dry growing season and limited pumping capacity, irrigations in UR treatments were less than the planned 80% of estimated ET. Irrigation amounts of 142 mm were uniformly applied across the test area from 26 May to 27

July. From 2 through 30 August, irrigations totaled 100, 130, and 160 mm in the VR strips of the low-, medium-, and high-irrigated zones, respectively. Therefore, the difference in total irrigation quantity between the low and high irrigation zones within the VR treatments was 60 mm.

2002 growing season. Soil EC was used as the criterion to determine the general productivity of a 6.2-ha area for site-specific irrigation of cotton in 2002. Soil EC measurements of the top 1-m of the soil profile were recorded using the Veris system in 2001 (Figure 4). The VR irrigation strategy followed the general hypothesis that, when resources are limited, the highest overall production will result from applying available resources to the more productive areas of the field (Lascano, 2002). The 2002 research area had been planted to corn in 2001 and, in 2002, was divided into strips irrigated by individual manifold units with alternating strips managed as either VR or UR (Figure 5). Areas with 1-m soil EC measurements > 35 dS/m were assumed "more productive" and received 120% of the base irrigation quantity within VR strips. All UR strips and the VR areas of soil EC < 35 dS/m received 100% BI. Evaluations of VR vs. UR application were based on total irrigation WUE.

Cotton (Stoneville 2454RR) was planted in the test area on 7 May 2002 and the crop maintained using normal cultural practices. Seasonal irrigation was initiated on 17 May and continued through 28 August. Rain, from the day of planting until 28 August, totaled 36 mm. Irrigations in UR treatments were ~80% of estimated ET. Seasonal irrigation amounts of 94 mm were uniformly applied on the test area from 17 June to 16 July. From 16 July through 28 August, irrigations totaled 216 and 260 mm in the VR strips of the "low" and "high" productive areas, respectively.

Results

Equipment Evaluation

The mechanical evaluation of the VR system included tests of the hydraulic and positioning systems. Figure 6 displays hydraulic performance data of the VR system on 4 August 2001 and, again, following several modifications on 30 August 2001. These charts show comparisons of desired, achievable, and measured flow rates of applicators within each of nine manifold units of spans 6, 7 and 8. Flow rates of individual manifold systems were offset from adjacent manifolds due to programmed differences in flow rates relative to field position. Data from the initial date indicated that measured applicator flow rates were somewhat higher and more scattered than the achievable flow rates. System improvements were made by increasing and stabilizing inlet water pressure at the pivot, renozzling the VR applicators, modifying plumbing components to prevent flow restrictions, and eliminating low-pressure drain valves. Hydraulic performance tests were conducted in 2002 following additional VR manifold installation on span 5 and redesign of stepwise flow rates of all manifolds. Measured applicator flow rates were within 5% of achievable flow rates when VR experiments began in 2002.

To date, the controller, remote terminal units, and solenoid valves have functioned flawlessly; however, the positioning system used to activate valves at appropriate locations in the field failed to perform as precisely as desired. An evaluation was conducted comparing measured pivot location to the pivot location sensor outputs of both the VR positioning sensor and the pivot manufactures sensor. Output data were systematically recorded as the pivot rotated around the field in both clockwise and counter-clockwise directions. Comparisons of pivot and VR sensor response to measured position are shown in Figure 7. The pivot and VR sensors showed deviations of up to 6° from the measured field location at 0/360° (north). This represents a positioning error at the outer edge of the pivot of ~40 m. As the pivot rotated through the 120 to 200° arc, the output signals of both sensors were consistently within a few degrees of the actual pivot position. Position data were generally similar in both pivot directions after multiple revolutions. The systematic difference between pivot and VR outputs indicated possible mechanical problems with the rack portion of the rack and pinion sensor mechanisms. This error was reduced by replacing pivot parts and reprogramming the count sequence within the VR controller. Error of up to 2° may be acceptable for most irrigation or chemical applications in this setting.

Cotton Lint Yield Response

Cotton lint yields were determined by three methods: 1) using stripper harvested, boll buggy weights from each of the treatment strips under the manifold units; 2) hand harvesting 4 m^2 areas at 64 (2001) and 65 (2002) geo-referenced sites; and 3) harvesting the entire area using a cotton stripper equipped with a yield monitor. No significant statistical differences in total yield or total irrigation WUE were evident between VR and UR treatments in 2001 or differences in WUE were measured between VR and UR treatments in 2002. Table 1 includes weighted irrigation amounts, lint yield based on burr cotton weights (boll buggy), average hand harvested lint weights, and integrated hand harvest lint weights; and total irrigation WUE for VR and UR irrigation treatments for the 2001 crop year. Integrated lint yields were derived from geo-referenced hand-harvested data from either the UR or the VR sites using Surfer® software (Golden Software, Inc., Golden Colorado). Yield based on boll buggy weights were 806 vs. 799 kg/ha for VR vs. UR treatments. Yield based on average hand samples were 1083 kg/ha (1100 kg/ha, integrated) from the VR irrigation treatment compared to 1125 kg/ha (1138 kg/ha, integrated) from the UR treatment. Estimates of WUE were similar for the two treatments. Table 2 gives cotton lint yield by manifold strip and harvest method for the VR and UR treatments for the 2002 experiment. Average lint yields are slightly higher in the VR than UR treatments due, in part, to the larger total water volume applied within the VR plots (409 mm and 387 mm, respectively). VR yields were 2.8, 2.7 and 4.6% higher than UR yields when determined from boll buggy, hand sample, and yield monitor yields, respectively. Table 3 shows WUE of VR and UR treatment areas as a function of harvest method. Although yields were higher in VR than UR strips, WUE was slightly higher in UR than VR areas.

Although average lint yields were similar, spatial distribution of yields were different depending on irrigation treatment. Figure 8 represents the integration of hand harvest data obtained at the 32 sites in the UR treatments as well as VR sites that received the UR irrigation quantity in 2001. This represents the yield response from uniformly irrigating the entire 5-ha area. This map shows two general areas of lower yields, an area with no slope and high clay content (west side) and a sloping area (> 0.5%) with low clay content (southeast corner). For comparison, the VR map shown in Figure 9 is composed of the yield data from the 32 VR sites. This map indicates that shifting water from the west side of the field to the east side reduced lint yield in the low water zone and increased yield in the high water zone. High yields seen on the far west side of the VR map may be due to irrigation from the adjacent field (VR controller not actuating valves at the precise location).

The 2002 spatial distribution of cotton lint yield from VR and UR treatments (hand harvested data) is shown in Figure 10. The UR yield generally shows higher yields in the "more productive" zones (EC > 35 dS/m). Applying additional water to these areas further increased yield in the "more productive" zone on the west (zone 3) as depicted by the darker shades in the VR graph. Integrated yields for this area were 1798 kg/ha for UR vs. 1882 kg/ha for VR irrigation. The potential value of VR irrigation is the prospect of improving irrigation WUE. This did not occur by adding additional water to areas with high EC values in 2002. The spatial distribution of WUE was more uniform with VR rather than UR irrigation (Figure 11); however, the integrated WUE of the UR treatment was slightly higher at 0.46 kg/m^3 compared to the WUE of 0.45 kg/m^3 of the VR treatment in the same area.

The small yield and WUE differences between VR and UR applications in 2001 were not unexpected. Irrigation treatments were started late in the growing season, initial irrigations were being made with VR equipment that had not been fully optimized, data used to base VR irrigation transition zones were limited, and the strategy for creating the zones was based on normal rainfall. In 2002, using 1-m soil EC as the criterion to establish management zones for VR irrigation resulted in higher lint yield with additional water inputs, but lower total irrigation WUE. These preliminary results illustrate that the in-season, site-specific water management of a cotton crop is complex. Further, due to the indeterminate growth habit of cotton in combination with the short growing season in the Texas High Plains strategies to optimize the allocation of finite water resources may need to consider additional factors other than slope and soil water holding capacity.

Acknowledgments

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Table 1. Cotton lint yield and total irrigation water use efficiency from VR and UR irrigation treatments TAES, Helms Farm, 2001.

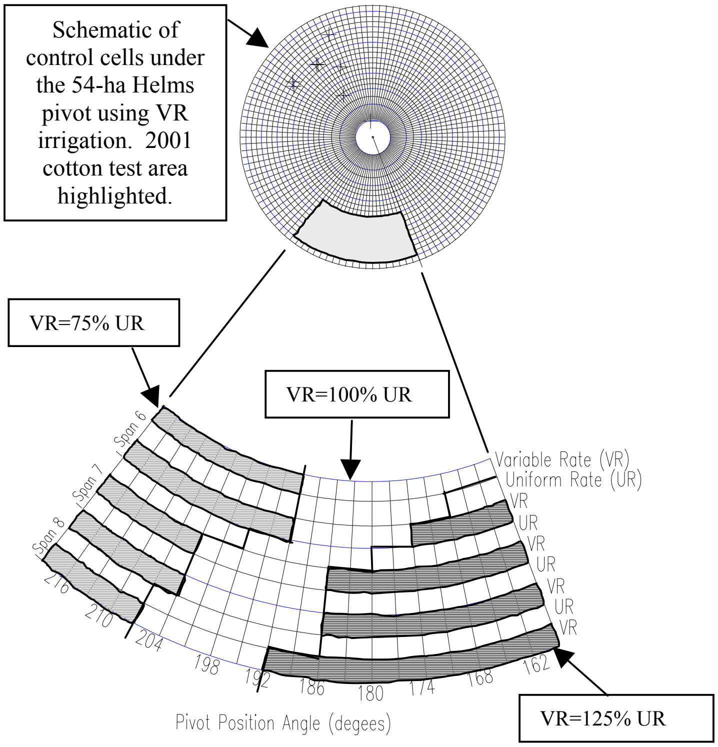
		Variable Rate Irrigation						Uniform Rate Irrigation					
Span	Man. Unit	Irr. Amt. mm	Yield Boll Buggy kg/ha	Yield Hand Harvest kg/ha	Yield Int. Hand kg/ha	WUE Boll Buggy kg/m^3	WUE Hand Harvest kg/m^3	Irr. Amt. mm	Yield Boll Buggy kg/ha	Yield Hand Harvest kg/ha	Yield Int. Hand kg/ha	WUE Boll Buggy kg/m^3	WUE Hand Harvest kg/m^3
6	a	258	850	965		0.33	0.37						
	b							273	910	1159		0.33	0.43
	c	267	837	1198		0.31	0.45						
7	a							273	777	1152		0.28	0.42
	b	280	853	1111		0.30	0.40						
	c							273	776	1081		0.28	0.40
8	a	280	785	1054		0.28	0.38						
	b							273	732	1110		0.27	0.41
	c	284	704	1085		0.25	0.38						
Averages		274	806	1083	1100	0.30	0.40	273	799	1125	1138	0.29	0.41

Table 2. Cotton lint yields (kg/ha) and weighted irrigation quantities of areas where variable and uniform irrigation applications occurred, TAES, Helms Farm, 2002.

		Variable Rate				Uniform Rate			
Span	Manifold. Unit	Wt. Irr. Amt. mm	Boll Buggy	Hand Harvest	Yld Monitor	Wt. Irr. Amt. mm	Boll Buggy	Hand Harvest	Yld Monitor
5	a					387	1632	1726	1573
	b	430	1654	2090	1695				
	c					387	1557	1560	1594
6	a	424	1874	1875	1821				
	b					387	1732	1847	1663
	c	402	1647	1816	1728				
7	a					387	1649	1932	1635
	b	395	1613	1622	1717				
	c					387	1686	1802	1725
8	a	393	1648	1761	1751				
	b					387	1539	1899	1788
	c	408	1629	1899	1733				
Average		409	1678	1844	1741	387	1632	1794	1663

Table 3. Total irrigation water use efficiency (kg/m^3) and weighted irrigation quantities of areas where variable and uniform irrigation applications occurred, Helms Farm, 2002.

Span	Manifold Unit	Variable Rate Boll Buggy	Variable Rate Hand Harvest	Variable Rate Yld Monitor	Uniform Rate Boll Buggy	Uniform Rate Hand Harvest	Uniform Rate Yld Monitor
5	a				0.42	0.45	0.41
	b	0.38	0.49	0.39			
	c				0.40	0.40	0.41
6	a	0.44	0.44	0.43			
	b				0.45	0.48	0.43
	c	0.41	0.45	0.43			
7	a				0.43	0.50	0.42
	b	0.41	0.41	0.43			
	c				0.44	0.47	0.45
8	a	0.42	0.45	0.44			
	b				0.40	0.49	0.46
	c	0.40	0.46	0.42			
Avg.		0.41	0.45	0.43	0.42	0.46	0.43



Schematic of control cells under the 54-ha Helms pivot using VR irrigation. 2001 cotton test area highlighted.

Figure 1. Schematic of the VR control cells under the Helms pivot and the 5-ha area used in the VR irrigation cotton study. In 2001, the control cells were divided into three-target irrigation areas based on slope down the furrow and clay content in the top 15-cm of the profile.

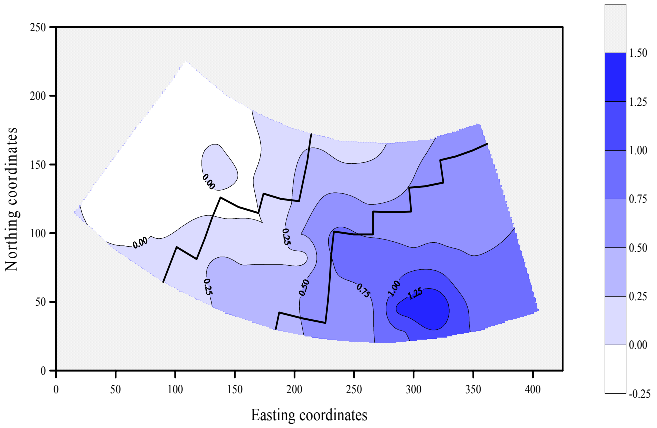


Figure 2. Furrow slope of the 5-ha area used in the VR cotton irrigation study, 2001.

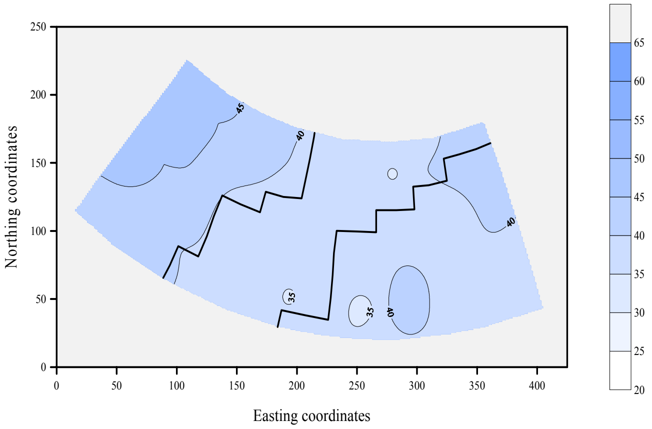


Figure 3. Percent clay in the top 40 cm of the soil profile.

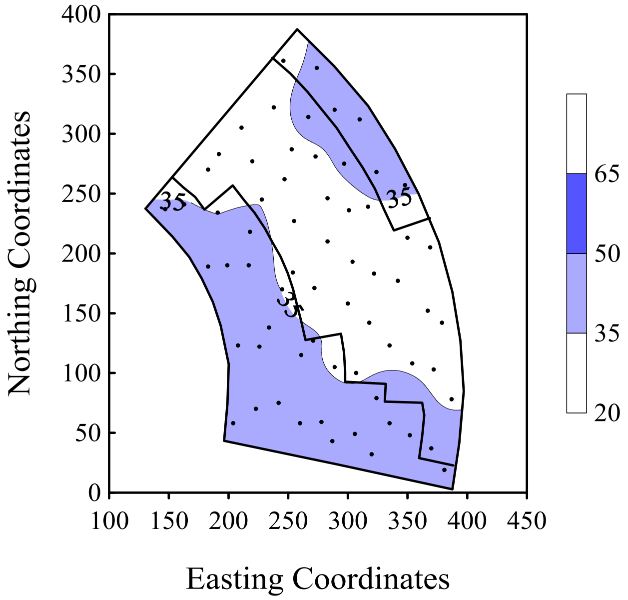


Figure 4. Soil electrical conductivity at one-meter depth used to determine management zones for VR cotton irrigation, 2002.

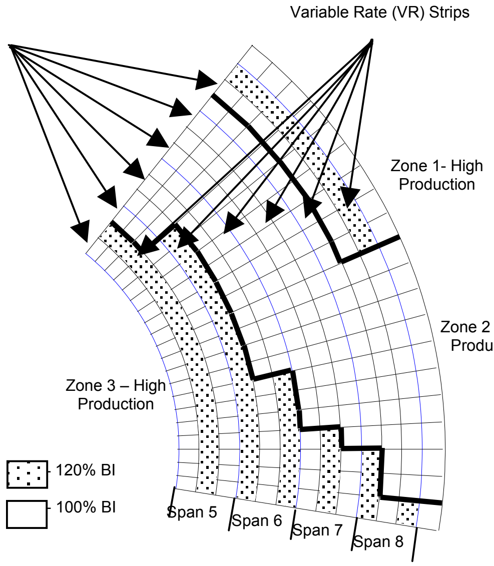


Figure 5. Map of VR and UR irrigation control cells, irrigation quantities, and boundaries between management zones, Helms, 2002.

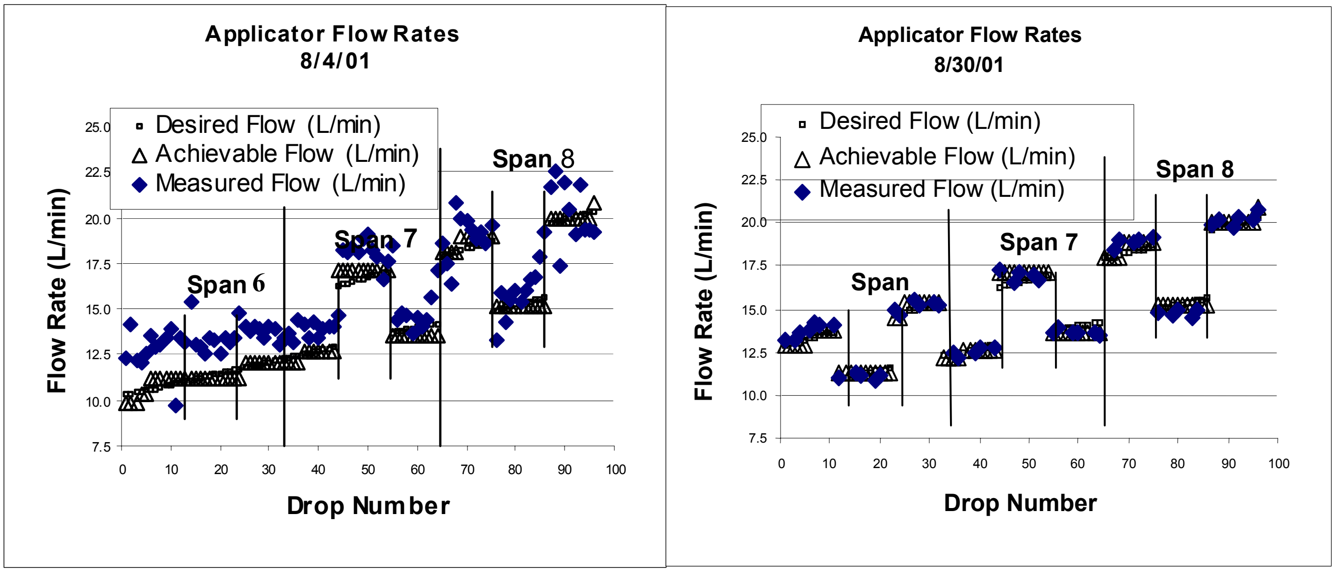


Figure 6. Comparisons of desired, achievable and measured flow rates of applicators within each of the nine manifold units of spans 6, 7, and 8 on 4 August and 30 August 2001.

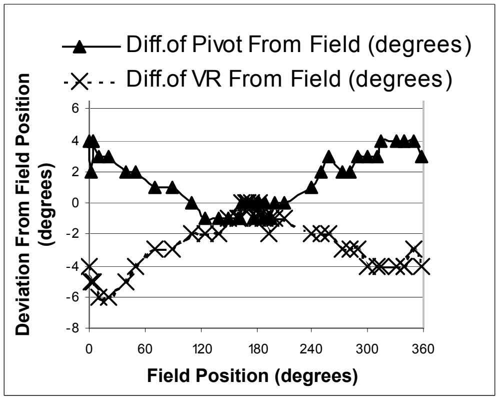


Figure 7. Deviations from actual field position of pivot and VR sensor indicators during one revolution of the Helms pivot.

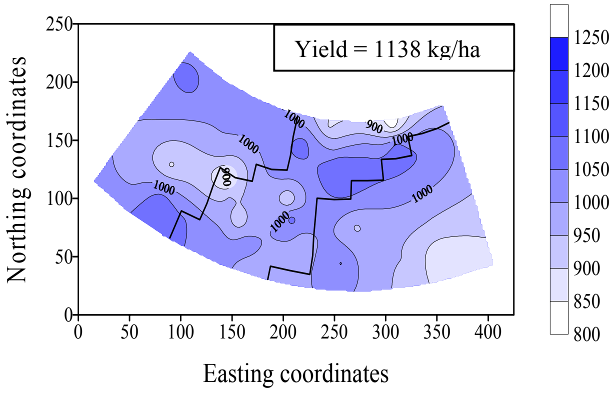


Figure 8. Yield map of hand harvested cotton yields in uniform irrigated areas at Helms, 2001.

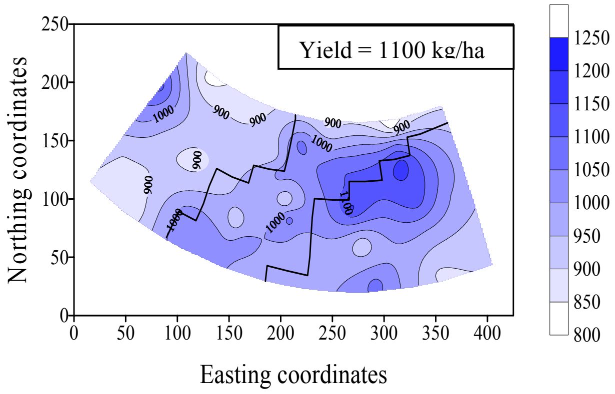


Figure 9. Yield map of hand harvested cotton yields in variable rate irrigated areas at Helms, 2001.

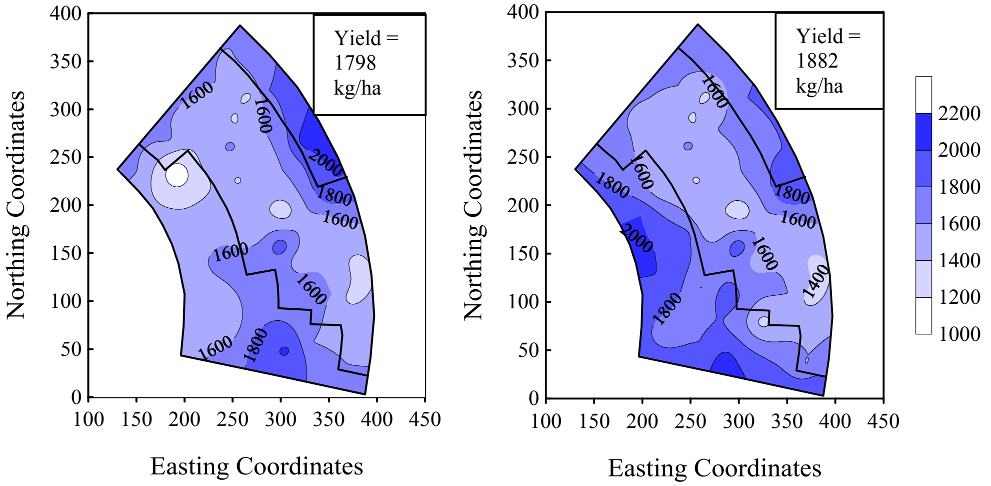


Figure 10. Yield maps of hand-harvested data representing uniform irrigation (left) and variable rate irrigation (right) of an identical area at Helms Farm, 2002.

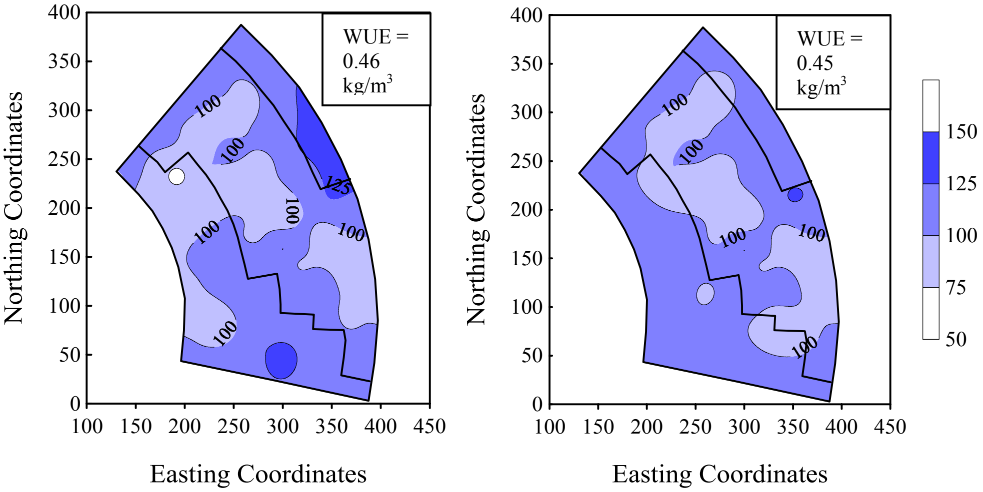


Figure 11. Spatial distribution of total irrigation water use efficiency (WUE) from hand-harvested data representing uniform irrigation (left) and variable rate irrigation (right) of an identical area at Helms Farm, 2002.

Tracking Spatial and Temporal Cotton ET Patterns with a Normalized Difference Vegetation Index

D.J. Hunsaker, P.J. Pinter, Jr., G. J. Fitzgerald, T.R. Clarke, B.A. Kimball, and E.M. Barnes

Abstract

Crop coefficients (K_c) are widely used to estimate crop evapotranspiration (ET_c) for determining irrigation scheduling. Generalized K_c curves are limited to providing daily estimates of ET_c for the "typical" crop condition within a field. However, precision irrigation requires spatial and temporal ET_c information in order to determine the proper water replacement to each management zone. An irrigation experiment conducted during 2002 in Arizona explored the use of remotely-sensed surrogate basal crop coefficients (K_{cb}) for quantifying spatial and temporal differences in cotton ET_c. The main treatment included two irrigation scheduling approaches that were based on ET_c calculation procedures of the Food and Agriculture Organization Paper No. 56 (FAO-56) but differed only by the K_{cb} estimation: 1) a locally-derived FAO-56 K_{cb} curve (FAO), and 2) K_{cb} values based on ground-measured normalized difference vegetation index (NDVI) using a previously defined K_{cb}-NDVI relationship (developed for a different cotton cultivar and row-orientation than for the experiment). Additional variables (3 plant densities, 2 N levels) were included to induce variations for crop ET_c patterns within irrigation scheduling treatments. The ET_c estimation and irrigation scheduling using the FAO-56 K_{cb} curve provided better irrigation management than the previously defined K_{cb}-NDVI relationship, resulting in significantly higher yields for FAO than NDVI. The K_{cb}-NDVI relationship employed in the experiment underestimated measured K_{cb} values during much of the season. The primary problem was related to factors, e.g., the different row-orientation, that effectively lowered NDVI values compared to those that occurred in the previous experiments and were used to develop the relationship. However, measured NDVI tracked the spatial and temporal variations in measured K_{cb} exceptionally well during the season. New K_{cb}-NDVI relationships based on the 2002 data were presented and are currently being tested during 2003 under a similar cotton irrigation scheduling experiment. Although additional research is needed to develop more robust NDVI-based K_{cb} prediction, findings to date indicate the potential for NDVI to provide near-real-time feedback for attaining K_{cb} that closely track actual crop ET_c trends within a field, a technique that could help govern site-specific cotton irrigation scheduling.

Introduction

A fundamental need for precision irrigation is an ability to quantify spatial and temporal differences for crop evapotranspiration (ET_c) to provide irrigation water replacement targets for various zones within irrigated systems. Sadler et al. (2000) proposed several methods for optimizing irrigation water management for spatial and seasonal variability, such as integrated global positioning systems, geographic information systems, "smart" sensors, remote sensing, and computer modeling. A promising approach for precision irrigation management involves the use of surrogate crop coefficients that are based on remotely-sensed observations for providing near-real-time ET_c estimates within spatially variable zones.

Crop coefficient (K_c) estimation of ET_c (Doorenbos and Pruitt, 1977) is a practical and widely applied method, which involves multiplying an appropriate K_c by grass-reference evapotranspiration (ET_o) to compute crop ET_c. A K_c curve for an entire the cropping season is traditionally expressed as a continuous function in time or some other time-related index, such as thermal units. The Food and Agricultural Organization (FAO) of the UN, Paper 56 [FAO-56] (Allen et al., 1998) presented revised crop coefficient procedures for estimating ET_c, which are expected to become the *de facto* crop coefficient standard for the US and abroad. In addition to the single K_c approach, FAO-56 introduced dual crop coefficient procedures where the single K_c is separated into a basal crop coefficient, or K_{cb} (primary crop transpiration), and a soil evaporation coefficient (K_e). The dual crop coefficient method with K_{cb} and K_e allows computation of more precise estimates of daily ET_c, particularly for days following irrigation or rain.

The FAO-56 dual procedures provide an excellent framework for calculating daily ET_c. However, successful application is highly dependent on the ability to derive an appropriate K_{cb} curve that matches the actual crop growth and ET_c conditions that occur during a given season (Allen et al., 1998). Because the K_{cb} curves used with FAO-56 procedures are time-based, they often lack the flexibility required to capture atypical crop development and water use patterns caused by weather anomalies (Bausch and Neale, 1989). The FAO K_{cb} curves are intended to represent ET_c for optimum agronomic and water management conditions, and as such, K_{cb} adjustment procedures to estimate ET_c when crop growth and water use deviate from "standard" conditions due to nutrient, crop density, pest, or other factors are not easily implemented. Whereas precision irrigation management requires information for determining variable ET_c conditions, accounting for spatial variations of water use with FAO-56 procedures is extremely difficult.

Remote sensing offers a means to overcome some of the shortcomings of time-driven K_{cb} curves by providing real-time spatial information on K_{cb} and crop ET_c use as influenced by the actual crop patterns. Multispectral vegetation indices (VIs), computed as differences, ratios, or linear combinations of reflected light in the visible (blue, green, or red) and near infrared (NIR) have been found to be closely related to several crop growth parameters (Moran et al., 1995). The simple ratio (NIR/red) and the normalized difference vegetation index, or NDVI [NDVI=(NIR-red)/(NIR+red)] have gained wide acceptance for estimating plant cover, plant biomass, and leaf area index. The potential for using VIs as near real-time surrogates for crop coefficients was proposed over two decades ago by Jackson et al. (1980). The concept was eventually established by Bausch and Neale (1987) who derived K_{cb} for corn in Colorado based on several VIs. Bausch and Neale (1989) and Bausch (1995) incorporated VI-based corn crop coefficients with existing scheduling algorithms and reported improvements in corn irrigation scheduling due to better estimation of water use and more appropriate timing of irrigations. Although limited research has been conducted to expand the development of VI-based crop coefficients for crops other than corn, simulation studies suggest that VIs could be used to obtain crop coefficients for several other important agricultural crops (Choudhury et al., 1994). Hunsaker et al. (2003) using data from previous cotton experiments developed relationships to estimate cotton K_{cb} with NDVI measurements. The objective of this research was to test a strategy, which implemented the NDVI-based K_{cb} for cotton within the FAO-56 dual procedures, for predicting real-time spatial water use patterns for determining appropriate irrigation scheduling.

Methods and Materials

An irrigation scheduling experiment with cotton was conducted during 2002 on a 1.3-ha field site, located in central Arizona at the University of Arizona, Maricopa Agricultural Center (MAC). The soil is classified as a Casa Grande series with sandy loam to sandy clay loam textures (Post et al., 1988). Deltapine 458BR (*Gossypium hirsutum* L.), a mid-to-full maturing transgenic cotton variety grown in the state, was planted on 16 to17 April, 2002, in dry soil on raised beds, spaced 1.02 m apart, in a north-south orientation. Prior to planting, the field was precision leveled to zero-grade, and then flood-irrigated on 18 to 20 March to enable subsequent soil bed preparations and equipment installations. The date of crop initiation was assumed to occur on 22 April, when the first post-plant irrigation was given. The cotton was defoliated on 21 September and harvested in October.

Experimental Treatments

Thirty-two plots (each 11.2 by 21 m) were randomly assigned to 12 different experimental treatments (table 1). The primary treatment consisted of two irrigation scheduling approaches that were both based on the FAO-56 dual crop coefficient procedures, but differed in the method used to estimate the basal crop coefficient, K_{cb}. The first approach (FAO) used a locally derived cotton K_{cb} curve following FAO-56 guidelines (fig. 1). The second (NDVI) used K_{cb} estimates based on ground-measured NDVI and a previously defined relationship between K_{cb} and NDVI for cotton. However, the K_{cb}-NDVI relationship (described by Hunsaker et al., 2003) used was not developed under crop and field conditions similar to those in the present study. That is, the cotton was a different cultivar that exhibited somewhat atypical water use patterns expected for a full-season cotton. The cotton was also grown in an east-west row orientation rather than the present north-south orientation, and the soil type was a clay loam rather than a sandy clay loam. Despite these differences, the K_{cb}-NDVI relationship was the only one that existed for cotton at the time of the experiment. The relationship consisted of two regression relations: a linear function used from early vegetative growth to effective full cover, and a multiple regression of K_{cb} as a function of NDVI and cumulative growing-degree-days (GDD) after effective full cover. The K_{cb} values were restricted to 0.15 or larger for both the NDVI and FAO treatments.

Table 1. Summary of treatments for the 2002 Cotton Irrigation Scheduling Experiment at the Maricopa Agricultural Center.

	Experimental Variables			
Treatment name	Irrigation scheduling	Plant density	Nitrogen level	Number of replicates
FSH	FAO	Sparse	High	2
FSL	FAO	Sparse	Low	2
FTH	FAO	Typical	High	4
FTL	FAO	Typical	Low	4
FDH	FAO	Dense	High	2
FDL	FAO	Dense	Low	2
NSH	NDVI	Sparse	High	2
NSL	NDVI	Sparse	Low	2
NTH	NDVI	Typical	High	4
NTL	NDVI	Typical	Low	4
NDH	NDVI	Dense	High	2
NDL	NDVI	Dense	Low	2

Additional sub-treatment variables (table 1) were imposed to create conditions expected to alter crop water use, yet are not commonly nor easily accounted for in a typical implementation of FAO-56 ET_c procedures. Sub-treatments, equally embedded within the irrigation scheduling treatments, included three plant densities: Typical (T) $\approx$10 plants/m^2, single-line planting; Sparse (S) $\approx$5 plants/m^2, single-line planting; and Dense (D): $\approx$20 plants/m^2, double-line planting and two N fertilization levels: High (H), split N applications, based on optimum local practices; and Low (L), no N application.

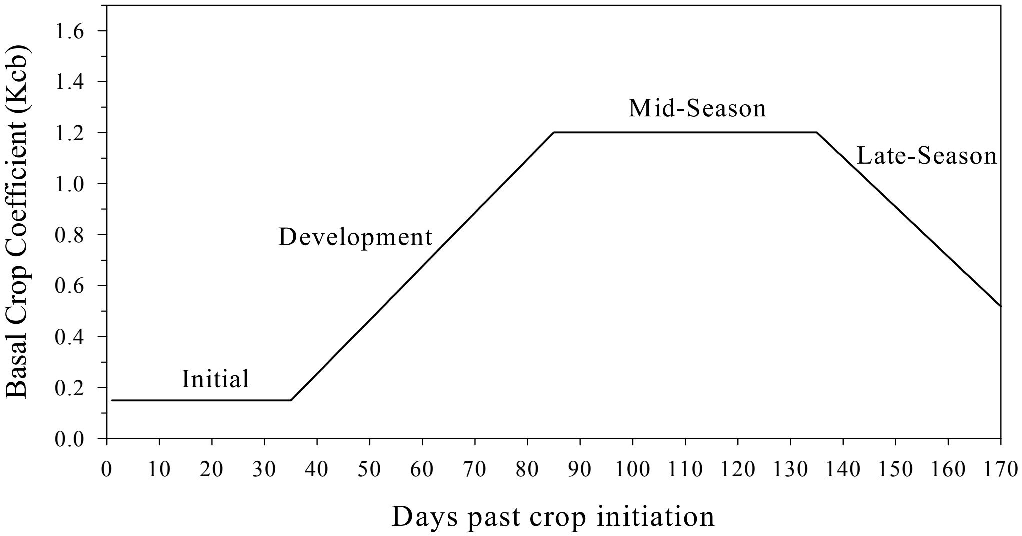


Figure 1. Locally derived FAO Kcb curve for Maricopa, Arizona, based on FAO-56 procedures.

Field Layout and Irrigation System

The 32 treatment plots were aligned in the field in a 4 (north-south) X 8 (east-west) array, each plot surrounded by border dikes. Two gated pipe systems, 152-mm in diameter, were installed in the east-west direction and extended the length of the field. Each system provided irrigation water for 16 treatment plots. Irrigation water was controlled by two alfalfa-valves located at the west-end of the gated pipe systems. Gated ports at 1.02 m spacings along the pipe were used to control separate water delivery to individual plots at flow rates ≈18 to 20 L s^{-1}. The irrigation water was measured with an in-line propeller-type water meter that had both a rate meter and a volume totalizer.

Crop Management and Irrigation Scheduling

Difficulties encountered in germination of the dry-planted cotton and in obtaining the desired plant densities resulted in replanting seeds within various plot areas. Consequently, a total of six irrigation applications were given to all plots from 22 April to 4 June to establish the crop. Experimental irrigation treatment scheduling was begun following the 4 June irrigation, upon establishment of the target plant densities.

Daily crop ET_c in mm was calculated as $ET_c = (K_{cb}\ K_s + K_e)\ ET_o$, where K_s is the soil water stress coefficient. Daily meteorological data, provided by an AZMET weather station (Brown, 1989) located on a well-watered grass site ≈ 200 m from the field site, were used to calculate the FAO-56 equation (Allen et al., 1998) for daily ET_o. Daily soil water balance computations were made separately for each treatment plot based on the FAO-56 procedures. Soil parameters from Post et al. (1988) and other parameters used for the FAO calculations are listed in table 2. The daily crop rooting depth (Z_r) and canopy height (h) for each plot were increased proportionately with K_{cb} up to maximum values of 1.7 and 1.2 m for Z_r and h, respectively, when the maximum K_{cb} for the plot was attained.

Table 2. Soil and crop parameters used in the FAO-56 dual crop coefficient procedures (Allen et al., 1998) for the 2002 FAO Cotton Irrigation Scheduling Experiment at the Maricopa Agricultural Center.

Parameter	FAO-56 acronym	Value and unit
Soil water content at field capacity	θ_{FC}	0.24 m^3 m^{-3}
Soil water content at wilting point	θ_{WP}	0.12 m^3 m^{-3}
Crop rooting depth	Z_r	1.7 m (maximum)
Depth of soil surface evaporation layer	Z_e	0.11 m
Total evaporable water	TEW	20 mm
Readily evaporable water	REW	9 mm
Fraction of soil surface covered by vegetation	f_c	Eq. 76 in FAO-56 (dimensionless)
Fraction of soil surface wetted by irrigation	f_w	0.95 (dimensionless)
Crop height	h	1.2 m (maximum)

Irrigations were applied to treatment plots when the estimated depletion of available soil water within the root zone reached 44%, an allowable depletion (AD) that was expected to minimize soil water stress for all treatments. The amount of water applied from irrigation replaced 100% percent of the estimated depletion, plus an additional 10% to account for nonuniformity of irrigation. Note that after 4 June, all FAO treatments were irrigated on the same days with equal amounts of water. For NDVI treatments, irrigation was applied on the same day to all replicates, but the irrigation date was based on the median day among replicates at which the AD reached 44%. Consequently, certain replicates within an NDVI treatment often received irrigation a day or two before or after their AD had been reached. However, individual NDVI replicates did receive their estimated soil water depletion on the day the actual irrigation occurred, plus 10%.

Final irrigations for all NDVI treatment plots occurred between 15 to17 August. The amount of water given to FAO plots for their final irrigation on 23 August was adjusted to increase their soil water level to the approximate level estimated for the NDVI treatments plots on 23 Aug. With the exception of the final irrigation for FAO treatments, the irrigation scheduling after 4 June was not altered from the methodologies above for any treatments, regardless of feedback from measurements, or other factors.

Fertilizer as urea ammonium nitrate (UAN-32) solution was injected into the gated pipe systems during irrigations of all High N treatment plots on 4 June, a rate that provided 84 kg N ha^{-1} to plots. A second application (7 to 14 July) of UAN-32 provided an additional 56 kg N ha^{-1} to the High N plots.

Field Measurements

Crop canopy reflectance factors were measured two to four times per week for all 32 treatment plots during the growing season. A total of 53 canopy reflectance measurements were made between 25 April and 24 Sept. Observations, taken across a 6-m long transect spanning the north edge of the final harvest area of each plot, were made with a hand-held, 4-band Exotech radiometer (Model BX-100; Exotech, Inc., Gaithersburg, MD) equipped with 15˚ field-of-view optics. Data were collected over a morning time-period corresponding to a nominal solar zenith angle of 45˚. The NDVI was computed from reflectance factors in near infrared (0.76-0.90 µm) and red (0.63-0.69 µm) wavebands as: NDVI = (NIR-red)/(NIR+red). NDVI data measured on cloudy days or on days when wet soil within a plot affected reflectances were not used to calculate the K_{cb}. The acceptable NDVI measurements for each plot were interpolated linearly, generating daily NDVI values for the entire season.

Volumetric soil water contents were measured for each plot ≈ twice per week and included measurements made immediately before and several days after each plot irrigation. Soil water content measurements were taken at depths from 0.20 m to 3.0 m, at 0.20-m increments, with site-calibrated neutron probes. Soil water in the 0 to 0.30-m soil layer was measured by time-domain-reflectometry (TDR). Neutron access tubes and waveguides for TDR were placed near the middle of each plot in a central cotton bed. Plant measurements, including crop height and crop width, were taken for all plots on a weekly basis during the season starting on 12 June.

Cotton was hand-harvested on 8-10 October in an undisturbed central area within each plot, 6 rows wide by 4 m long, to determine treatment yields.

Irrigation Scheduling Evaluation

Neither the soil water content nor canopy measurements were used as inputs within the FAO-56 procedures to "correct" irrigation scheduling during the experiment. However, the soil water data, along with relevant canopy measurements, were used within the FAO-56 procedures to quantify actual ET_c and to determine "actual" K_{cb} values for all plots using the back-calculation methodology described in Hunsaker et al. (2003). The NDVI-based K_{cb} and FAO K_{cb} curve and resulting irrigation management were evaluated in light of treatment yield performance and their ability to track the actual K_{cb} and ET_c conditions. Statistical analyses of yield, ET_c, and irrigation data were performed using the General Linear Models procedure of SAS (SAS, Inc., 1998).

Results and Discussion

Mean yield for the FAO irrigation scheduling treatment was significantly greater (16%) than for the NDVI treatment at 0.01 probability, indicating that better water management was provided for FAO treatments. Whereas the effect on yield due to plant density was not significant, final yield was greater ($p<0.01$) for the Low than High N treatment, suggesting that crop management was not optimum for the High N treatments for this experiment. For a given plant density and irrigation method, yield differences between nitrogen treatments varied from 5 to 17%, and averaged 10% across all treatments (fig. 2). Data for cumulative irrigation applied (table 3) reveals that for a given plant density and nitrogen level, NDVI treatments received 7 to 9% (78 to 92 mm) less irrigation water than their FAO treatment counterparts, with the exception of the NDH treatment, which received only 4% less than that for the FDH treatment. Statistically, differences for cumulative irrigation water applied were significant for the irrigation method ($p<0.01$), but not for nitrogen level. Less irrigation water applied to the NDVI treatments corresponded to a significant decrease ($p<0.01$) for their measured cumulative ET_c, which varied 5 to 9% lower, and averaged 7% less, than the measured cumulative ET_c for their FAO treatment counterparts (table 3).

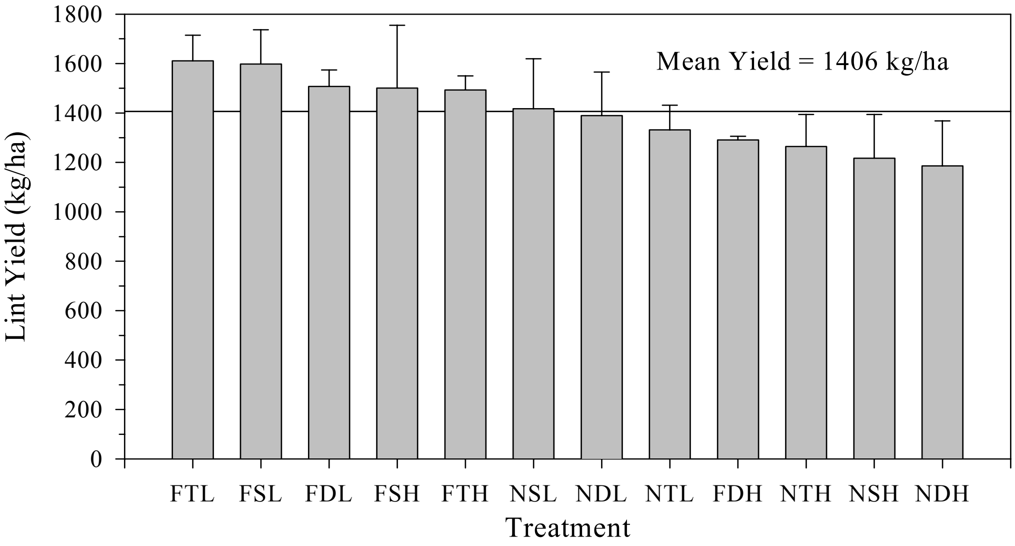


Figure 2. Yield averages for treatments shown in descending order for the 2002 Cotton Irrigation Experiment. Error bars indicate standard deviations. Treatments acronyms are explained in table 1.

Table 3. Measured irrigation, evapotranspiration, and lint yield treatment averages and parameter ratios between NDVI and FAO irrigation scheduling methods for treatments with the same nitrogen level, and plant density for the 2002 FAO Cotton Irrigation Scheduling Experiment.

	Sparse treatments			Typical treatments			Dense treatments		
Low nitrogen treatments	NDVI	FAO	Ratio*	NDVI	FAO	Ratio*	NDVI	FAO	Ratio*
Cumulative Irrigation (mm)	1019	1111	0.92	1017	1119	0.91	1036	1114	0.93
Cumulative ET_c (mm)†	884	961	0.92	916	982	0.93	931	990	0.94
Final Lint Yield (kg/ha)	1417	1598	0.89	1332	1610	0.83	1389	1507	0.92
High nitrogen treatments									
Cumulative Irrigation (mm)	1013	1102	0.92	1038	1122	0.92	1067	1112	0.96
Cumulative ET_c (mm)†	897	955	0.94	914	986	0.93	953	1004	0.95
Final Lint Yield (kg/ha)	1217	1501	0.81	1264	1493	0.85	1186	1291	0.92

*Ratio of NDVI and FAO treatment.

†Cumulative ET_c measured from 25 April to 21 September.

The FAO K_{cb} curve underestimated K_{cb} by a substantial amount for Typical and Dense stands within the High N level (FTH and FDH, respectively) during the first 75-80 days after crop initiation (fig 3a). Cumulative measured ET_c (Fig. 3b) for FTH and FDH on the 75th day exceeded estimated cumulative ET_c by 12 and 19%, respectively. This suggests that irrigation scheduling based on the lower than measured FAO K_{cb} curve ET_c estimates may have introduced water stress during the first half of the season, particularly for the FDH treatment. Following the last irrigation for FAO treatments, which occurred 124 days after crop initiation, K_{cb} and ET_c decreased relative to estimated values. Consequently, differences between the measured and estimated ET_c became closer at the end of the season where the measured seasonal cumulative ET_c for FTH and FDH

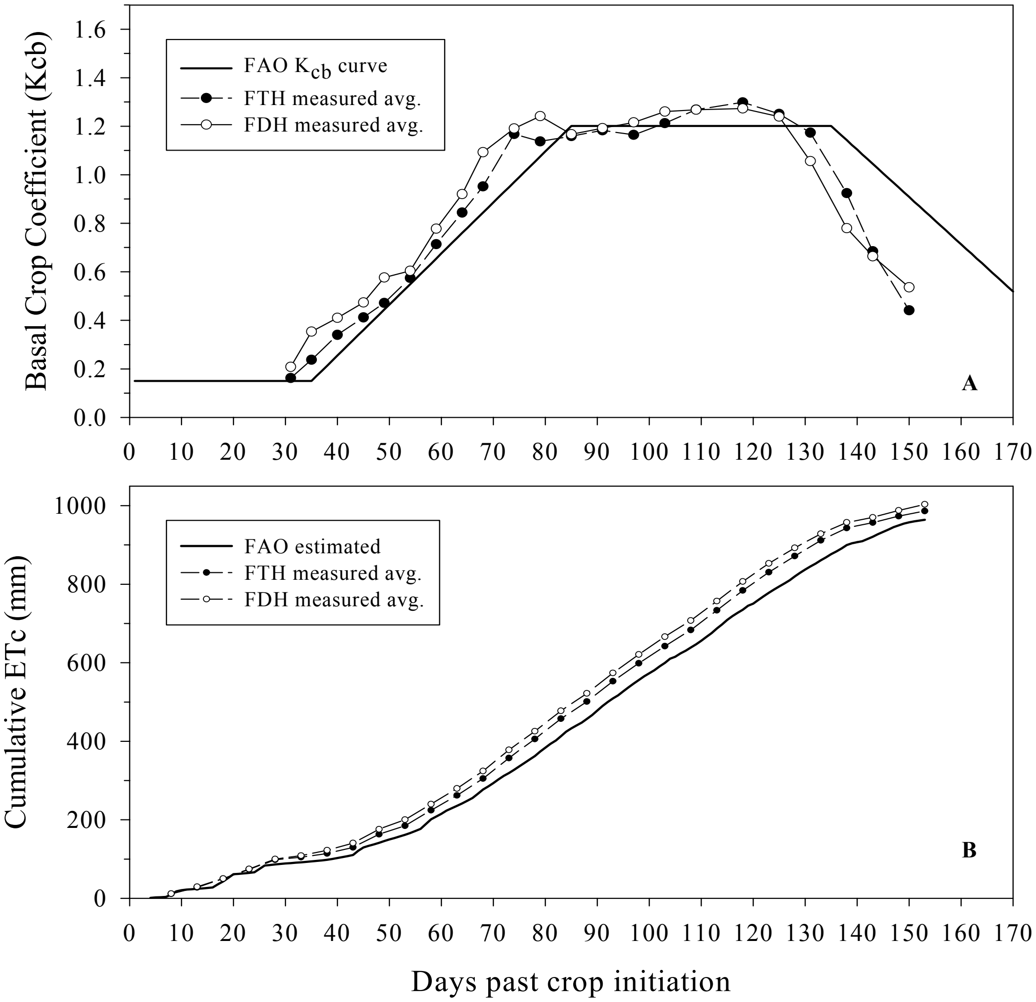


Figure 3. Estimated Kcb (a) and cumulative ETc (b) compared to average measured values for the FTH and FDH treatments for the 2002 Cotton Irrigation Scheduling Experiment.

were only about 2 and 4% greater than the 964 mm estimated using the FAO K_{cb} curve and procedures. Although Sparse treatments under FAO irrigation scheduling had smaller cumulative ET_c than the Typical and Dense treatments (table 3), they produced some of the highest yields (fig. 2), which may indicate the FAO scheduling caused less water stress within Sparse plots. For example, 75 days after crop initiation, the measured cumulative ET_c for the FSH (FAO-Sparse-High N treatment) exceeded estimated cumulative ET_c by 8%, compared to 12 and 19% for FTH and FDH, respectively.

The K_{cb}-NDVI relationship used in irrigation scheduling tracked measured K_{cb} poorly throughout much of the season for all NDVI treatments, as illustrated in figure 4a for the Typical and Dense stands within the High N level (NTH and NDH, respectively). The primary problem was that the NDVI values used to calibrate the K_{cb}-NDVI relationship were higher than the NDVI values of the present study until about mid-season. Trends for NDVI, normalized to days past crop initiation and cumulative GDDs, for the two NDVI data sets revealed that values were offset initially by about 50%, ≈ 25 days after crop initiation. Separation slowly decreased until the NDVI values for the two data sets eventually coincided ≈ 70 days after crop initiation. Whereas measured K_{cb} values, normalized for crop day and cumulative GDDs, were consistent between the calibration and

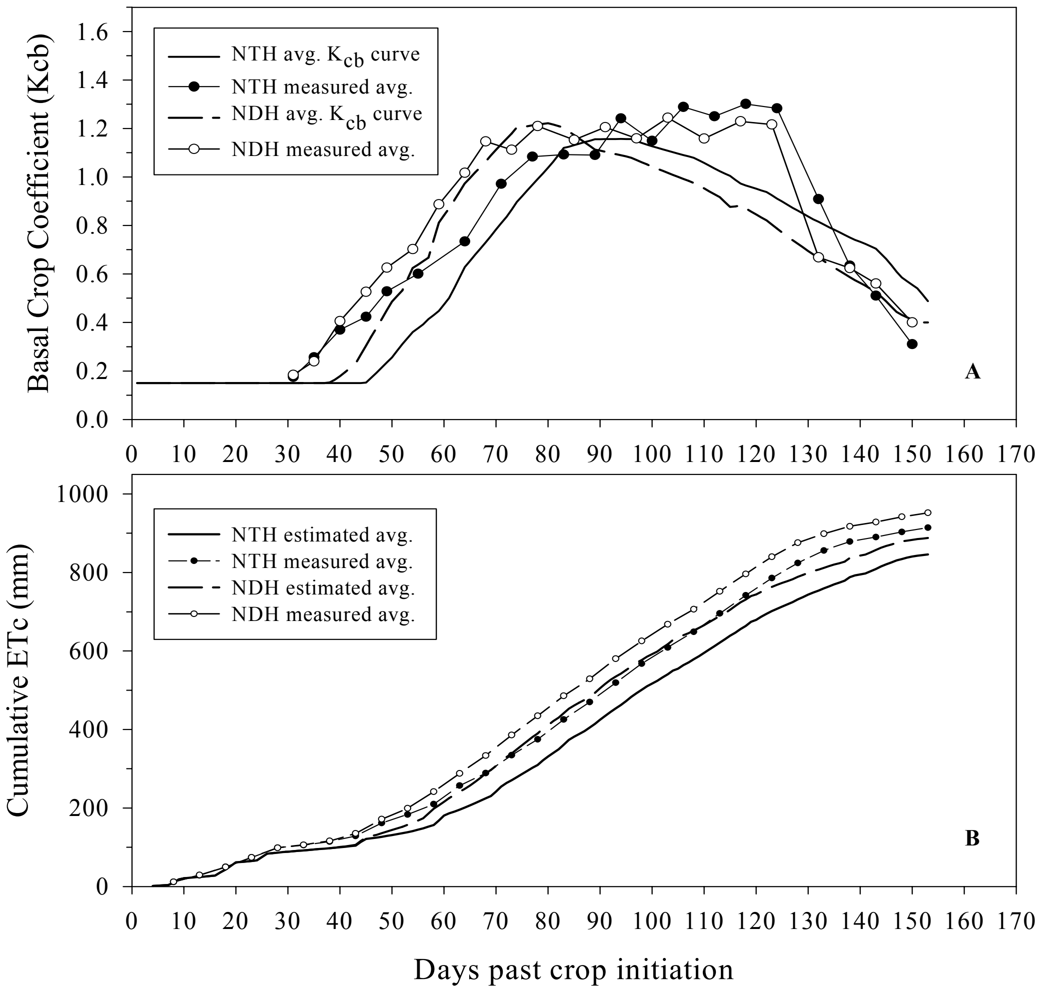


Figure 4. Estimated Kcb (a) and cumulative ETc (b) compared to average measured values for the NTH and NDH treatments of the 2002 Cotton Irrigation Scheduling Experiment.

experimental data during the first 70 to 80 days past crop initiation, the lower NDVI caused the K_{cb}-NDVI relationship to greatly underestimate the measured K_{cb} until mid-season (fig. 4a). Reasons offered for the variation in NDVI values between the two data sets include the differences in soil background effects, row-orientation, cotton cultivar, waveband width used for NIR and red, and irrigation system.
Cumulative measured ET_c (fig. 4b) for NTH and NDH from 55 to 75 days after initiation exceeded the estimated cumulative ET_c by 23-33% and by 13-26%, respectively, indicating the poor irrigation scheduling for the treatments during the first half of the season. Following a brief period near mid-season in which the estimated K_{cb} curves tracked measured K_{cb} reasonably well, the K_{cb}-NDVI relationship once again greatly underestimated measured K_{cb} until late in the growing season.

The lack of success in tracking actual K_{cb} with the initial K_{cb}-NDVI relationship led to an accumulation of larger soil water deficits for NDVI than FAO plots and resulted in delayed and inappropriate irrigation application amounts, which often were smaller than that required to refill the crop rooting zone for NDVI treatments. Overall, the effects on FAO treatments caused by the ET_c underestimation were less pronounced in terms of yield and cumulative measured ET_c than for NDVI treatments. There was a strong negative correlation (r = -0.88) between final yield and the average measured depletion of the available soil water just prior to irrigation applications. For NDVI treatment plots, measured available soil water depletion at irrigation was often 55-60%.

Based on the results, the previously defined K_{cb}-NDVI relationship proved inappropriate for scheduling irrigations for the particular cotton cultivar and row-orientation used in this experiment. On the other hand, the variability in the measured K_{cb} data (fig. 5) demonstrates that a single FAO K_{cb} curve would be inadequate to quantify spatial and temporal differences for crop water use that occurred. Although the particular K_{cb}-NDVI relationship used in the experiment failed to calculate appropriate K_{cb} values, NDVI data actually tracked the measured K_{cb} variability for 2002 exceptionally well. Consequently, new K_{cb}-NDVI relationships were developed from the 2002 data, which are presently being tested during a second cotton irrigation scheduling experiment in 2003. The primary relationship (fig. 6) describes the cotton K_{cb} as a function of NDVI from initial growth through approximately the end of the mid-season stage. The primary curve, fit to a 4th order polynomial with a resulting r^2 of 0.98, included the K_{cb} and NDVI data for each treatment plot from initial growth until the NDVI of the particular plot decreased more than 0.0135 below the maximum NDVI value attained for the plot. When NDVI decreased more than 0.0135 below maximum NDVI (which was ≈0.90 for most plots), the K_{cb}-NDVI trend did not follow the primary relationship. This point was typically reached for all plots near cutout, about 130 days after crop initiation. Consequently, a late-season K_{cb}-NDVI relationship (fig. 6) was fit to a 3rd order polynomial (r^2 =0.62) to more adequately estimate K_{cb} during the latter stages of the growing season.

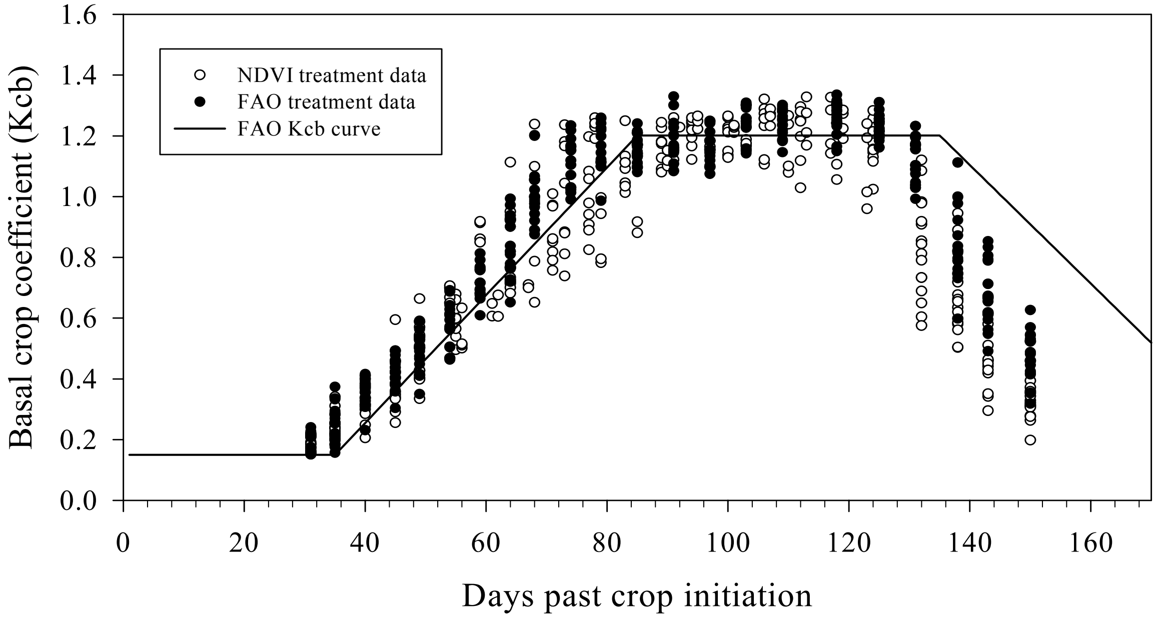


Figure 5. Measured Kcb data and FAO Kcb curve as a function of days past crop initiation for 2002 cotton irrigation scheduling experiment.

Preliminary results from the 2003 experiment (data not shown) indicate that the new primary relationship is tracking the differences in K_{cb} and providing appropriate irrigation schedules for the NDVI treatments.

Conclusions

NDVI appears to be a useful parameter for tracking cotton K_{cb} values needed in ET_c estimation and irrigation scheduling. A locally derived FAO K_{cb} curve should give reasonable ET_c estimates for average cotton conditions, but adjusting K_{cb} to estimate spatially variable crop water needs for precision irrigation management will be difficult without some type of remote sensing technique. Implementing VI-based crop coefficients within FAO-56 procedures for precision irrigation scheduling could potentially be more successful and far-reaching than other remote sensing methods, because of the widespread familiarity and use of the crop coefficient methodology. NDVI data, which can be routinely measured either on the ground, in the air, or by satellite, would be required frequently, but not daily, since the smooth general shape of the K_{cb} curve over a growing season would allow data to be extrapolated over a period of up to a week. The soil adjusted VI (SAVI) which is less sensitive to soil background effects than NDVI may provide improved estimates for K_{cb} during early season conditions. However, the variability observed for SAVI as the crop approaches and reaches full canopy may preclude SAVI as a reliable VI surrogate for K_{cb} during critical portions of the season.

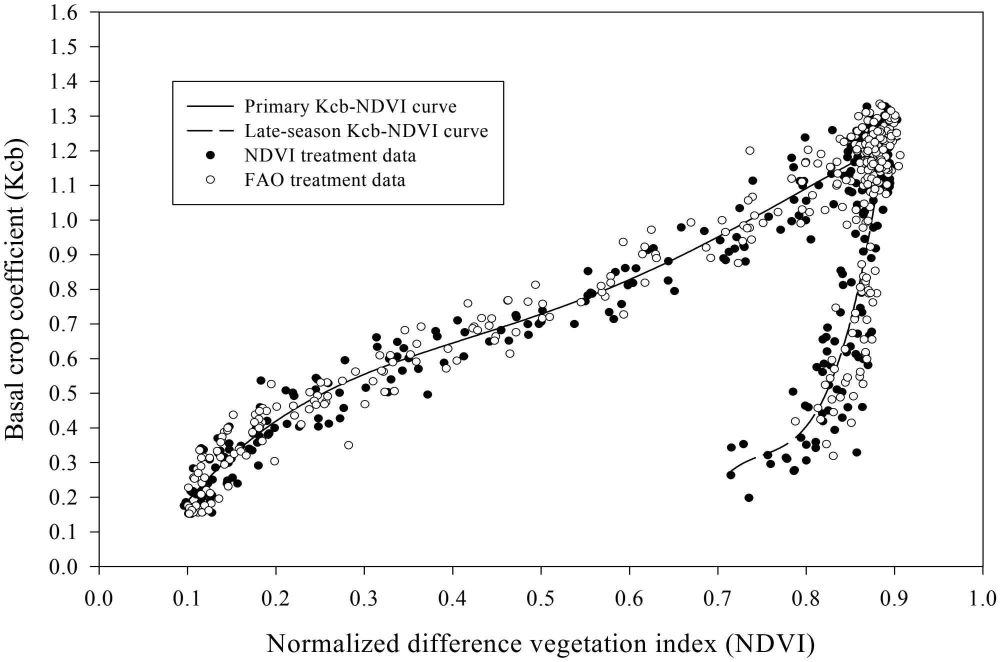


Figure 6. Primary and late-season Kcb-NDVI relationships developed from treatment data of the 2002 cotton irrigation scheduling experiment.

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Estimating Cotton Crop Water Use from Multispectral Aerial Imagery

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Abstract

Precision irrigation can improve field-scale water use by improving timing and placement of water. However, current numerical models used for irrigation scheduling rely on single point measurements to predict irrigation needs for entire fields. To incorporate the spatial dimension, imaging remote sensing approaches were investigated in Central Arizona for estimating water use by cotton growing in a furrow-irrigated field with large variation in soil texture. Aerial imagery was obtained every two to three weeks using a high resolution camera system equipped with narrow band-pass filters and calibrated with ground-based reference tarps. A directed sampling approach was used to establish optimal locations to install neutron access tubes and estimate canopy height and width for use in calculating basal crop coefficients (K_{cb}). The normalized difference vegetation index (NDVI) was used to estimate K_{cb} for cotton via a previously defined relationship. The K_{cb} plus estimated soil evaporation coefficients were multiplied by reference evapotranspiration (ET_o) determined from a nearby weather station and summed during each irrigation interval to provide water use maps. These maps were validated using soil water balance with periodic soil moisture measurements. The study demonstrated how maps showing the spatial and temporal dynamics of crop water use can offer insight into effects of soil properties and crop response and help define and manage zones in surface irrigated fields.

Introduction

Precision irrigation requires a measure of spatial variability, but it is not feasible to measure the parameters needed to calculate crop coefficients at every location in a field. The use of surrogate crop coefficients for evapotranspiration (ET) estimation based on remotely sensed imagery could provide the needed spatial dimension. If a relationship between the imagery and the ground data needed for estimating crop coefficients could be established, then the imagery could be converted to water-use image-maps.

Remote sensing can be used to infer plant and soil characteristics. Vegetation indices (VI), such as the normalized difference vegetation index (NDVI), have been shown to relate to many crop parameters (Moran et al., 1997), including canopy width and height. The NDVI is defined as the ratio of reflected energy in the near-infrared (NIR) and red parts of the spectrum: [NIR-red]/ [NIR+red]. The potential for using VIs as surrogates for crop coefficients was proposed many years ago by Jackson et al. (1980). This approach has been further developed as described by Hunsaker et al. (2003b) where they also discuss the use of NDVI for estimating the basal crop coefficient (K_{cb}) in cotton in the same field described in this study. The objective of this study was to use a previously established relationship between NDVI and K_{cb} along with soil water depletion and local meteorological data to produce a seasonal water-use map of a cotton field.

Materials and Methods

Description of field and location

The experimental site was a 3.4-ha field planted to cotton (*Gossypium hirsutum* L., cv Delta Pine 448B) on 15 April, 2002 at the University of Arizona's Maricopa Agricultural Center (MAC) located approximately 40 km south of Phoenix (33º 04’ 21” N; 111º 58’ 45” W) at an elevation of 360 m. The field straddles the transition between two soil series (Post et al., 1988): Mohall sandy loam (fine-loamy, mixed, hyperthermic Typic Haplargid) is dominant on the northeast portion of the field, and Casa Grande sandy clay loam (fine-loamy, mixed, hyperthermic Typic Natrargids) spans most of the southwest region (Fig. 1). This is an arid area, receiving only 185 mm of rainfall per year with daily summer temperatures ranging from 25° to 46°C. The field had an on-going tillage study imposed with 4-row "skips" where no cotton was grown. The field was furrow irrigated from the east.

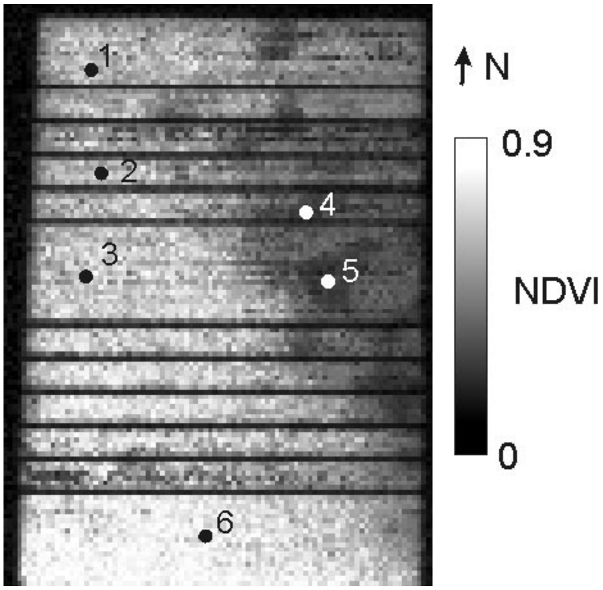

Figure 1. Mid-season normalized difference vegetation index (NDVI) of field with neutron access tube locations indicated. Dark to light pixels represent low to high NDVI values. Low NDVI values indicate areas of sparse, shorter cotton plants with visible soil background while higher values indicate larger, vigorous plants and full canopy. The diagonal NW to SE feature is the dividing line for two soil types, one with a higher sand content on the NE side of the field. The E to W dark lines are skip rows where cotton was not planted.

Remote Sensing

In 2002, imagery was acquired (Table 1) on nine dates at two to three week intervals using a Duncan MS3100 camera that acquired three coincident, 8-bit images in three wavebands. The wavebands were centered on 670 nm, 720 nm, and 790 nm with a 10-nm bandwidth. Flight altitudes were 1070 m (3500 ft.) above ground level and the camera had a 15º X 20º field of view resulting in a pixel resolution of about 0.3 m. Calibrated reflectance tarps (Group VIII Technologies, Provo, UT) were placed in a nearby field during each flight, and images were acquired within 7 minutes of acquiring images of the tarps. Coincident, ground-based radiometer measurements were taken over the tarps and other targets for use in calibration of the imagery to reflectance. These procedures and calibration tarps are similar to those described by Moran et al. (2001). Geometric registration was accomplished by measuring coordinates of markers place in the images with a Trimble Ag114 receiver with real-time differential correction.

Sampling and Image Processing

Neutron access tube locations were chosen based on a directed sampling study in this field the previous year. Directed sampling provides a measure of field variability from measurements at fewer locations as compared to grid sampling, and it can be more cost effective (Pocknee, 1996). Additionally, canopy height and width were

Table 1. Flight numbers and dates, planting date, and Day of Year (DOY).

Flight No.	Date (2002)	DOY
Planting	15 Apr	105
1	21 May	141
2	12 Jun	163
3	25 Jun	176
4	11 Jul	192
5	26 Jul	207
6	13 Aug	225
7	3 Sep	246
8	18 Sep	261
9	1 Oct	274

not measured at the neutron access tube locations but were collected in other locations of the field. Canopy height and width were, however, estimated at the locations of the six neutron access tubes (Fig. 1) for use in calculation of K_{cb} using the following procedures.

A statistical procedure developed by Lesch et al. (1995a, b) and implemented in the ESAP-RSSD (ECe Sampling, Assessment, and Prediction – Response Surface Sampling Design) software package was originally written to generate optimal soil sampling designs from bulk soil electrical conductivity survey information by selecting a minimum set of calibration samples based on the observed magnitudes and spatial locations of the data, with the explicit goal of optimizing the estimation of a linear regression model. The regression model is then used to predict all remaining (i.e., non-sampled) areas. The default setting in the ESAP-RSSD program selects 12 georegistered calibration locations for sampling, thus directing the user to these locations. In this study, the ESAP-RSSD program was used to direct ground sampling based on aerial Normalized Difference Vegetation Index (NDVI) images as input rather than electromagnetic induction data. The NDVI images were first converted to reflectance using the above-mentioned ground tarps and procedures and georegistered. Ground sampling based on the ESAP-RSSD results was conducted shortly after image acquisitions, usually within 24 hours. Data collected from the ESAP-RSSD directed ground locations were used to calibrate the images to produce canopy width and height image-maps of the field. Neutron access tube locations were measured with a differentially-corrected global positioning system (DGPS) and located in these georeferenced image-maps. Mean pixel values were extracted from the imagery in 2-m diameter areas around the canopy height and width locations and neutron tubes for use in developing K_{cb} curves. The 2-m diameter size was chosen as representative of the ground sampling area because this corresponded to the canopy height width measurement areas and DGPS data were accurate to within plus or minus 1 m, or 2-m diameter.

The ESAP-RSSD software requires that the data meet some assumptions in order to produce accurate sampling designs (Lesch et al., 1995a, b):

1) The covariate data (NDVI) must represent a dense grid.
2) A linear relationship must exist between the primary attributes (canopy height and width) and the covariate.
3) The residuals of the regression model between the primary attribute and covariate must be spatially uncorrelated.

The images acquired provide a dense grid where every location in the field was effectively sampled. A linear relationship was shown to exist between canopy height and width but is not presented here. The ESAP-RSSD software generates a design that optimizes the sampling locations by choosing spatially distributed and uncorrelated locations. Thus, the assumptions for use of the ESAP-RSSD software were met with the use of NDVI images and supporting ground data. Canopy height and width were accurately interpolated to the neutron access tube locations. These locations were spatially uncorrelated and a simple regression model could relate NDVI to canopy height and width.

Ground Sampling

At each location identified by the ESAP-RSSD procedure, plant height and canopy width were measured. Plant height was measured by placing a 2-m long rod on the soil surface and measuring the height of plants at each 0.5-m interval in two adjacent 1.02-m (40-in.) rows. The mean was taken as the plant height for each location. Canopy width was measured along this 2-m length by visually estimating the canopy edges and measuring across the row.

A neutron access tube and TDR waveguide were installed in the middle of a cotton bed at each of the six locations based on the previous year's ESAP-RSSD sampling design. Volumetric soil water contents were measured at each location beginning on 29 May 2002 using neutron scattering and time-domain-reflectometry (TDR) techniques. Soil water content for the 0 to 0.3-m soil layer was measured with the TDR, and at 0.2 m increments to a soil depth of 2.0 m with a site-calibrated neutron probe. Usually, soil water measurements were made the day before and three days after each irrigation. However, there were occasions during the season when irrigation water was applied before the water content measurements could be made at the locations. Following the termination of irrigation in mid-August, water contents were measured approximately once a week at all six sites until the crop was defoliated.

ET and K_{cb} Estimations

Cumulative cotton evapotranspiration (ET) for each of the six locations was calculated as the soil water balance residual (eq. 1) for time periods between two successive soil water measurement dates:

$$ET = (\theta_1 - \theta_2)\, Rd + I + R - DP \qquad (1)$$

where θ_1 and θ_2 are the volumetric water contents of the effective rooting depth on the first and second date of sampling, respectively, in $m^3\ m^{-3}$, Rd is effective crop root depth in mm, I is the depth of irrigation in mm, R is rainfall in mm, and DP is deep percolation below the root zone in mm. The change in soil water storage was determined for a soil depth of 1.7 m, the estimated maximum Rd for cotton (Allen et al., 1998). However, cumulative ET was not determined from the water balance for periods when irrigation occurred between two successive soil water measurement dates due to large uncertainties in the amount of water applied and subsequent drainage below the root zone. Consequently, seasonal cumulative ET for each site was determined as the summation of cumulative ET that was measured from the soil water balance for periods when irrigation was not applied, and estimations for cumulative ET for the periods when irrigation was applied. The estimation procedures used for determining cumulative ET for non-measured periods were presented by Hunsaker (1999, pp 929-930), but will be briefly described below.

For each site, basal crop coefficients (K_{cb}) were derived for the periods of measured cumulative ET (typically 7 to 9 days long) using the FAO-56 dual crop coefficient procedures (Allen et al., 1998). The dual crop coefficient relationship to ET can be defined as follows:

$$ET = (K_{cb}K_s + K_e)\ ET_o \qquad (2)$$

where ET and grass reference evapotranspiration (ET_o) are cumulative amounts for the period in mm, K_{cb} is the basal crop coefficient, K_s is the water stress reduction coefficient, and K_e is the soil water evaporation coefficient. For eq. 2, ET is known from the soil water balance, and ET_o is known, as calculated using local meteorological data within the FAO-56 ET_o equation (Allen et al., 1998). Assuming that the values for K_{cb} for each day of a given period were constant, daily FAO-56 calculations for K_s and K_e were made for the days within the period. The K_{cb} value was repeatedly adjusted until the right side of eq. 2 calculated the same cumulative ET as the measured cumulative ET for the period. Daily values of K_{cb} for periods between measurement periods (i.e., periods with irrigation) were then estimated by linear interpolation based on measured K_{cb} values immediately before and after the period in question (Fig. 2). The FAO-56 calculations were made to estimate the daily ET for those unmeasured periods. Prior to the first measurement period (early June), a cotton K_{cb} of 0.15 was assumed for the first 30 days for all sites, based on the FAO-56 K_{cb} guideline for cotton. Interpolation of daily K_{cb} was then made from the 31st day to the first measured K_{cb} for each individual site. Soil and other parameters used for the FAO-56 calculations are listed in Hunsaker et al. (2003b, Table 2) with two exceptions. Values for canopy height (h) and fraction of soil surface covered by vegetation (f_c) were estimated from calibrations developed between measured values and NDVI for each of the nine overflights. Daily values for h and f_c were interpolated between the parameter estimates for successive overflight dates.

Predicted daily ET as a function of days past planting (DPP) for each of the six neutron access tubes was calculated with the FAO-56 dual crop coefficient procedures but using daily K_{cb} values determined from a previously defined relationship between K_{cb} and NDVI for cotton (Hunsaker et al., 2003a, b). The relationship consisted of two regression relations: a linear function used from early vegetative growth to effective full cover (NDVI=0.8), and a multiple regression of K_{cb} as a function of NDVI and cumulative growing-degree-days (GDD) after effective full cover. The K_{cb} values were restricted to 0.15 or larger. Daily values for NDVI for each location were interpolated from observations made during the nine overflights. Using the linear regression developed between cumulative NDVI and the predicted cumulative ET at the neutron access tube locations (Fig. 3), a seasonal cumulative water-use map was generated (Fig. 4).

Root Mean Square Error (RMSE) and coefficient of determination (r^2) values were calculated from a regression derived from the nine measured versus predicted ET values for the cumulative ET measured periods (Fig. 2 and Table 2).

Results and Discussion

The processes in this field were dominated by soil variability because of the two soil types present. Thus, ET and water-use were expected to vary. Neutron access tube locations 1, 2, 3, and 6 (see Fig. 1) showed similar patterns in K_{cb} between the measured and predicted seasonal curves (Fig. 2). The periods between about 80 and 120 days past planting (DPP) showed higher values of K_{cb} for the predicted model, but no ground data were collected during this period and the measured values do not follow the predicted. These locations were in parts of the field with vigorous plant growth and development (see Fig. 1). Points 4 and 5 were located in parts of the field with smaller plants where the canopy never closed completely, and the soil had more sand. The predictive model under-predicted the measured K_{cb} at these "sparse" locations early in the season (Fig. 2). The model was developed for cotton grown on a different soil, and the Kcb-NDVI relationship may have been different in this field. The model does not increase K_{cb} from the minimum value of 0.15 until an NDVI value of 0.2 is reached.

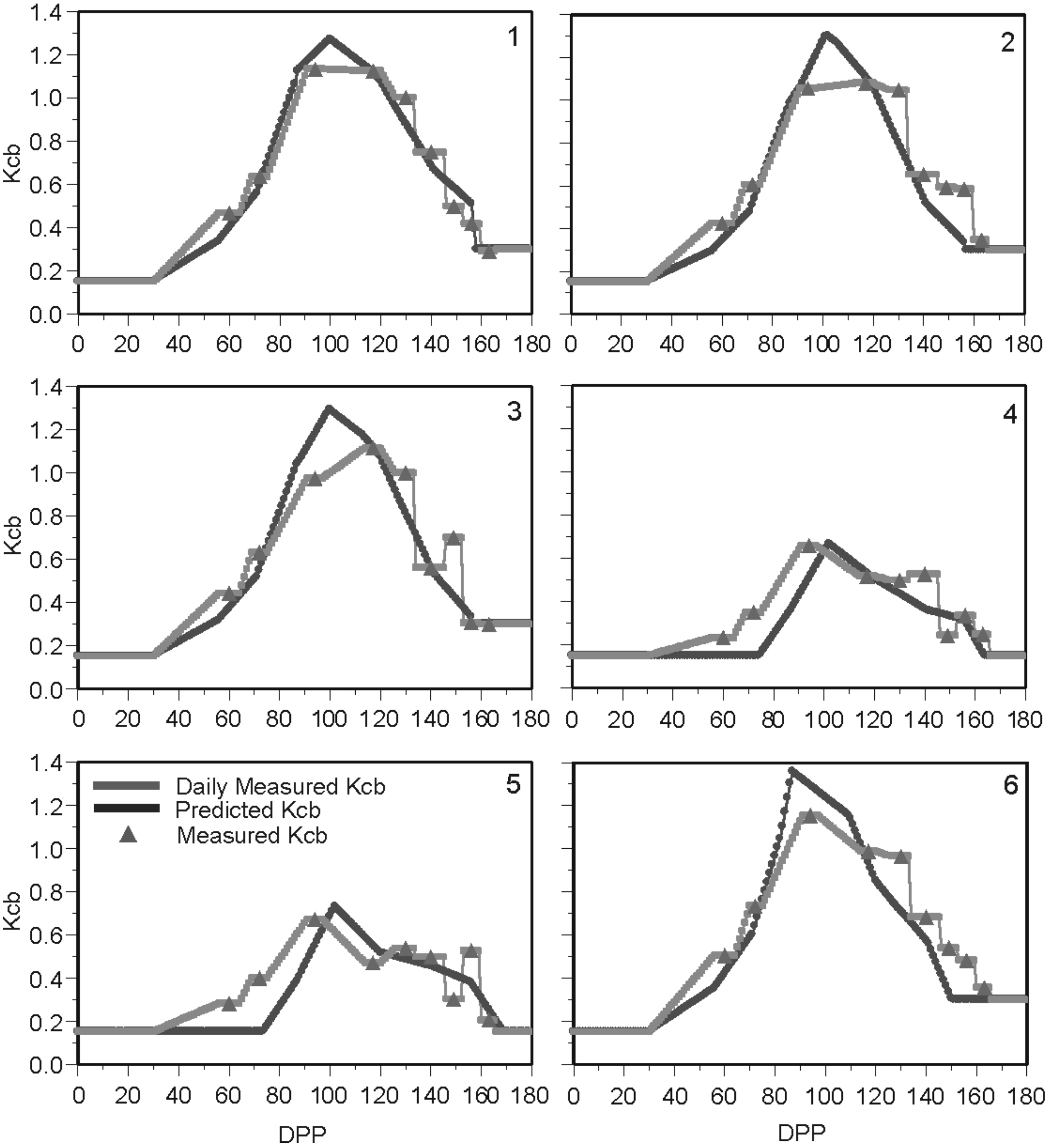

Figure 2. Days Past Planting (DPP) vs. basal crop coefficient (K_{cb}) at each of the six neutron access tube locations (1-6). Predicted K_{cb} values were estimated from a previously defined relationship with NDVI and is discussed in the text. Daily measured K_{cb} was calculated with soil moisture measurements from neutron access tubes and interpolated between the dates using FAO-56 procedures. The actual measured K_{cb} values are indicated by triangles and are in the middle of the measured cumulative ET periods.

Table 2. Root mean square error (mm) and coefficient of determination (r^2) for the cumulative measured ET (mm) periods derived from regressing the measured versus predicted ET values (see text). Mean predicted ET (mm) is presented as a comparison for the RMSE values. These are summarized by location across the nine measured cumulative ET periods and by period across the six neutron access tube locations. Day of year (DOY) shows the day of the midpoint of the each of these periods.

Location	Mean Pred. (mm)	RMSE (mm)	r^2
1	342	3.6	0.97***
2	303	5.6	0.93***
3	313	6.6	0.91***
4	158	4.5	0.81***
5	186	6.5	0.69***
6	316	7.3	0.90***

Measured Cumulative ET Period	DOY	Mean Pred. (mm)	RMSE (mm)	r^2
1	165	23.8	1.6	0.98***
2	177	25.5	1.9	0.98***
3	199	52.2	4.5	0.96***
4	222	50.4	3.1	0.97***
5	234	36.9	2.9	0.93***
6	244	43.8	5.7	0.66*
7	254	13.7	3.7	0.03 ns
8	261	15.1	2.8	0.01 ns
9	267	8.5	1.4	0.36 ns

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The NDVI did not reach 0.2 until relatively late (about 75 DPP), so the model did not increase K_{cb} appropriately. It is well established that soil background color can have a strong influence on NDVI (Huete, 1988). One possible solution would be to use another vegetation index, such as the soil-adjusted vegetation index (Huete, 1988) to develop a relationship with K_{cb} and correct for sparse areas in the field.

The seasonal cumulative ET (ET_s) in mm vs. seasonal cumulative NDVI ($NDVI_s$) for all six neutron access tubes (Fig. 3) showed a strong relationship for ET calculated from the predicted K_{cb} values in Fig. 2. The measured ET_s based on the daily measured K_{cb} showed good correlation to the predicted K_{cb} for the higher values corresponding to the vigorous locations 1, 2, 3, and 6. The regression under-predicted ET_s at the sparse locations 4 and 5 because predicted K_{cb} was under-predicted early in the season, as discussed above. The y-intercept shows evaporation for bare soil over the season and corresponds well with the value of 235 mm obtained using the FAO-56 procedure by setting $K_{cb} = 0$.

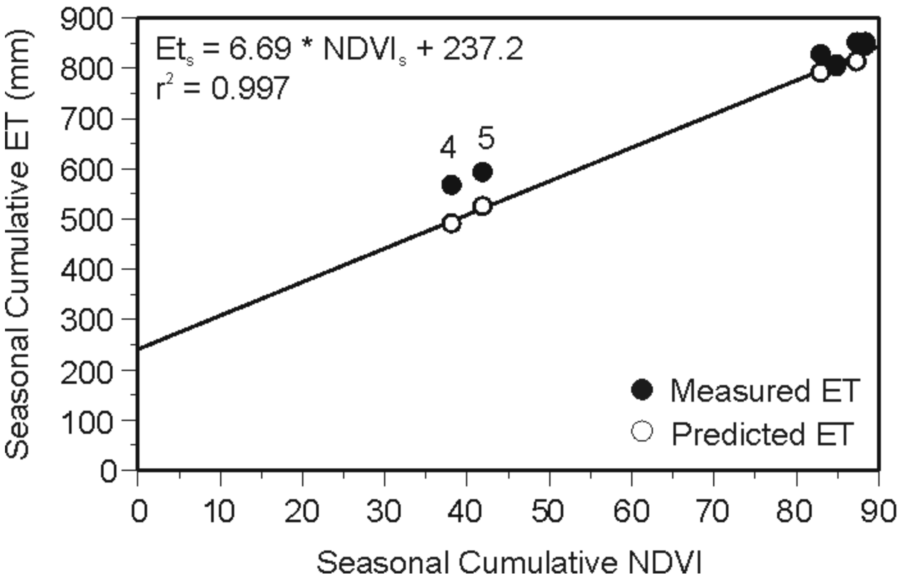

Figure 3. Seasonal cumulative NDVI (NDVI$_S$) vs. predicted (open circles & regression line) and measured (closed circles) cumulative ET (ET$_S$) in mm. The time period for calculating the cumulative values was DOY 141 to DOY 274, the dates between the first and last aerial image acquisitions. The measured ET values are the actual seasonal cumulative values measured at the six neutron probe locations (with interpolation between dates) and the predicted values are those estimated from the FAO-56 model described in the text for the neutron probe locations. The value of 237 mm at the y-intercept indicates estimated evaporation from a bare soil surface. Data from the sparse locations 4 and 5 are indicated.

For each location across all dates, the predictive power was quite strong for the vigorous locations (Table 2). At sparse locations 4 and 5, the r^2 values were highly significant but there was more scatter in the data. The RMSE values were about twice as high relative to the mean of the predictive model.

The RMSE and coefficients of determination for each of the nine measured cumulative ET periods and locations are separated out in Table 2. Within each period, there was a strong correlation between the measured and predicted ET for the first 5 periods. The RMSE values were within 9% of the mean for the predicted ET values for these periods, and the r^2 values were highly significant. Periods 6 to 9 showed weaker to poor correlations and greater RMSE relative to the predicted mean ET. This poor performance could have be due to a number of factors: 1) The original directed sampling locations for these dates were chosen based on other indices, not NDVI. The residuals for these points could have been spatially correlated when used to calculate NDVI and violated this assumption of the models upon which ESAP-RSSD is based. 2) NDVI and canopy height and width relationship became weaker later in the season as senescence began. 3) Periods 7 and 8 experienced significant rain events that were likely not uniformly distributed across the field and therefore difficult to accurately model. 4) The model accuracy decreased during the latter half of the season. The most likely causes of poor r^2 and higher RMSE values are points 3 and 4 above. Noteworthy is that the r^2 of periods 7 and 8 were basically zero.

The seasonal cumulative water-use map (Fig. 4) was arbitrarily divided into four levels to represent bare soil and three levels of crop water-use. Not surprisingly, it looks like the mid-season NDVI image in Fig. 1. As stated earlier, biophysical functions in this field were controlled by soil features. The black values represent

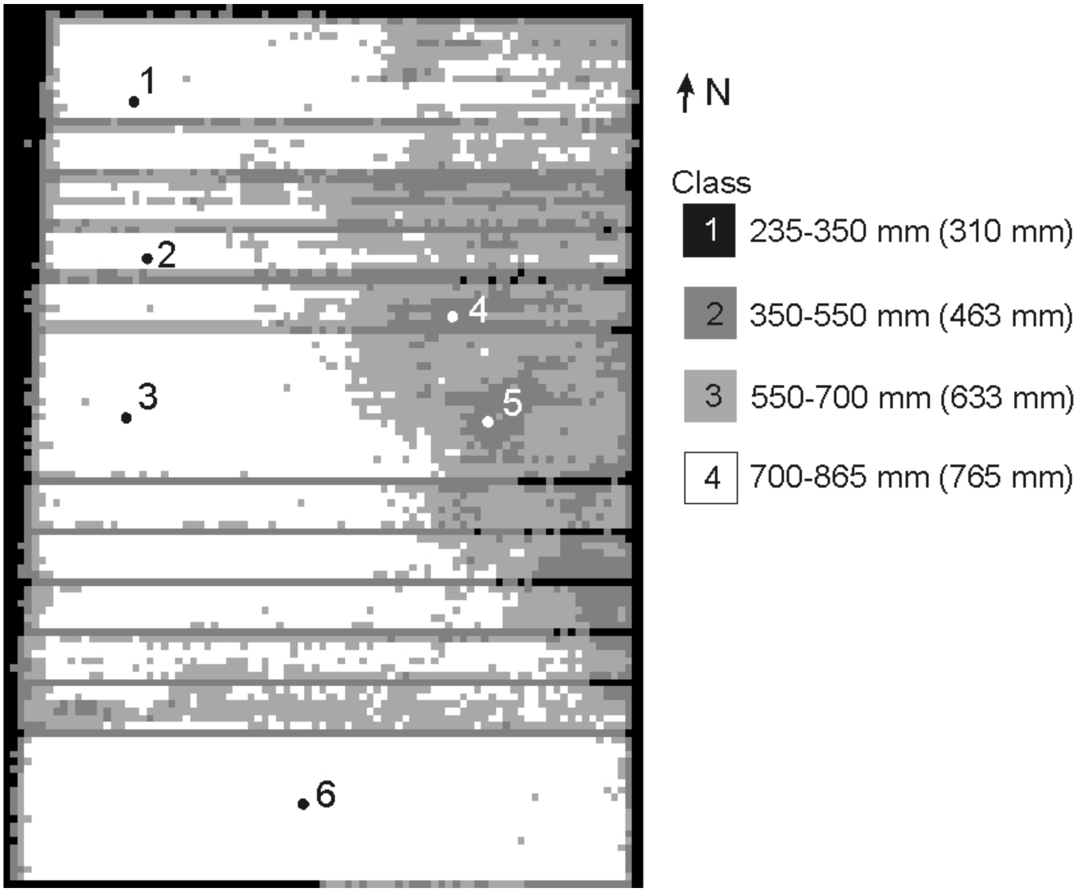

Figure 4. Seasonal cumulative water use map. The four classes represent values from low to high seasonal water use. The values in parentheses are the means for each level. The lowest value, 235 mm represents the amount of water lost during the season from soil evaporation. The values were based on those predicted at the neutron access tube locations and extrapolated to all other locations by using the equation presented in Fig. 3 relating cumulative NDVI to cumulative ET. See text for details. The six numbered points show the locations of the neutron access tubes. The spatial patterns clearly show soil differences and skip rows.

bare or almost bare soil and encompass the field edges and some of the skip row areas. Class 2 shows the sandier soil and corresponds to the locations of neutron access tubes 4 and 5, in the sparse areas. Class 3 shows predominantly sandy areas but along with class 2, occupies the skip row areas. Although there were no plants in the skip rows, pixel averaging to 2-m resolution created pixels with values combining soil and plant characteristics along these edges. The areas of greatest water-use are shown in white, and occurred over the less sandy soil. There also may have been some influence due to management as seen in the lower sections of Fig. 4 where point 6 was located. An on-going tillage trial tested the effects of various methods of soil incorporation for cotton stubble. This may have influenced the crop, producing vigorous plants in the most southern section of the field and less vigorous plants in the two narrow sections just north of this because of treatment differences.

Summary and Conclusions

Combining remote sensing with predictive models of ET can allow the temporal modeling approach to be interpolated across the spatial dimension. A combination of sampling design, ground sampling, image acquisition and processing, and computer modeling is needed to expand the use of ET models for precision irrigation. Additionally, the approach demonstrated here allows sampling of only a few ground locations lowering the acquisition cost of otherwise expensive “ground truthing”.

Disclaimer

Mention of specific suppliers of hardware and software in this manuscript is for informative purposes only and does not imply endorsement by the United States Department of Agriculture.

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ALFALFA PRODUCTION USING SUBSURFACE DRIP IRRIGATION

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Abstract

The studied was established in a medium textured soil in a arid region of northern Mexico (Comarca Lagunera). Yearly average precipitation of the region is 250 mm having annual evaporation of 2500 mm. The overall objectives of the study were to evaluate dry matter production and to determine under which irrigation criteria the highest water use efficiency (WUE) index is obtained as well as to compare buried drip irrigation with traditional (surface) and sprinkler (center pivot) irrigation systems in alfalfa cropping system.

Five irrigation treatments were evaluated using subsurface drip (tape) with alfalfa. These treatments where: to replenish soil water using 100, 90, 80, 70, and 60% of Eto estimated as the pan evaporation times a coefficient , Kt = 0.8. From this, effective rainfall was subtracted for obtaining the water depth to be applied according the treatment. Buried (30 cm depth) tape (0.375 mm wall tick) laterals space was 70 cm with emitters each 20 cm. The flow of the tape was 2.5 lph with operating pressure of 10 PSI.

After two years of evaluation, the treatment of replenishing water using 80% of Eto under buried drip irrigation showed the highest yield of green forage, 64% (with 15 % of humidity) compared with traditional surface irrigation system and increases of 23% compared with sprinkler irrigation (center pivot). The highest WUE of 1.9 kg of dry matter per cubic meter was obtained with the treatment of 70% of Eto.

Key words: buried drip irrigation, water use efficiency, dry matter, alfalfa

Introduction

The Comarca Lagunera Region in Northern Mexico, it is one of the most important dairy industries in the country. Annually 36,000 hectares of alfalfa are grown for feeding cows with average yield of 73.5 $ton.ha^{-1}.yr^{-1}$ of green forage (SAGARPA, 2001). The main issues with this crop are the length of the productive life (about 3 years), low yields and high water demand. It is estimated a yearly water depth ranging from 170 to 210 cm depending of the level of irrigation technology used, (Rodríguez and Orona, 1991).

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One strategy for increasing water use efficiency of crops is the use of advanced irrigation methods like subsurface drip irrigation. Recent research results have shown that this irrigation method in alfalfa may increase dry matter production in about 28.3% compared with surface irrigation (Phene, 1999), also, Godoy *et al* obtained an increase of dry matter yield of 16 to 23%. Increase ranging from 37 to 74% in seed production is reported by Neufeld, 2001. On the other hand, an increase of 47% of green forage (with 15% of humidity) may be obtained with this irrigation method (Rivera *et al,* 2001).

The objectives of this research were: a) to evaluate the response of alfalfa (dry matter) to different irrigation criteria using subsurface drip, b) to evaluate the water use efficiency (WUE) of all irrigation criteria studied and c) to compare subsurface drip irrigation method with sprinkler (center pivot) and traditional (surface) irrigation methods.

Materials and methods

Yearly average (20 years) precipitation in the experimental site is 250 $mm.yr^{-1}$ and 2500 mm of yearly evaporation (relation 1:10). Soil texture of the site was medium with electrical conductivity of 3.1 $dS.m^{-1}$. Five irrigation criteria were evaluated consisting in replenishing water to the soil in amounts of 100, 90, 80, 70 and 60% of reference evapotranspiration (Eto) computed as daily pan evaporation times a coefficient Kt = 0.80 subtracting effective rainfall, Ppe (Aguilera 1980).

Irrigations were applied twice a week. Hydraulic characteristics of the irrigation system are shown in table 1. Green forage and dry matter were evaluated harvesting one square meter in three sits of the experimental plot: at the beginning, in the middle and at the end. Samples of forage were oven dried at 70°C for 72 hr.

Table 1: Hydraulic characteristics of the irrigation system

Characteristics	Description
Tape	T-Tape
Wall tick	15 mil(0.375 mm)
Operating pressure	10 PSI
Emitter flow	0.5 lph
Flow per meter	2.5 lph
Space between emitters	20 cm.
Space between laterals	70 cm.
Buried depth	30 cm.
Irrigation intervals	Twice a week (monday and thursday)
Irrigation treatments	100, 90, 80, 70 y 60 % of Eto -Ppe

Results

Green forage and dry matter yields

Table 2 shows average yearly yields of green forage and dry matter for two years of study; this implies 10 and 12 cuts per year for the first and second year respectively. Meaningful statistical difference was obtained among treatments being statistically equal irrigation treatments of 100, 90, 80 and 70% of ETo. Nevertheless, replenishing water to the soil with 80% of evaporation showed the highest annual yields of both green forage and dry matter (114.7 and 21.2 tons per hectare respectively). For the second year also statistical difference was obtained with the same trend.

Table 2.- Yearly average of green forage and dry mater yields (tons per hectare).

Irrigation treatments (% ETo)	**Years**			
	2000		**2001**	
	Green forage	**Dry matter**	**Green forage**	**Dry matter**
100	107.8 a	20.4 a	109.3 b	20.7 b
90	106.8 a	19.9 a	125.8 ab	23.4 ab
80	**114.7 a**	**21.2 a**	**134.9 a**	**24.9 a**
70	107.3 a	20.1 a	126.6 ab	23.7 ab
60	83.2 b	16.2 b	108.1 b	21.1 ab

Different letters indicate statistical difference (DMS, 95 %)

Water consumption

Table 3 shows yearly average water depths applied and water use efficiencies (WUE). WUE is the ratio of yearly dry matter yield (kg.ha.year $^{-1}$) and water volume available for consumption [(Lr + Ppe) *10,000 m ^{2}], where Lr is the water depth applied and Ppe is the effective rainfall. During the first year WUE ranged from 1.1 to 1.5 kg dry matter per cubic meter showing the highest efficiency the treatment of 70% of Eto. For the second year, WUE was higher fluctuating from 1.1 to 1.9 kg dry matter per cubic meter used; for this year the treatments of 70 and 60% of Eto showed the highest values of WUE (1.9 kg dry matter per cubic meter used). This finding is similar to tht reported by Somohano, 2003 but less than the data reported by Godoy, *et al* (2003) and Figueroa *et al* (2003) (3.13 and 3.35 kg dry matter per cubic meter used respectively). Nevertheless the WUE reported by this authors are average of three and five cuts during the first year and do not specify if they took in to account the irrigation for establishment of the crop and if they considered effective rainfall.

Table 3.- Yearly water depths (Lr), effective rainfall (Ppe), available water (Ad) and WUE.

Year	Variables	Irrigation treatment (% de ETo)				
		100	**90**	**80**	**70**	**60**
2000	Lr (cm)	160.1	144.1	128.1	112.1	96.1
	PPe (cm)	18.9	18.9	18.9	18.9	18.9
	Ad (cm)	179	163	147	131	115
	WUE (kg/m3)	1.1 c	1.2 bc	1.4 ab	**1.5 a**	1.4 ab
2001	Lr (cm)	172.5	155.2	138	120.7	103.7
	PPe (cm)	6.6	6.6	6.6	6.6	6.6
	Ad (cm)	179.1	161.8	144.6	127.3	110.3
	WUE (kg/m3)	1.1 c	1.4 b	1.7 a	**1.9 a**	**1.9 a**

Different letters indicate statistical difference (DMS, 95 %)

Table 4 shows a comparative analysis of different variables for three different irrigation methods. Variables for the surface irrigation method correspond to regional averages; in this way, regional yield average is 77 tons .ha $^{-1}$ of green forage with water depth of 170 cm. On the other hand, variables for center pivot were obtained from a typical farmer using this type of irrigation system (property Nuevo Leon). WUE and yields correspond to averages of two years with this irrigation method.

Table 4.- Comparison among irrigation methods

Variables	**Irrigation method**		
	Surface	**Center pivot**	**Subsurface drip (tape)**
Green forage (ton/ha) (15% de H.)	16.7	22.4	27.4
Water depth (cm.)	170	146.2	133
WUE (kg/m^3)	0.98	1.53	2.1
Yield increase respect to traditional irrigation method		34.1%	64%

From table 4 it can be computed water savings of 3,700 and 2, 380 m^3 . ha $^{-1}$. year $^{-1}$ for drip and center pivot respectively.

Forage quality

Table 5 shows some variables indicating forage quality. Statistical analysis did not detect differences among treatments. Nevertheless a trend was detected related with higher quality on those treatments where more water was applied. No differences were detected between drip and surface irrigation methods for this variable, nevertheless, Phene (1999) obtained increments in raw protein contents of about 18 to 100%. Probably these findings in our study were due to the crop variety used, WL 711, which has been rated as highly nutritive quality (HQ).

Table 5.- Forage quality for the treatments studied

Variables	Drip irrigation			Surface irrigation
	100% ETo.	80% ETo.	60% ETo.	
Raw Protein (%)	25.5	24.9	24.9	24.5
Digestible protein (%)	18.2	17.8	17.7	16.9
Acid detergent fiber (ADF %)	27.3	27.6	27.8	26.8
Neutral detergent fiber (NADF %)	36.8	36.9	36.7	38.8
Net energy, ENPL (Mc/kg)	1.58	1.56	1.56	1.6
Total digestible nutrients (%)	69.5	69.2	68.9	69.9

High quality (HQ) alfalfa varieties may have more digestibility and net energy. This differences are equivalent to 100 kg of milk for each ton of dry matter in comparison to normal alfalfa varieties according to computations with the computer program Milk 95 (Nuñez *et al* 2000).

Conclusions

- The irrigation treatment of 80% of Eto showed the highest green forage and dry matter yields (124.8, and 23 ton.ha $^{-1}$ respectivelly).
- Over the two years of evaluation the highest WUE was obtained by the 70% of Eto treatment (1.5 and 1.9 kg dry matter m^{-3} for the first and second year respectively).
- Subsurface drip irrigation showed yield increases (green forage) up to 64% higher than traditional surface irrigation method and 23% higher than sprinkler irrigation (center pivot).

Recommendations

Water use efficiencies should be the paradigm of agricultural areas under rainfall uncertainty where forage production is important. This may be achieved by some strategies as:

- To shift to less demanding water varieties
- To change to pressurized irrigation systems
- To use as irrigation criteria to replenish a percentage of Eto or pan evaporation as shown in this paper.
- To irrigate as frequent as possible but with low water depths
- If traditional irrigation systems are to be used, to level the field and make irrigation runs according the available flow (lps), texture and to use a irrigation calendar accordingly.

- To maintain the irrigation system as operational as possible performing frequent hydraulic evaluations.
- No matter how efficient the irrigation system might be…good management practices are important too.

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INTEGRATED WATER RESOURCES MANAGEMENTS ON-FARM LEVEL

These researches were carried out within the framework of the project " On-farm soil and water recourses management for sustainable agricultural systems in Central Asia ", which was financed by the Asian Bank in cooperation with the International Center of Agricultural Researches in the Dry Areas (ICARDA). The researches were conducted by collaboration with National Scientific Centers in during of 2000-2002 years. Agriculture of Republic Uzbekistan is being occupied by more than 60 % of the total population and more than 90 % of foodstuffs are produced in this sector. Irrigated agriculture is producing over 90 % of the total agricultural production of the Republic. At the same time, yields of main agricultural crops such as cotton and wheat are still low. Accessible water resources are practically exhausted. Overall objectives of Uzbekistan as well as other republics of the Central Asia are maintenance with the foodstuffs; achievement of ecological stability; increase of the people's income. That is why the Integrated approaching to the natural and manpower resources management is necessary for achievement of these purposes, instead of existing fragmentary technologies. Integrated approach is considered as a strategy for achievements of the purposes. Such approach allows taking into account political, economical, social and ecological aspects. Although studying of the soil and water resources management in Uzbekistan and neighbor countries has the long history, existing recommendations appreciably have outdated already, because agricultural restructuring is carried out intensively, former technical and economic estimations have been executed for the large state farms based on artificial financial relations. Therefore, available knowledge should be tested in the new conditions, be improved, and developed in view of developing realities. Thus, the developing social and economic situation and a status of the natural environment in the Central - Asian region demand new strategy of rational use of available water resources. The water-savings in all spheres of water use and water consumption is a unique source of water for sustainable development of economy of the new independent states and stabilization of ecological conditions in the region.

The project has consisted of the following components:

I. Development of improved strategies for on-farm soil, water, and crop management (water management, irrigation methods, fertility, tillage, crop diversification)

II. Assessing and improving farm-level irrigation and drainage management to ensure sustainability of irrigated cropping systems (leaching, drainage, irrigation methods and scheduling, crop selection).

III. Assessing and improving utilization of marginal water sources (recycled water, drainage water, etc.).

IV. Upgrading of potential of National agricultural and water-economic research services in the countries of Central Asia by the organization of training courses.

The researches were carried out in cooperation with ICARDA, Central Asian Scientific Research Institute for Irrigation (SANIIRI), Uzbek Cotton Growing Research Institute (UzCGRI) and Gallaaral branch of the Andizhan Institute of the Grain and Leguminous Crops, and also with farmers and workers of co-operative farms.

Within the framework of Component I the following irrigation technologies: furrow and djoyak (zigzag), contour irrigation technologies to improve uniformity of irrigation water distribution and to decrease the washout of fertile soil layers, utilization of K-9 and other polymers to reduce soil erosion, testing portable polyethylene shoots PPS-50 for improving water-use efficiency through reduction of irrigation rates, utilization of corrugated hoses for optimizing the process of preparation for irrigation have been tested in Boikozon farm of Parkent rayon Tashkent oblast conditions with land's slope 0.09-0.11 (Kambarov B.F.,Ikramov R.K., Yuldashev T.U., Rachimov N.R.). Trial experiments on improved irrigation technologies have been established on experimental plots planted under winter wheat, maize, potatoes and melon. Also were testing a certified technology of fodder beet, maize, and cotton irrigation under utilization of plastic film and its adoption for production conditions (Bezborodov G.A.). In all variants irrigation were carried out with optimum Irrigation technologies elements (the furrow's discharge and length, irrigation cutting time, net and gross irrigation rates). It were demonstrated economy of water up to 900-cub m water per ha, reduce up to zero soil erosion, water use efficiency encreasing up to 1,5-2,0 times. Increase of labor productivity irrigators up to 2-2,5 times. For the first time the new irrigation device with water-releases PPS-50 regulating the charge is developed and designed. For the first time in Uzbekistan winter wheat irrigation tests on contour furrows are executed. Also the new technology with application PPS-50 and hydrants – extinguishers for such irrigation were created. The method for identifying of optimum elements of irrigation (the furrow's discharge and length, irrigation cutting time, net and gross irrigation rates) on the slopping lands was advanced. Scientific novelty consists: for the first time infiltration parameters at various designs furrows (djoyaks, utilized polymer K-9, contour furrows) and crops (a winter wheat, maize, potato, melon) were established experimentally on the basis of the theory of movement of an irrigation jet and water infiltration in soils in sloping lands.

Since April, 2002 investigations were carrying out on furrow irrigation technology on low slopes (flat areas) and subjected to salinization lands of Dzhambul farm of Khodgeily rayon of Republics Karakalpakstan. Due to rational of water use for cotton irrigation through furrows, and also creation of irrigation sites with a passer irrigation on furrows from single-breasted irrigation channels, achieves increase of water-availability up to 10-15 % (Kurbanbaev E.K., Karimova O.).

Self-pressured drip and drip-jet irrigation systems were constructed, production researches of irrigation technology of young vineyards and a vegetable - melons (water-melons, melons, tomatoes, the Bulgarian pepper, cucumbers, a potato in inter rows on the soils with slopes (0,1-0,15) are realized. The economy of water has made from 40 up to 60 % (Palvanov T.I., Ikramov R.K., Novikova A.V., Karimov S.).

Researches are executed according to potential and efficiency of use marginal (collector-waste waters) in agricultural systems of mentioned above cooperative farm Boikozon. The developed technique of an estimation of potential marginal waters is under production conditions tested, the adaptation convenient for simple peasants for rise and water delivery from a waste collector on adjoining along it irrigated sites is created. Yields of potato, corn, string beans, and also apples were higher than on the control (Ikramov R.K., Маматов C.).

In two farms ("Kushman ata" and "Iskander" in S.Rashidov rayon of Syrdarya oblast) on alluvial proluvial plains of Hungry steppe on the average a watercourse of Syr-Darya on the soils subjected salinization, production researches of efficiency irrigation of cotton by sprinkler machines " Bainlih" (Germany) and seasonal - stationary system with medium-jet devices, were constructed from polyethylene are executed within the framework of the project (irrigation of repeated crops - chickpea, a spring wheat, carrots, cucumbers, water-melons, melons). On cotton irrigation it is achieved reduction of specific expenses of water on unit of a crop more, than in 2 times (Ikramov R.K., Maltsev S.N.).

Crop rotations are advanced by crops diversification and anti erosion processing of soils raising efficiency rainfed soils in Gallaaral rayon of Dzhizak oblast. It is established, for purposes: maintaining of positive humus balance, rational use of a moisture, reduction of water and wind erosion, processing soils after cleaning with the subsequent processing flat hoes or disk instruments, increasing of the general productivity of rainfed arable lands are necessary bringing leguminous crops to the circuit of a crop rotation (Yusupov H.).

On central experimental base Uzbek Cotton Growing Research Institute (UzCGRI) in Tashkent oblast were carrying out researches on diversification and intensification of agriculture at cultivation of a cotton and winter wheat as basic crops and anti erosion soil processing.

It is established, that sowing of crop of repeated leguminous cultures (mash-chickpea) after winter wheat and intermediate crops in short crop rotation cotton - winter grain improves agrophysical properties of soils and increases the contents of nutrients (humus, nitrogen). By researches of various circuits of the minimized autumn technology of preparation of soils it is established, that the greatest yields are reached by winter wheat sowed on a growing cotton by seeder CZK-2,1, together with at a plowed land (Hasanov B., Halikova F.).

Within the framework of the Component II production research on water salt regimes in irrigated lands subjected to salinization in farm "Kushman-ata" of S.Rashidovskiy rayon of Syr-Darya oblast (alluvial-proluvial plain - Hungry steppe, an average watercourse Syr-Darya) is executed. By Field experiences were tested water saving irrigation technology through furrow and by discrete way with the help of the switch of a stream on a background of the capital lay-out executed within the framework of the project, providing creation of minimally necessary washing mode of an irrigation. Efficiency of technology of winter-spring washings of the salted soils before and after carrying out of a capital lay-out is shown. Optimum combinations of irrigation regimes, ground and drainage water availability at which high crops yields are provided at the minimal expenses of water and work have been identified by inspection of the technical condition of the closed horizontal and open drainage, ground waters and soil salinity of aeration zones. It was determinate by mathematical modeling of water-salt regime on a background of drainage under a cover of a cotton and wheat. Besides are constructed and equipped 8 lysimeter with soils, which are not broken structure. For the first time researches on studying a share of participation of ground waters in root zone are carried out at cultivation of a winter wheat and repeated maize (Ikramov R.K., Tsai O.G.).

Within the framework of the Component III 2001-2002 production researches in farm "Kushmanata" of S.Rashidovskiy rayon of Syr-Darya oblast on use on an crops irrigation (cotton, sesame, pistachios, corn and trees of a mulberry) mineralized collector -drainage waters were carried out. Irrigation Variants by collector-drainage water in a "pure" kind (3,5-5,6 gram/litr), mixed with irrigating water (up to 3 gram/litr) and irrigating water from the channel (up to 1,5 gram/litr) were investigated. Researches have shown, that by sufficient degree of soil drainage in conditions of Hungry steppe with the high maintenance of ions of calcium in soil - absorbent complex, and also the chemical compound of collector-drainage waters concerning on negative ion to sulphatic, and on cation to Na-magnesian, deterioration of physical properties of soils does not occur. Depending on growth of a mineralization of irrigation water, crops productivity is a little reduced, however their cultivation remains profitable. Negative influence on crops quality it is not revealed. At the same time, by using of mineralized collector-drainage waters on crop's irrigation, from spring by the autumn there is a big restoration soil salinity, that demands additional expenses of water and work for soil leaching and a drainage (Ikramov R.K., Mamatov S.).

Experimental Site in territory of farm "Dustlik" Besharik rayon of the Fergana oblast where wind speed reaches up to 15-24 m/s have been established for testing saline water utilization for windbreak forest strip. Two experiments have been set up at the established experimental site. First experiment have been based on the existing windbreak forest strips. The other one have been initiated by planting drought- and salt-tolerant tree varieties: black poplar, Bollet poplar, oleaster, English elm, willow, and quince. Shrubs was represented by pistachios, pomegranates, figs, and mulberries. These research showed opportunity for using on irrigation available drainage-waste waters, influence of forest strip for deflationary processes preventing and due to it increase of cotton yields (Mirzadzhanov K.M).

Researches on Subsoil irrigation of winter wheat were carried out In territory of Fergana branch of UzCGRI with the closed horizontal drainage, in conditions grassland and heavy mechanical texture. A mineralization of subsoil waters within the limits of 1-3 г/л. Due to regulation of a drain flows, depth of a level of subsoil waters was supported in limits from 0,57 - 1,91 m, depending on the period of year and a phase of development of crops. Winter yields by subsoil irrigation were up to 0.58-0.63 t/ha more than in comparison with the control. The economy of irrigating water has made about 1000 m3 per ha (Mirzadzhanov K.M).

Within the framework of the given project crops irrigation regimes were scheduled by using the automatic mini meteorological station in which the evaporator class A is established with using standards of the USA Ministry of Agriculture. Crops root zone's soil moisture were predicted accordance to drawing up of daily balances of a soil moisture, and crop's irrigation were scheduled by adopting FAO CROPWAT-7.0 Model in Uzbekistan conditions.

Supervision over soaking up pressure of ground use тензиометров - ирромeтров supervised humidity of ground and approach of terms поливов.

Monitoring of Social and economic efficiency soil and water resources management on pilot sites in Parkent rayon of the Tashkent oblast and Sh .Rashidov rayon of Syr-Darya oblast have been carried out since November, 2001.

On the Component IV farmers of pilot objects, scientific employees of national institutes of Republic Uzbekistan who had participated in realization of the given project, have passed special training at the Training Courses, seminars and Farmer's Field Day, which had been organized for implementation of new technologies and management methods.

Economic Analysis of Variable Rate Applications of Irrigation Water in Corn Production

Yao-chi Lu, E. John Sadler, and Carl R. Camp*

INTRODUCTION

Traditionally, producers treated the entire field as if it were a homogeneous unit, even though there were variations in soil types, soil fertility, and yield potentials. They applied average rates of inputs over the entire field. As a result, some areas were under applied while others were over applied, resulting in lower profits and chemical and nutrient losses to surface and ground water.

Precision agriculture is a knowledge-based system that enables producers to apply precise amounts of fertilizers, pesticides, water, seeds, or other production inputs to specific areas where and when plants need them for optimal growth. It is a promising group of technologies that could theoretically increase crop productivity and profitability, reduce chemical use, and decrease environmental degradation.

Variable rate technology (VRT) is probably the best-developed part of precision agriculture (Searcy, 1994; National Research Council, 1997). Many VRT products are presently available to producers via equipment dealers (Lu, et al., 1997). According to a Purdue University survey of agricultural chemical dealers, 13 percent of respondents used controller-driven VRT for applying fertilizers (Akridge and Whipker, 1997).

Since precision agriculture is still in an early stage of adoption, few economic analyses have been published. Lowenberg-DeBoer and Swinton (1995) reviewed the profitability of precision agriculture and found most of the studies focused on fertilizer applications, especially potash and phosphate. The reason for this is that abundant literature is available on relationships among fertilizer, soil nutrients, and yields, and fertilizer costs form a large portion of the total costs. The results of their review showed that of the 11 studies reviewed, only two studies showed potential profitability.

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Since the Lowenberg-DeBoer and Swinton's review, several other economic studies have been reported in conferences. In the Third International Conference on Precision Agriculture held in 1996, 12 economic papers were presented. Again, much of the interest then focused on the benefits and costs of fertilizer applications. Seven out of 12 papers presented involved fertilizer applications. As with the Lowenberg-DeBoer and Swinton review, the results of economic analyses were mixed.

There have been only two economics articles published in the international Journal of Precision Agriculture since its inception in 1999. Wang (2000) evaluated economic and environmental effects of variable rate nitrogen and lime application for claypan fields in north central Missouri. He compared VRT rates for two different uniform N applications, URT–N1 and URT-N2. URT-N1 was based on topsoil depth within claypan fields, and URT-N2 was based on a typical N rate for corn production in the area. The results indicate that VRT was more profitable than URT-N1 in all four fields and URT-N2 in two of the four fields.

Bongiovanni and Lowenberg-Deboer (2000) evaluated the profitability of variable rate lime application in Indiana. Three VRT strategies: agronomic recommendation, economic decision rule, and information strategy, were compared with the uniform application for the whole field. The agronomic recommendation strategy used the agronomic recommendation rules, the economic decision strategy used the economic rule that profit is maximized when the marginal product is equal to the marginal cost, and the information strategy used site-specific information to determine the economically optimal uniform rate of lime. Results indicated that all three VRT application strategies were more profitable than the uniform application strategy and, among the three VRT application strategies, the economic strategy increased the highest average annual return over the uniform application, followed by the information and agronomic strategies.

Watkins, et al. (1998) used the EPIC (Environmental Policy Integrated Climate) simulation model to estimate seed potato yield over a 30-year period for four different ranges within a field. The simulated yields were used to evaluate the long-term profitability and nitrogen losses for VRT and uniform nitrogen applications while considering nitrogen carryover effects. A dynamic optimization model was used to determine optimal steady-state nitrogen levels for each range and for the entire field. Average nitrogen losses and economic returns were evaluated for both VRT and uniform nitrogen applications. They found that the VRT nitrogen application was not profitable when compared to uniform application. Nitrogen loss from the field was about equal for both VRT and uniform applications.

There are very few studies analyzing the profitability of VRT application of irrigation water. In a follow-up study, Watkins, et al. (2002) evaluated profitability and environmental outcomes associated with VRT applications of nitrogen and irrigation water in seed potato production in Idaho. Again, the EPIC crop growth model was used to simulate seed potato yields and nitrogen losses for four different ranges under both uniform and VRT water applications. A dynamic optimization model was used to determine optimal levels of nitrogen for each range under each irrigation scenario.

Average nitrogen losses and economic returns were evaluated for all management strategies. Results indicated that VRT nitrogen application was, again, not profitable and there was little to no reduction in nitrogen losses when compared to uniform applications. VRT application of irrigation water produced the greatest economic return and the greatest reduction in nitrogen loss regardless of which nitrogen management strategy was employed. These results indicate that VRT water management may be more important than VRT nitrogen management for some fields in irrigated agriculture.

This paper evaluates the economic feasibility of VRT applications of irrigation water in corn production in South Carolina.

MATERIALS AND METHODS

Source of Data

The data were obtained from an experiment conducted at the site-specific center pivot irrigation facility in Florence, SC, USA, during the 1999-2001 corn growing seasons. Corn ('Pioneer 3163') was planted with a 6-row planter that had in-row subsoilers to a depth of 40 cm. Row spacing was 0.76 m, and the final plant populations in the three years ranged from about 64,000 to 66,000 plants/ha. Conventional surface tillage culture was used. Irrigation and N treatments were imposed using a commercial, three-span center pivot irrigation system that had been modified to provide site-specific water and fertilizer applications. The experimental design used 4x2 factorial randomized complete blocks (RCBs) where sufficient area existed within soil map unit boundaries as delineated by USDA-NRCS on a 1:1200 scale. Where insufficient area was available, randomized incomplete blocks (RICBs) were used. The plot sizes were nominally 9.1 m x 9.1 m at the outer boundaries and 6 m x 6 m in the central control area. On larger soil map areas, multiple RCBs were imposed. The number of RCB blocks was 39, of RICB, 19, resulting in a total of 396 plots. Each plot was irrigated according to a specific irrigation strategy. All irrigation applications were controlled by a computer interfaced with the commercial pivot control panel and a PLC control system to operate valves. Treatments were imposed continually on the same plots, so yield responses reflect the cumulative effects of water or nutrient excesses or deficits. Each year, a 6.1-m length of two rows near the center of each plot was harvested using a plot combine. The harvested grain was weighed, corrected to 15.5% moisture, and the yield was expressed per unit ground area. A detailed description of this experiment is described in Camp, et al. (2003).

Net returns, defined as total returns minus total variable costs, were used to measure profitability. The variable costs include costs of seeds, fertilizers, lime, herbicides, insecticides, irrigation, drying and hauling, operation of tractors and machinery, labor, and interest on operating capital. The cost data were obtained from the enterprise budget of the Clemson Extension Service, Clemson University (2002), and modified for each irrigation strategy. The irrigation cost was estimated at $4/acre-inch, or about 40 cents/ha-mm. The costs for drying and hauling were estimated at $9.80/Mg. The other variable costs are the same for all strategies. The price of corn was obtained from USDA Agricultural Statistics (2002). The average prices of $80/Mg for corn and 40 cents/ha-mm for irrigation water were used in this analysis.

A corn response function for water, or water production function, for each of the 396 plots was estimated and used to determine the optimal amount of irrigation water and yields under yield-maximizing and profit-maximizing strategies. The estimated plot production functions (total of 396) were used to compute net returns for each plot under the different strategies.

Irrigation Water Application Strategies

For this study, we compared economic returns and irrigation efficiency of VRT and uniform applications. The profit-maximizing and yield-maximizing strategies were used for both application methods. For uniform applications, the optimal amounts of irrigation water used in VRT applications were assumed to be used uniformly in the field. Two other strategies, Irr 100 and Irr ET, also were used for comparison. The six strategies are as follows:

1. VRT applications
    a. Profit-maximizing
    b. Yield-maximizing
2. Uniform applications
    a. Profit-maximizing
    b. Yield-maximizing
    c. Irr 100
    d. Irr ET

For each plot, the amount of irrigation water that maximizes yield and profit was obtained from the estimated production function for each plot. The amount of irrigation water that maximizes yield can be obtained by equating the marginal physical product (MPP), or the slope of the production function, to zero, and that for maximizing profit can be obtained by equating the MPP to the ratio of the price of water to the price of corn. Unless irrigation water is free, the yield-maximizing irrigation amount will not give maximum profit. In general, the higher the water/corn price ratio, the more profitable the profit-maximizing strategy than the yield-maximizing strategy.

Irr 100 is for the design and normal practice (keeping tensiometers in the NkA soil above a constant reading). Irr 100 is constant for each year, as it was the 100% treatment. Irr ET was the irrigation amount that would have replaced ET (evapotranspiration) exactly. Irr ET was estimated from the ASCE Etr guidelines with crop coefficient for corn (Allen, et al., 1998; Walter, et al., 2000). The Irr ET yield was computed from production functions assuming the amount of water exactly equated with computed Etr. Had our Irr 100 been perfect, Irr 100 would have been equal to Irr ET. Differences indicate sub-optimal operation of the pivot. Irr ET and Irr 100 amounts are constant over the field, but the corresponding yields vary in space because the production functions vary.

Since we assume that the average profit-maximization amount of irrigation water is applied to all plots in the field under uniform application, the total amount of irrigation water per hectare for both VRT and uniform applications are the same. By using this assumption, there is no saving in irrigation water for using VRT applications. Consequently, the benefit of VRT application must be derived solely from increased yields.

Estimation of Production Functions

To determine the optimal amounts of irrigation water that maximize yields or profits, we need to estimate a corn response function to water, or production function. Several algebraic functional forms have been used as production functions (Griffin, 1984). Many studies indicated that the quadratic function is most appropriate for crop production functions (Barrett and Skogerboe, 1978; Hexem and Heady, 1978; Musick et al.,1976; Watkins, et al., 1998). In a previous study (Lu, et al., 2003), several forms of production functions, including quadratic, squared root, and double-log polynomial functions, were estimated with ordinary least squares, and the results confirmed that the quadratic equation was the most appropriate for the particular set of data used in this study.

The following form of production function was estimated using ordinary least squares:

$$\mathrm{Y} = \alpha + \beta W + \gamma W^2$$

where α, β, and γ are coefficients to be estimated. A production function for each of the 396 plots for the years 1999, 2000, and 2001 was estimated and used to determine the amount of irrigation water that maximizes yield and net return.

RESULTS AND DISCUSSIONS

Estimated irrigation amount, corn yield, and net return

The optimal amount of irrigation water, yields, and net returns under VRT and uniform applications using variable strategies are presented in Table 1. The results indicate that the VRT applications yielded larger net returns than the uniform applications, using either yield-maximizing or profit-maximizing strategies. Of the two VRT application strategies, the profit-maximizing strategy conserved more irrigation water and produced slightly larger net returns than the yield-maximizing strategy. For example, in 2001, the profit-maximizing strategy used 155 ha-mm/ha of irrigation water to produce 12.16 Mg/ha of corn and yielded $486/ha of net returns, while the yield-maximizing strategy used 206 ha-mm/ha of irrigation water to produce 12.40 Mg /ha of corn, but yielded $482/ha of net returns.

The difference in net returns would be higher if the price of irrigation water were higher relative to the price of corn (Lu, et al., 2003). For uniform applications, the profit-maximizing strategy produced larger net returns than all other strategies. Again, in 2001, the profit-maximizing strategy produced $477/ha net return, while the yield-maximizing, Irr 100, and Irr ET strategies produced net returns of $463/ha, $438/ha, and 417/ha, respectively.

Table 1. Estimated irrigation amount, corn yield, and net return per hectare for VRT and uniform applications.

Application	Strategy	1999			2000			2001		
		Water	Yield	Net return	Water	Yield	Net return	Water	Yield	Net return
		ha-mm	Mg	$	ha-mm	Mg	$	ha-mm	Mg	$
Variable rate	Profit-max	247	10.61	340.11	236	11.05	375.37	155	12.16	486.08
	Yield-max	282	10.80	339.37	256	11.11	372.07	206	12.40	482.26
Uniform	Profit-max	247	10.41	326.17	236	10.78	356.40	155	12.04	477.31
	Yield-max	282	10.58	324.44	256	10.85	353.27	206	12.14	463.72
	Irr 100	218	10.20	314.89	203	10.51	340.04	200	12.14	437.95
	Irr ET	253	10.46	322.88	212	10.60	346.24	240	12.07	417.48

However, VRT applications require different equipment and control systems. To adopt VRT of irrigation water, producers have to make additional capital investment for this new technology. Thus, before VRT can be widely adopted by producers, the system must be proved profitable. The benefits of reduced irrigation water cost plus the value of increased yields or quality of products must be greater than the additional costs associated with VRT. The differences in net returns for VRT and uniform applications range from $8.77/ha in 2001 to $18.97/ha in 2000 if the profit-maximizing strategy is used, and from $14.93/ha in 1999 to $18.88/ha in 2000 if the yield-maximizing strategy is used. If growers use the profit-maximizing strategies, the breakeven point for the costs of additional equipment is about $9.00/ha. That is, the additional cost of new equipment and controls must not exceed $9.00/ha.

Changes in relative prices of corn and irrigation water will also change the benefits of VRT. Often, VRT will result in savings of irrigation water and higher yields, but in this analysis, we assumed that the average amount of irrigation water used in uniform applications is the same as for the profit-maximizing strategy. Therefore, there is no savings in irrigation water and changes in the price of water will have no effect on the difference between VRT and uniform applications. However, increases in corn price will make VRT much more profitable than the uniform application. For example, in 2001, if the price of corn increased from $80/Mg to $90/Mg and the price of irrigation water remained the same, the breakeven cost for new equipment and control would increase from $8.77/ha to $16.17/ha.

Costs of VRT equipment and control

At the time this experiment was initiated, the VRT equipment and control were not commercially available. The three-span center pivot irrigation system was modified to provide site-specific water and fertilizer applications. The VRT equipment and control used in this experiment include the control system and the water delivery system. The control system includes the PC/PLC (computer and programmable logic controller) and associated hardware, remote PLC units, LCD display, transmitters, electronic components, conduit, fittings and enclosures. The water delivery system includes PVC pipe and fittings, solenoids, filters, low pressure drains, pressure regulators, rubber hose and quick connectors, nozzles, drop pipes, etc. The total cost for the control system was \$19,480 and the water delivery system was \$ \$29,900 in 1999 for a total of about \$50,000. Thus, the VRT system used in the experiment is too expensive to be profitable.

Site-specific irrigation equipment and controls designed and used for research are different from commercially produced equipment and controls in several respects. In order to achieve research objectives, the research equipment was designed to make precision irrigation applications on areas smaller than those required in practice and required greater precision both spatially and in volume applied. For example, each of the 3-tower systems used in this experiment can irrigate only 14 acres (5.67 hectares) as compared to many commercial systems that can irrigate 130 acres (52.65 heactares). In most cases, commercial equipment is not available; hence, standard, commercial equipment must be modified or new equipment designed and constructed for the research project. Further, when commercial VRT application hardware and controls are not available, the application hardware and control system must be assembled from available commercial components to achieve the desired application. Often these components may be oversized or have reserve capacity because of limited size availability and to ensure consistent performance under unknown operating conditions. All of these factors combine to make research equipment less compact, require more parts that are often connected in an inefficient manner, and more expensive per unit area. Consequently, research equipment and controls are seldom suitable for commercial uses, the cost is almost always greater than that of commercial equipment and controls designed for the purpose, and should not be used for economic evaluations.

It has been estimated that a commercial system costs about \$110/acre (a cluster upgrade for about \$56/acre and variable rate for \$54/acre) or \$271.60/ha (Harting, 2003). Assume that the average useful life of the system is 15 years and there is no salvation value at the end of its useful life. By using the capital recovery method (Boehlje and Eidman, 1984) at 6% interest, we estimated that the annualized additional cost for VRT is \$27.97/ha, which exceeds the breakeven point of using the VRT applications. Thus, at present, VRT is probably not profitable for corn in the Southeast USA compared with uniform applications. However, VRT costs are decreasing with further research and refinement of the system, and new commercial equipment and controls designed for site-specific applications are becoming more cost effective. Furthermore, the costs of these equipment and control systems will decline when VRT is widely adopted and these equipment and control systems are mass-produced commercially

SUMMERY AND CONCLUSIONS

This paper compared the net returns from VRT with uniform applications of irrigation in corn production under different strategies. The data were obtained form an experiment conducted at the site-specific center pivot irrigation facility at Florence, SC, USA, during the 1999-2001 corn growing seasons. Two VRT strategies (profit-maximizing and yield-maximizing) were compared with four uniform application strategies (profit-maximizing, yield-maximizing, Irr 100, and Irr ET).. For each year, a water production function was estimated for each of the 396 plots using the ordinary least squares. The estimated production functions were used to determine the amount of irrigation water that maximizes yield or profit.

The results indicate that the VRT applications yielded larger net returns than the uniform applications, using either yield-maximizing or profit-maximizing strategies. Of the two VRT application strategies, the profit-maximizing strategy conserved more irrigation water and produced larger net returns than the yield-maximizing strategy. The difference in net returns could be higher if the price of irrigation water is higher relative to the price of corn. Among the uniform applications, the profit-maximizing strategy produced larger net returns than either yield-maximizing, Irr 100, or Irr ET strategies.

However, for VRT is to be widely adopted by producers, the benefits of reduced irrigation water cost plus the value of increased yield or quality of products must outweigh additional costs for different equipment and controls required for the VRT application. Because the VRT system used in this experiment was built for research purposes that required additional details and resolution, the costs were much higher than those would have been used for commercial growers. Thus, the VRT system built for the experiment is not profitable for corn in the Southeast USA.

Even for the estimated current cost of a retro-fitted commercial system, the additional costs of VRT equipment and control system exceed the value of increased yield. Thus, at present, the VRT application of irrigation water is not profitable compared with uniform applications. However, VRT costs are decreasing with further research refinement of equipment and control systems and with these systems mass-produced commercially when VRT is widely adopted by producers.

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Using an "off-the-shelf" Center Pivot to Water Corn, Cotton and Soybeans on Mixed Soils Using a Concept of Precision Irrigation"

Joe Henggeler[1]

ABSTRACT

A test was conducted for two years on corn, cotton and soybeans to determine the ideal irrigation deficit/frequency for that crop. The field had two distinct soil types (SAND) and (SILT) as delineated by using a Veris 3100 EM machine. The various portions of both soil type were calculated for each compass degree; on average the pivot soil type was 26% sandy. Yields were separated by soil type. For each crop, yield data versus irrigation deficit treatments were used to develop net return curves based on the application amounts. For each crop three protocols were established to evaluate the economic impact of irrigating the entire field (1) using the ideal deficit irrigation for sand, (2) the ideal deficit for silty soils, and (3) concept of using a "precision irrigation," whereby that section of the field was irrigated using the deficit that gave highest net returns. This concept entails that added rotations are made with the pivot. Results were modeled.

Results showed that cotton tended to respond better to precision irrigation. This is because the net return-irrigation deficit curves were more distinct between the sandy and silty soils for cotton. In the cases of corn and soybeans, the ideal deficit for the two soil types were close enough together that precision irrigation increased net returns only little.

INTRODUCTION

Most center pivot companies offer an upgraded panel box that is capable of allowing the grower to irrigate portions of the circle, while traveling dry over other portions of the pivot circle. This special feature in panel boxes is sometimes provided free by the irrigation company has a sales incentive. Even when purchased, the cost of the panel up-grade is not prohibitive (approximately $3,000 to $5,000 more), especially when seen in light of acres involved and life of the system. Utilization of these types of control panels is examined in this paper as a means of precision irrigation.

Crop water use varies throughout the season. Irrigators can manage this change in water use over time by:

1. keeping the irrigation interval the same, but changing application amount
2. keeping the application amount the same, but changing interval
3. or a combination of one and two.

The over-whelming majority of irrigators using center pivots in the Midwest and mid-South, follow the second practice and apply a single application amount throughout the season. This amount is termed the irrigation deficit. The ideal irrigation deficit for a crop in a particular climate is a function of soil type.

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Empirical studies have been conducted to determine these ideal deficit amounts. Sometimes management concerns can over-ride the desire to apply the ideal deficit amount. This is the case of application amounts that cause run-off or get pivots stuck, or for flood irrigators, deficit amounts whose intervals are so long that the soil may crack first. However, there is --barring these other circumstances—generally an ideal application amount for a crop and soil type.

In fields with a homogenous soil type, precision irrigation becomes a mute point and is not required. However, if two or more distinct soil type exist under a pivot, precision irrigation may be beneficial. In this study *precision irrigation* is limited to only those management capabilities found in an up-graded pivot control panel. Distribution of water down the pivot lateral is always fixed. What can only occur is that as the pivot rotates it can be either "on" or "off" in terms of applying water. The precision irrigation management scheme thus involves dividing the field into certain arcs comprised mostly of Soil A that receive one application deficit/frequency scheme, with the remaining arcs (Soil B) receiving a second deficit/frequency scheme. Conceptually speaking, it is as if there are two separate fields being watered indepedently. One minor negative consequence is that this procedure leads to more hours of operation per year on a pivot, since the total number of circles made will be the sum of those required for watering Soil A plus those required for watering Soil B.

The smallest management zone in the controllers is an arc of one degree, thus for a normal 135-acre pivot the smallest zone of management would be an arc of 0.38 acres. However, a 5-degree span is probably as detailed as one can be in hand-discerning soil maps, thus the practical minimal size is 2 acres. Additionally, current control panels limit the numbers of line code in their control programs. For example, Zimmatic's controller, in its simplest form, allows only 16 lines of instruction, allowing at the most only eight zones (there must be separate "start" and "stop" lines for each zone). The panel does allow for multiple programs to be stored, so assuming two deficit/frequency schemes are used, then the pivot circle could be broken into 16 arcs, for an average management zone size of about 8 acres. The irrigator would use a Program A and a Program B which are kept in memory.

METHODS AND MATERIALS

Yield curves for corn, soybean, and cotton based on irrigation deficit/frequency were developed from two years of experimental research on a single field composed of two broad soil types. Irrigation frequencies, or deficits, range from 0.75 inch per application to 3.00 inch per application for soybean and cotton. The frequency range for corn ranged from 0.50 inches to 2.50 inches per application. For each crop there were five deficit/frequency treatments. All treatments on the individual crops received approximately the same amount of irrigation.

The tests were conducted on a three-tower center pivot located at the University of Missouri Delta Center Research Center near Portageville, Missouri. This area is located near the New Madrid fault, the epicenter of a very large earthquake that occurred in the early part of the 19th Century. Said to be the largest earthquake in recorded history, this event churned up pockets of sand within existing alluvial fields creating "sand boils". The research pivot was located on such a field.

A Veris 3100 EM machine was used to differentiate the soil types (Fig. 1). The fingerprint of the EM survey corresponds to the aerial photographs of the field (Fig. 2). Experimental results indicated that the largest demarcation in terms of yield response was based on soil texture as being either a sandy or non-sandy,

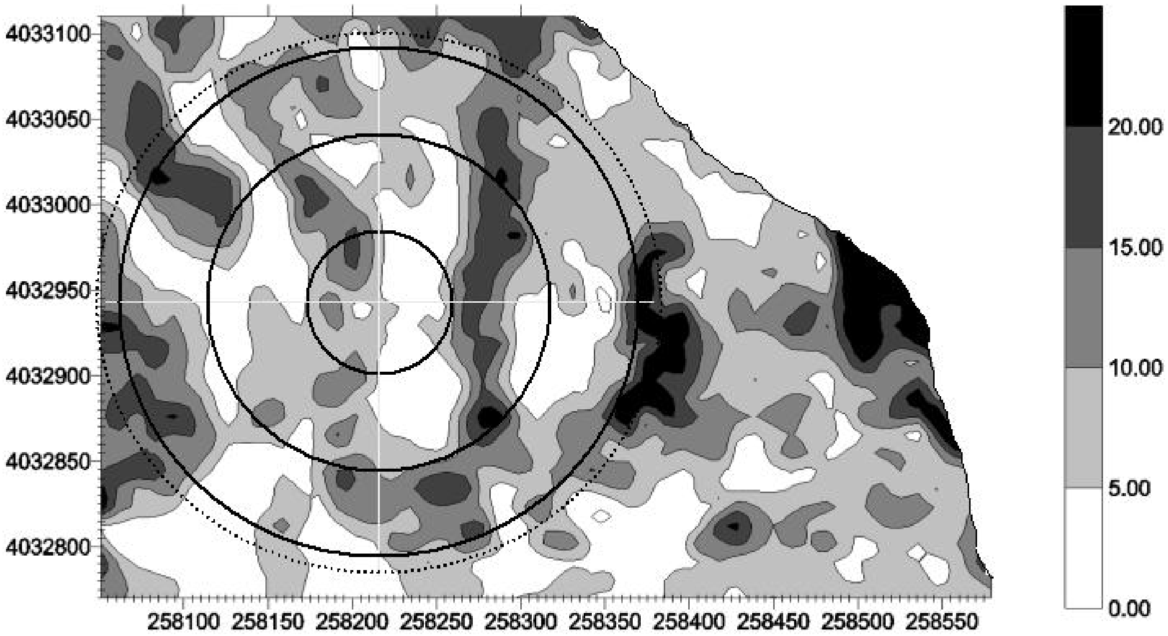

Fig. 1 Results of mapping apparent soil electrical conductivity (EC_a) with a Veris 3100 machine using the deep setting. Areas in the 0 to 5 EC_a range were grouped as one management group (SAND) and areas with values greater then 5 comprised the other group (SILT). The outline of the three pivot towers and overhang can be seen.

Fig. 2. Aerial view of same field showing location of where the pivot waters.

corresponding to apparent electrical conductivity (EC_a) values of 0-5 and 5-25, respectively, and designated SAND and SILT, respectively. The three crops were grown during the 2001 and 2002 growing season. A third of the pivot area was dedicated to each crop. Sections were rotated between years. Crops were planted in concentric circles in 30-inches rows.

The 1/3 portion of the field dedicated to a single crop was sub-divided into 15 equal sections (5 treatments by 3 reps) having an arc of approximately eight degrees. The control panel was used to apply the correct amount of water to the appropriate plot. The computer program, ***Arkansas Scheduler***, was used to time the irrigations. Harvest was accomplished by cutting alleyways between experimental units. A harvesting pass gathered two-row yield samples on the 15 experimental units. Approximately five separate passes were made at different radial distances down the lateral. The large number of yield samples collected was to ensure that ample yield samples would be available for both soil types. Corn and soybean samples were measured for moisture and yields converted to standard moisture levels (15% and 13%, respectively). Harvested seed cotton was ginned to determine lint yield.

Later, a soil map with the treatment boundaries and harvested rows drawn in was used to determine if the particular samples came from a SAND portion of the field or a SILT portion of the field. Plots that contained both soil types were not used. Yield results from two years for each deficit/frequency treatment were average for use.

Enterprise budgets develop by a local agricultural economist from the University of Missouri Outreach and Extension Service were used to calculate net returns for each deficit used. Total input costs were based on yield received and typical equipment charges. Irrigation costs were based on the gross amount of inches applied at $1/acre-inch) and a set charge of $30 per irrigation. A second-degree polynomial equation relating net economic return versus deficit was developed for each crop and soil type. The derivative of these equations were solved for zero to obtain the deficit that produced the highest net return, except in the case of cotton on sandy soil which had a very linear net return-deficit function.

Final economic analysis was made be comparing net return estimates under three main scenarios:

1) The pivot was operated normally using the ideal deficit/frequency for SAND throughout
2) The pivot was operated normally using the ideal deficit/frequency for SILT throughout
3) The pivot was operated in a precision irrigation mode, in which, for each 5-degree arc, the deficit/frequency that produced the most net return was used on that arc

RESULTS

The average yield for two years for the three crops based on the irrigation deficit is seen in Table 1. Figure 3 show the net return versus irrigation deficit curves for the three crops and two soil types.

Table 1. Average yields for corn, soybeans and cotton (bu/acre for corn and soybeans, lbs of lint for cotton) for five different irrigation deficits, Portageville, MO, 2001-2002.

	Corn					**Soybeans**					**Cotton**				
	------- inches per application -------					------- inches per application -------					------- inches per application -------				
	0.50	**1.00**	**1.50**	**2.00**	**2.50**	**0.75**	**1.00**	**1.50**	**2.00**	**3.00**	**0.75**	**1.00**	**1.50**	**2.00**	**3.00**
SAND	203.8	223.9	212.8	199.5	168.2	47.1	59.5	60.2	49.6	50.7	1369	1237	1275	1216	1118
SILT	206.4	211.9	213.5	202.2	194.7	58.5	54.5	59.2	62.3	57.2	1151	1115	1296	1177	1147

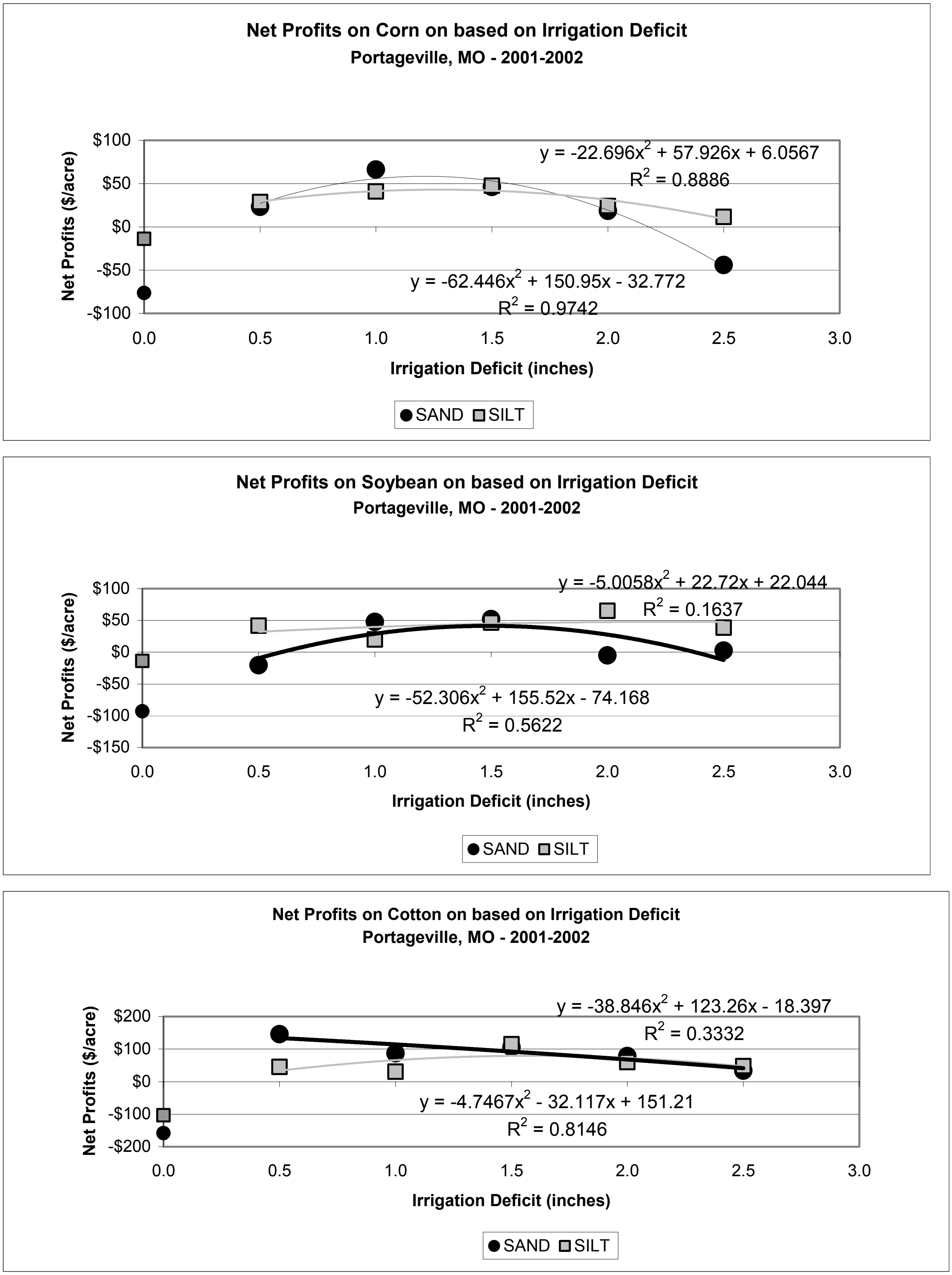

Figure 3. Net return versus irrigation deficit for SAND (left) and SILT (right) with corn (top), soybean (middle) and cotton (bottom).

The ideal irrigation deficit for the three crops and two soil types was determined by taking the first derivate of the net return versus deficit equations (these are seen imbedded in the graphics from Fig. 3). The one exception to this was the cotton-sand equation, whose linearity gave a false solution to the ideal deficit amount. In this case 0.50 inches was chosen from the shape of the curve. These ideal deficit values are seen in Table 2.

Table 2. Ideal irrigation application deficit for corn, soybeans, and cotton for sandy and silty soils

Soil Type	Corn	Soybeans	Cotton
	------------------ inches per application ------------------		
SAND	1.21	1.75	0.50
SILT	1.28	2.06	1.92

The proportion of SAND and SILT down the radial distance from the pivot point varied depending on direction from the pivot point. The percent of SAND varied from 0 to about 80%. Overall, the field was 31% sand. Figure 4 shows the graph of the SAND distribution around the full 360 degrees of the circle.

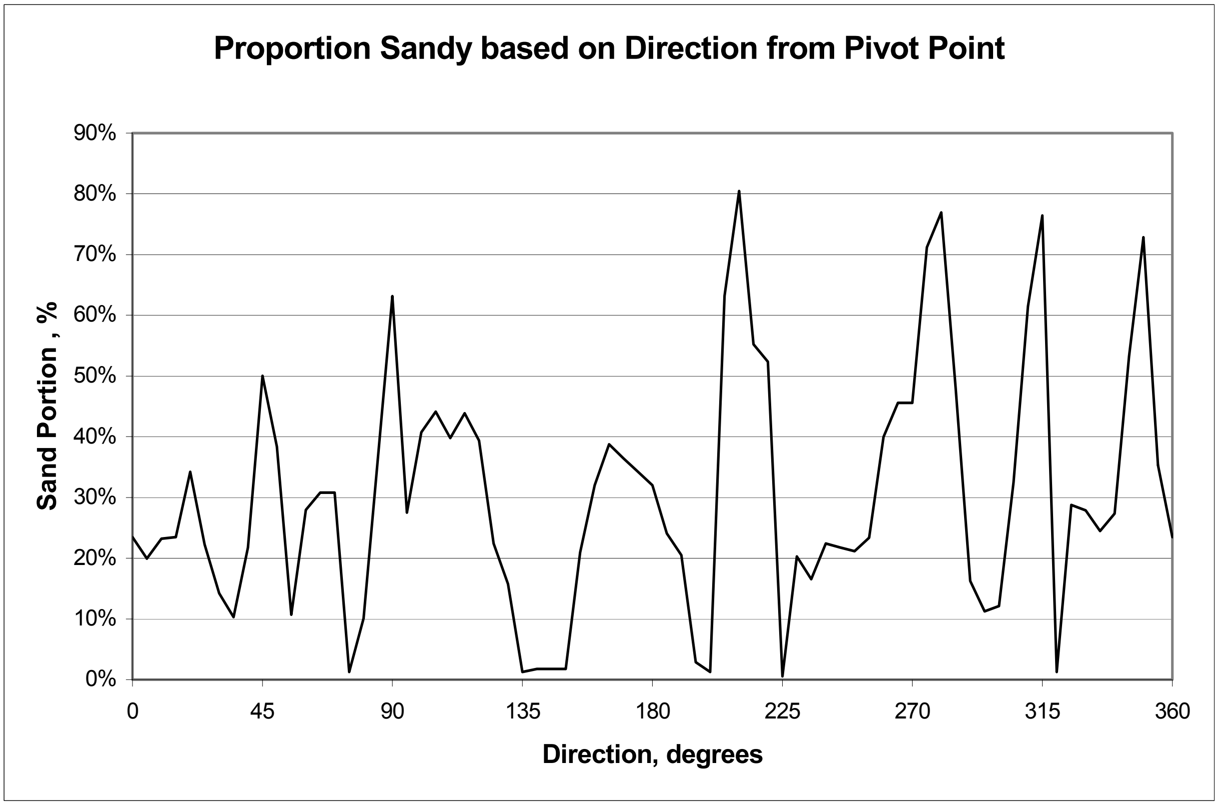

Fig. 4. The percentage of SAND in the pivot at various degrees of the compass.

The economic analysis was computed by assuming that the pivot could be operated for each crop in one of three ways:

1) Manage deficit/frequency by choosing a deficit that enhances yields and net returns for SAND soils
2) Manage deficit/frequency by choosing a deficit that enhances yields and net returns for SILT soils
3) Use a concept of precision irrigation where portions of the field would be managed based on which of the two deficit/frequency strategies provided highest net returns for that portion of the field.

Table 3 shows the results of the three strategies.

Table 3. Net returns from using the three possible irrigation management strategies on three separate crops.

Soil Type	Corn	Soybeans	Cotton
	------------------- $/acre -------------------		
SAND	$47.65	$46.19	$52.76
SILT	$47.62	$46.56	$82.25
Precision Irrigation	$47.67	$46.71	$84.68

CONCLUSIONS

Although the precision irrigation management strategy always produced the greatest amount of net profit, it must be pointed out that analysis did not include the added cost had the panel upgrade had to be purchased (around $2 to $3 per acre per year). In this case, only precision irrigation on cotton would be feasible. Assuming a $2.50 cost per acre per year for the upgrade, dollars would have been traded if the grower had been using the ideal deficit for silty soils (1.93 inches). However, if he had been using the ideal deficit for sandy soils (0.50 inches), then the precision irrigation strategy produced $29.42 per acre more net profit.

The driving factor in the economic feasibility of the panel up-grades as a means of precision irrigation is based on the difference in optimum net returns between the two soil types. In the case of corn and soybeans, the peak net return points for both soil types were very close to each other. In cotton, using the ideal deficit that produced the peak net return for the silty soils (1.92 inches per application) on the sandy soils caused a loss of $60.00 per acre on the sandy portions. Likewise, using the ideal deficit that produced the peak net return for sandy soils (0.50 inches per application) on the silty soils, likewise caused a net profit loss of about $60.00 per acre.

It is interesting to note that managing cotton by irrigating to the most vulnerable portion of the field (i.e., the sand), advice often given to producers, was not wise in this case.

Utilization of Controls for Managing Limited Water Supplies

By
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Summary:

Water for food, fiber and forage production continues to be a world concern. Currently most discussion about mechanical move irrigation systems focuses on the placement of the water. While where and how water is placed for irrigated crop production is critical, other components of an irrigation system are also important for the optimum management of water supplies.

This paper will focus on control options available for center pivot irrigation equipment and how these options help growers better manage limited water. Specific examples will be discussed. Data on the costs and benefits of manual and automated control will be included and compared. Data will include initial investment, operation and maintenance costs. In addition a brief discussion will be included on updating existing mechanized irrigation equipment to take advantage of the gains, which can be achieved.

Objective:

To discuss specific examples of how controls can assist a grower better manage limited water supplies when using center pivot irrigation equipment.

Introduction:

Since the energy concerns of the mid 1970's and drought cycles significant research and commercial development has been focused on reducing pumping costs and reducing the potential for wind drift and evaporation. Center pivots have seen a dramatic increase in improved irrigation efficiencies.

Recently more farmers have recognized due to limited or unknown water supplies, they need to change their management strategies to maximize returns. Besides concerns for maximizing water use efficiency, growers are also concerned with managing more center pivots with less labor as they irrigate more farmland. They have explore options including changing the method of irrigation. One option some consider is drip irrigation and particularly sub-surface drip (SDI). While drip and SDI in particular may reduce the volume of water required to irrigate it dose not meet the need in many cases for the flexibility of management and the grower's needs to reduced their labor input. SDI control systems tend to be more complex and costly. In addition changes to the system are costly and flexibility difficult to achieve.

Mechanical move irrigation equipment manufacturers have continued to develop controls to help make management of irrigation systems easier for growers since the early 1990s allowing maximum operational flexibility while reducing labor requirements.

When sufficient water supplies are not available to optimally irrigate an entire field and the grower has maximized their irrigation efficiency for their center pivot, new techniques are explored. One technique is to manage the entire pivot for reduced yields. Another technique is to split the field and raise two different crops - one with higher crop water needs than the other. Also more growers are varying their application rate by sectors for soil types. Controls to change the water application depth, reverse the equipment or to completely shut the water off are important to these scenarios. While it is possible to do many operations with mechanical control panels, many times it is easier, more dependable and more cost effective to do with automated control panels.

In addition to managing the water differently for the different crops, commonly the crops will have different nutrient requirements particularly nitrogen. Instead of the farmer needing to be in the field to make a change in the nitrogen application, an automated control panel may be used in conjunction with the fertilizer injection pump.

Lastly to maximize profitability farmers may want to manage the available water or nitrogen applied differently as the center pivot moves around the field and crosses varying soil types. Again an automated panel provides the flexibility to meet the farmer’s need.

Discussion:

In the past mechanical switches mounted on or around the pivot point were used to ‘trigger’ necessary changes to the pivot operation such as end gun shutoff, auto reverse, stops for service roads and application depth changes. These in some cases are difficult to change settings and do not offer flexibility of operation. In addition the number of changes is limited. Once the switches and stops are set most customer will not change the settings. Generally it is difficult to do more than one change or maybe two operation changes in the field due to the physical mounting of the switches.

Most mechanical move irrigation equipment manufacturer’s today offer both manual and automated control panels. To maximize the effectiveness of the automated panel, the position of the center pivot in the field is critical. Manufacturers’ use a variety of devices such as resolvers or encoders to provide a signal to the automated panel providing information on where the pivot is in the field, usually in degrees to a known reference point such as a road or North. Another piece of critical information is water pressure. Mechanical panels have switches with a single set point. Most automated panels are equipped for analog inputs from a pressure transducer. This allows decision making and programming for a range of pressures. In addition the automated panels have a variety of digital and analog inputs and outputs.

With these inputs and other information available at the pivot point, the automated control panel monitors pressure, wind speed, rainfall, position, voltage, control circuit status, operating direction and water status to name a few.

This information allows the operator to 'program' changes to the operation of the pivot based on the inputs and not have to be in the field to make the changes manually. Whether public power or an internal combustion engine provides power, an automated panel may be the best choice to meet the grower's needs to minimize labor and most efficiently manage available resources.

Examples (these are generalized scenarios and may not reflect actual situations but are designed to be instructive):

Example 1 – New 130 acre center pivot five miles from farmhouse, grower is limited on water to 15 inches during the growing season, center pivot is on public power. Typically the grower's primary crop requires 18 inches of water to produce optimum yields for his management system. The grower decides to split the field into two crops – one his primary and apply 18 inches and a second crop, which typically uses less water.

The grower has a couple of choices as how to manage this.

- Always be in the field to make the decision as to how to operate the center pivot
- Add the mechanical switches to a manual panel
- Utilize an automated panel and program crop operations

Typical costs to meet this customer need:

- Annual additional costs to manually operate the panel $ 1,125
    - Based on
      Labor cost of $45 per hour
      $0.32 mileage allowance

- Mechanical switches for a manual pivot panel $ 1,675
    - Switches to allow
      Autoreverse plus endgun shutoff
      Pressure

- Automated panel addition cost compared to a manual $ 2,745

The grower would have a payback of less than 2½ years over total manual operation and under 2 years over the mechanical switches for the investment in the automated panel. Plus the mechanical switches do not allow any flexibility such as programming on the automated panel to allow for varying operations on each revolution or based on sensor input.

Example 2 – New 130 acre center pivot ten miles from farmhouse, grower has two distinct soil types – approximately one half is loamy sand and the other half a clay loam and the center pivot and pump are on public power. Off-season most years the soil profile is recharged to near field capacity. On similar fields the grower has learned that early in the season he probably will need to begin irrigation on the loamy sand before the clay loam. The grower decides to use the same crop but manage the water applied differently.

The grower has a couple of choices as how to manage this.

- Always be in the field to make the decision as how to operate the center pivot
- Add the mechanical switches to a manual panel
- Utilize an automated panel and program the changes

Typical costs for this example

- Annual additional costs to manually operate the panel $ 1,690
    - Based on
      labor cost of $45 per hour
      $0.32 mileage allowance

- Mechanical switches for manual pivot panel $ 2,025
    - Switches to allow
      Autoreverse plus endgun shutoff
      Pressure
      Application depth changes

- Automated panel addition cost compared to a manual $ 2,745

In this example the grower would have a payback for the automated panel of less than 1½ years for either case and have the additional features of the automated panel.

Example 3 - Existing five year old 130 acre center pivot five miles from farmhouse with a mechanical panel, public power, grower is limited on water to 12 inches during the growing season instead of 18 he feels is necessary for optimum yield. Typically the grower's primary crop requires 18 inches of water to produce optimum yields for his management system. The grower decides to split the field into two crops - one his primary and apply 18 inches and a second crop, which typically uses less water.

Again the grower has a couple of choices as how to manage this.

- Always be in the field to make the decision as to how to operate the center pivot
- Add the mechanical switches to his existing manual panel
- Upgrade to an automated panel

Typical costs

- Annual additional costs to manually operate the panel $ 1,410
    - Based on
      labor cost of $45 per hour
      $0.32 mileage allowance

- Mechanical switches for manual pivot panel $ 1,515
    - Switches to allow
      Autoreverse
      Application depth changes
      Including labor to upgrade

- Automated panel $ 3,015
    - Conversion costs
      Assuming a modular panel
      Includes upgrade labor

The grower would have a payback of just over 2 years over total manual operation and under 2 years over the mechanical switches for the investment in the automated panel. And as stated earlier the mechanical switches do not allow flexibility such as programming so the pivot does not do the same operation on each revolution.

Conclusions:

With the changes growers are seeing requiring better and more efficient management this is moving them to consider center pivots with automated control panels. In many cases the payback can be within two years. In addition the automated panel will bring the grower other features not available in the manual panels such as diagnostics, record keeping and programming.

One area of concern to many growers as they consider automated panels is reliability and durability. As with other technologies in the agricultural sector the automated control panels used by center pivot manufacturers have under gone a number of changes since their introduction over ten years ago. These changes in many cases focused meeting the reliability and durability requirements of the farming community. Today due to changes in design and manufacturer in many cases the maintenance costs for an automated panel are similar to a manual panel. Plus the impact of transient and induced voltage has been greatly reduced due to improved printed circuit board design.

As shown by the three examples above in many cases farmers can see a payback in less than two years for the additional investment in an automated panel and may in many cases justify upgrading existing panels to better manage their available water resource and fertilizer.

As water resources for food, fiber and forage production continues to be a world concern and available time growers have to manage their irrigation is a challenge, more will move to mechanical move irrigation and automated control panels 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.

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 two 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.

Soil Moisture Sensors and Grower “Sense”Abilities: 3 Years of Irrigation Scheduling Demonstrations in Kern County

By Blake Sanden, Brian Hockett and Ronald Enzweiler

ABSTRACT

Starting Winter 2001 an irrigation scheduling demonstration program was initiated in Kern County by UC Cooperative Extension and the area Resource Conservation District Irrigation Mobile lab to instrument grower’s fields with neutron probe access tubes, tensiometers, electrical resistance blocks (Watermarks®) and a continuously recording data logger with a visual display that does not require downloading to a computer. Growers were faxed one page weekly irrigation scheduling recommendations also containing a seasonal summary of CIMIS ET estimates, soil moisture and applied water history. Additional fields on the Westside of Kern County were added to this program in 2002 as part of a CalFed Ag Water Use Efficiency project. More grower fields were set up in 2003.

A total of 101 fields covering 8,687 acres belonging to 21 different growers were instrumented over this time period covering 12 different crops, 11 soil textures and 9 different irrigation system types. The frequency of grower reference to field loggers and faxed irrigation schedules ranged from almost nil to very high; with a serious look at these soil moisture data averaging once every 7 to 14 days. Overall grower response was positive, with most stating that the program had made their irrigation more efficient and/or improved crop yield and quality. Often the degree of scheduling responsiveness was limited by ranch logistics and available labor. Many of these fields, primarily low volume systems using expensive water on the Westside, were near were optimal or deficit irrigated before entering the program, and, in some cases, soil moisture deficits recorded with this demonstration effort called for **increasing** applied water. The estimated water use efficiency (WUE) using crop ET calculated from local CIMIS weather station potential evapotranspiration (ETo) and appropriate crop coefficient values (Kc) divided by the applied water was very high, averaging 96% for 2002 (the most complete year). This estimate was almost identical to the 97% WUE determined by field measurement of soil water depletion with the neutron probe.

However, every grower has said that the most helpful part of the program has been the “human element” – direct interaction with the consultant through field/lunch meetings and phone calls. Despite the simplicity of the logger used in this study, most growers needed repeated visits to interpret soil moisture trends recorded by field data loggers and to explain the calculations used in faxed irrigation schedules.

INTRODUCTION

For more than a half century, a great deal of work has gone into the development of soil moisture monitoring technologies. Benchtop testing and field calibration in small plots and lysimeters are important activities and lend themselves well to generating scientific papers. Comparisons of heat dissipation blocks, gypsum blocks and tensiometers go back more than 60 years (Cummins and Chandler, 1940). Evaluation of the neutron probe was the hot topic of the 1960’s (Van Bavel et al., 1961) with some of the common generalities used for this old standard (i.e. probable error ~ 0.1 inch per reading or 6 inches of soil (Stone, 1960)) still standing today.

With the advent of the silicon revolution and desktop computers, microchips have created an exponential increase in the number of devices for monitoring and recording soil moisture changes. This now makes the sophisticated signal tracking needed for TDR and FDR (Time and Frequency Domain Reflectometry) processing possible in small package equipment. Capacitance changes of soil media due to changing water content have been long documented, but only in the last ten years have the size and expense of these type of sensors become feasible, not cheap – *feasible,* for field use. Papers on the calibration and comparison of these devices were common in the late 1990's (Paltineanu and Starr, 1997).

Growers have been inundated with the presence and promise of high tech offerings for the ag industry; from commodity trading on the internet to GPS driven tractor guidance systems and soil sampling. Whether you want real-time cotton prices, satellite imagery of your operation or web-based access of cell phone uplinked weather and/or soil moisture data from automated sensors installed in your field there are lots of vendors to sell you product. An internet search of "soil moisture sensor" returned more than 50,000 references!

The physics and complexity of tracking irrigation, drainage and crop water use can be intimidating for the most educated of farmers. When you throw in this dizzying area of technology, most growers see the exercise of "real-time irrigation scheduling/soil moisture/plant stress monitoring" not becoming easier, but actually becoming a bigger problem and expense than it's worth. A continuation of the old calendar scheduling approach means ranch logistics are not complicated with changing water schedules. Especially in the San Joaquin Valley, where we have no summer rain and May through August ETo does not vary significantly, a calendar driven irrigation schedule, especially with low-volume micro systems, can work very well. Grower's are not always convinced that there is a significant payback for adding additional monitoring into their decision making and farming expense.

Many orchard, vineyard and vegetable growers have tried using tensiometers. The appeal is that the device is simple to install/maintain and the principal of operation easy to understand. For about $150 you can install two of them at one location to give you an estimate of soil moisture "tension" at the 18 and 36 inch depths. Those who are convinced that this effort increased their profits usually continue using the device, but even many of them get busy in the middle of the season and do not maintain a sufficient internal water level and/or lose track of the record of readings. A small minority of growers (mostly winegrape growers and some orchards) know that they don't have the inclination or expertise to mess with monitoring and they will hire an irrigation consulting service for $15 to $20/acre (San Joaquin Valley). A neutron probe monitoring service is about $800/site.

More recently a more reliable variation of the old gypsum block, a "granular matrix" modified electrical resistance block made by Irrometer called the Watermark® has gained popularity with some growers and consultants as in inexpensive and "maintenance free" alternative to the tensiometer. At about $30 each, these sensors are currently the least expensive on the market. Recognizing the potential acceptance and value of these simpler devices some university ag extensionists have continued to examine the accuracy of the tensiometer and Watermark® blocks and compare them to some of the high tech sensors in publications more accessible to growers (Hanson, et al., 2000).

At issue is technology transfer and proving the value of potentially expensive equipment. And there's the rub, combine the variability of soils, crop type, different irrigation systems and grower management from one farm to the next and it is nearly impossible to guarantee the benefit of any one particular monitoring system. As a University of California irrigation extension advisor there is only one consistent answer I can give growers when I'm asked, "What's the best way to monitor my irrigation and crop ET?" – I reply, "Depends!"

This is not a satisfactory answer for most growers, who want a simple answer with a guaranteed benefit. Fortunately, most growers realize that optimal profit for their operation "depends" on a lot of variables and most of their decisions have some element of risk. But if an input, such as soil moisture monitoring, is not perceived as absolutely essential then growers will only "risk" the use of that input if: 1) the cost is minimal, say $10/ac, and will not eat up a big part of the crop profit margin, 2) they understand the how, when and why of using that input and the final benefit to crop performance.

These two factors, minimal cost per acre and simplicity of concept/use, were the two constraints that underlay the last three years of soil moisture monitoring/irrigation scheduling demonstrations in Kern County.

PROCEDURES

A total of four programs with different funding sources have been used to carry out field instrumentation and grower demonstrations. (Programs (1) and (3) had additional objectives beyond those covered below.)

1) Sugarbeet Nitrogen Fertilization & Irrigation Scheduling Demonstrations for 2001 & 2002 (California Beet Grower's Association)
2) Kern County Irrigation Scheduling Demonstrations (Pond-Shafter-Wasco Resource Conservation District Mobile Irrigation Lab and CA Dept. of Water Resources)
3) Quantification of Benefits Attributable to Irrigation Scheduling as an On-Farm Water Management Tool (CALFED Water Use Efficiency Program, CA Dept. of Water Resources)
4) Kern County Grower Cost Share Program for Soil Moisture Monitoring (Individual Kern growers and the PSWRCD Mobile Irrigation Lab)

Core objectives of soil moisture monitoring/scheduling demonstrations:

1) Demonstrate efficient irrigation scheduling using a combination of:
    a Historical ET
    b "Real time" CIMIS ETo updates and crop Kc
    c Soil moisture monitoring
2) Evaluate the uniformity and water use efficiency for a variety of crops, irrigation systems and soil types.
3) Evaluate and compare different methods of soil moisture monitoring using weekly readings of:
    a. Neutron probe – total water content
    b. Tensiometers – soil moisture "tension"
    c. Watermark – electrical resistance estimate of soil moisture "tension"
4) Compare continuous monitoring with an inexpensive logger using Watermark resistance blocks to weekly monitoring. Evaluate grower "friendliness" and usefulness of method.
5) Interest growers in purchasing soil moisture sensors/logger system to improve water crop performance and dedication to more than "seat-of-the-pants" scheduling.

Key technology assumptions for grower response and program success:

- "One-shot" soil moisture estimates (tensiometers, soil moisture feel, etc.) are often poorly recorded and give growers an incomplete picture of the dynamic water content changes in the crop rootzone.

- Grower use of soil moisture monitoring will increase significantly if the monitoring system costs are about $10/acre. This includes monitoring multiple depths and locations.
- Equipment is easy to install, requires little/no maintenance and will perform for several years.
- Real-time soil moisture trends over the last 4 to 6 weeks are logged so that **they may be viewed at the field** any time without time-consuming downloads and data processing.
- Graphic displays of soil moisture changes, as opposed to one or a series of numbers, will be most easily understood be growers.

EQUIPMENT & FIELD LAYOUT

At present, the only sensor/logger combination that fulfills the above requirements utilizes six Watermark® blocks (manufactured by the Irrometer Co,) and the AM400 logger (M.K. Hanson). The resistance across the stainless steel electrodes embedded in these sensors has been calibrated to give an approximation of the soil matric potential (soil moisture "tension") equivalent to a tensiometer reading. The AM400 logger performs this calibration and stores one reading (from 0 to 199 centibars) for each of up to 6 sensors every 8 hours. A thermistor comes with the logger to provide for soil temperature correction of the readings.

The unique feature of this logger compared to other inexpensive loggers now on the market is the graphic LCD screen about 1.5" tall by 3" wide that, with the push of one button, displays a chart of the last 5 weeks of data (105 records) for a particular sensor without having to do a data download to a laptop or hand-held PC. A numeric display at the top of the LCD gives the sensor, soil temperature and current soil moisture. The button is pressed up to 6 times to view each of the sensors. Though an entire season of data can be stored on this logger, the face plate must be removed for access to the serial port for downloading. A simple graphing software is provided by the manufacturer, but all logger programming is fixed at the factory. The benefit of this approach allows a grower to install such a system without ever having to hook up to a computer. Inexpensive Category 3, 24 gauge communication wire can be used to hook up to sensors as far away as 1000 feet. Retail cost for 6 sensors, 1 logger, 1000 feet of 4 pair-Cat3 wire and a 4x4 post is about $650. Figure 1 illustrates a typical layout for a furrow field.

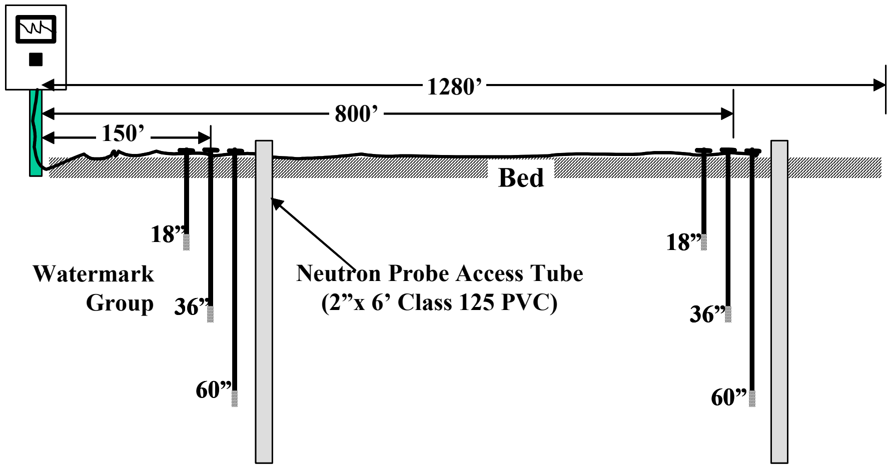
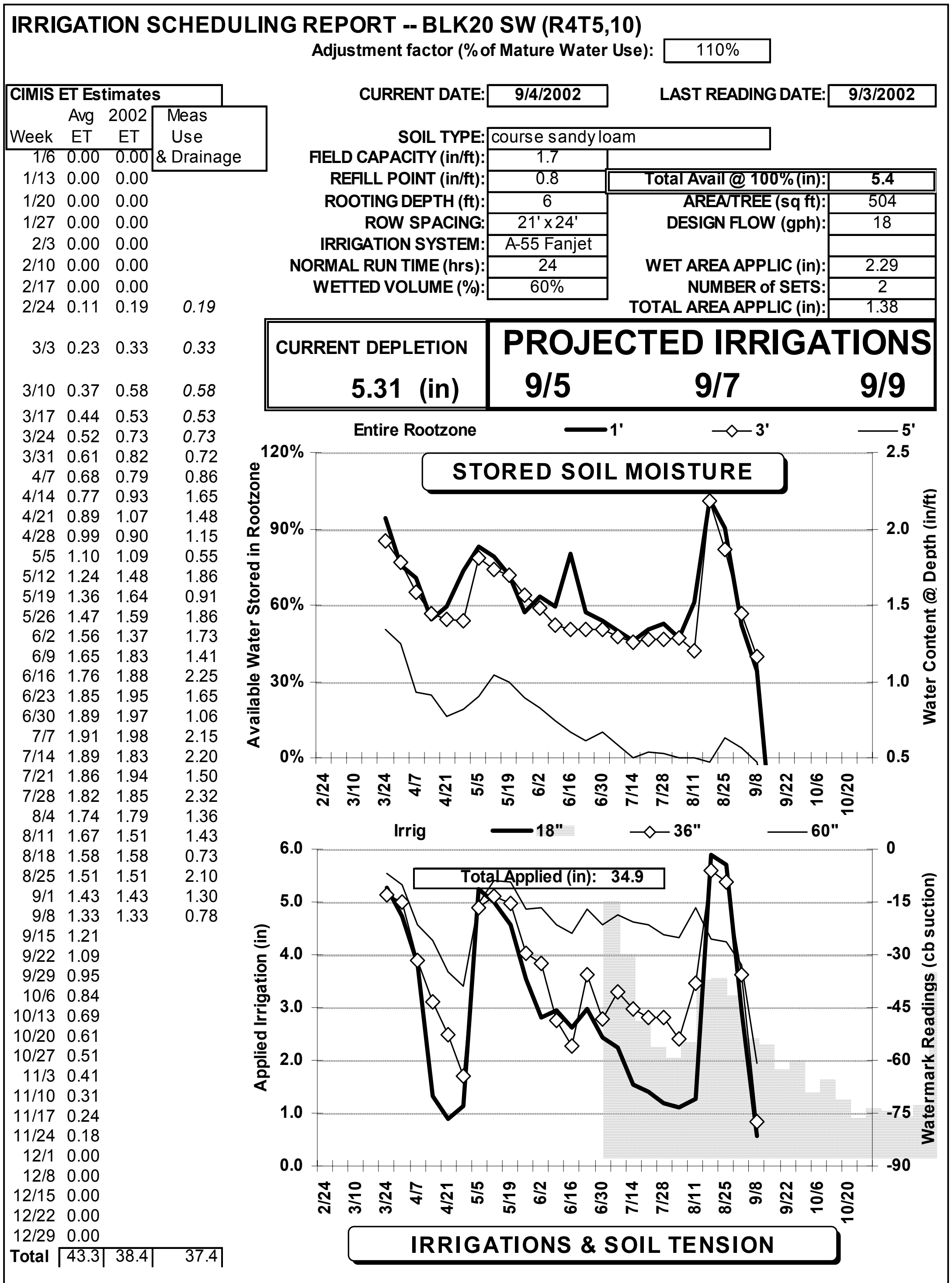


Fig. 1. Typical field layout of monitoring sites with surface irrigation. Spacing of Watermark sensor groups varied according to irrigation system, but usually set @ 18, 36 and 60 inch depths. (Not to scale.)

Watermark sensors were glued to the ends of ½" Schedule 315 PVC pipe cut to the desired installation length. A "tee" was glued to the top to facilitate installation and removal in annual crops. A PVC access tube was installed within 1 foot of all sensor groups at all sites to allow for neutron probe water content measurements to a depth of 6 feet with the exception of 8 systems installed this year. Growers purchased these systems, we assisted in the installation and they have been monitoring them on their own this season. (Some CalFed project fields are monitored only with the neutron probe.) In permanent crops with micro systems, sensor groups were placed near the end of the hose and by the "tee" in a 'typical' row. Small household-scale flowmeters were also installed in the hose serving the monitoring site to get an exact record of applied water. In some almond orchards, sensors were placed by a Nonpareil tree and wire buried under the drive row to a sensor group installed on the adjacent pollinator variety. In some vineyards and one subsurface drip irrigated almond orchard more information about the degree of subbing from the drip hose was desired and sensors were buried at a 2 foot depth at a 2 to 6 foot distance from the hose.



IRRIGATION SCHEDULING REPORT -- BLK20 SW (R4T5,10)

Adjustment factor (% of Mature Water Use): 110%

CURRENT DATE: 9/4/2002
LAST READING DATE: 9/3/2002
SOIL TYPE: course sandy loam
FIELD CAPACITY (in/ft): 1.7
REFILL POINT (in/ft): 0.8
Total Avail @ 100% (in): 5.4
ROOTING DEPTH (ft): 6
AREA/TREE (sq ft): 504
ROW SPACING: 21' x 24'
DESIGN FLOW (gph): 18
IRRIGATION SYSTEM: A-55 Fanjet
NORMAL RUN TIME (hrs): 24
WET AREA APPLIC (in): 2.29
WETTED VOLUME (%): 60%
NUMBER of SETS: 2
TOTAL AREA APPLIC (in): 1.38

CURRENT DEPLETION 5.31 (in)

PROJECTED IRRIGATIONS 9/5 9/7 9/9

CIMIS ET Estimates			
Week	Avg ET	2002 ET	Meas Use & Drainage
1/6	0.00	0.00	
1/13	0.00	0.00	
1/20	0.00	0.00	
1/27	0.00	0.00	
2/3	0.00	0.00	
2/10	0.00	0.00	
2/17	0.00	0.00	
2/24	0.11	0.19	*0.19*
3/3	0.23	0.33	*0.33*
3/10	0.37	0.58	*0.58*
3/17	0.44	0.53	*0.53*
3/24	0.52	0.73	*0.73*
3/31	0.61	0.82	0.72
4/7	0.68	0.79	0.86
4/14	0.77	0.93	1.65
4/21	0.89	1.07	1.48
4/28	0.99	0.90	1.15
5/5	1.10	1.09	0.55
5/12	1.24	1.48	1.86
5/19	1.36	1.64	0.91
5/26	1.47	1.59	1.86
6/2	1.56	1.37	1.73
6/9	1.65	1.83	1.41
6/16	1.76	1.88	2.25
6/23	1.85	1.95	1.65
6/30	1.89	1.97	1.06
7/7	1.91	1.98	2.15
7/14	1.89	1.83	2.20
7/21	1.86	1.94	1.50
7/28	1.82	1.85	2.32
8/4	1.74	1.79	1.36
8/11	1.67	1.51	1.43
8/18	1.58	1.58	0.73
8/25	1.51	1.51	2.10
9/1	1.43	1.43	1.30
9/8	1.33	1.33	0.78
9/15	1.21		
9/22	1.09		
9/29	0.95		
10/6	0.84		
10/13	0.69		
10/20	0.61		
10/27	0.51		
11/3	0.41		
11/10	0.31		
11/17	0.24		
11/24	0.18		
12/1	0.00		
12/8	0.00		
12/15	0.00		
12/22	0.00		
12/29	0.00		
Total	43.3	38.4	37.4

Fig. 2. Typical irrigation schedule for permanent crop low volume system. "CIMIS ET Estimates" are historical and real time values from the nearest weather station multiplied by appropriate crop coefficients. "Measured Use & Drainage" is calculated from neutron probe depletion.

Project tensiometers were used in a total of 9 fields over the years for comparison to Watermark readings, but only for the 18 and 36 inch depths. In these settings the Watermark and tensiometer were installed within 4 inches of each other. All monitored project sites were visited weekly during the season for 1 to 2 years depending on entry into the demonstration program. Data was recorded, averages of the weekly readings compiled for the two sites in a given field and the results faxed to the grower in a weekly report showing accumulated water content changes and recommended irrigation dates.

RESULTS

Figure 2 at the left shows a typical weekly schedule for a microsprinkler almond orchard. Neutron probe (NP) readings (indicated under "Stored Soil Moisture") show a more dramatic decline in soil moisture at the 5 foot depth than does the Watermark (WM) reading, but in general the WM readings are a good indication of changing water status. Both methods indicate slow drying in the lower rootzone; indicating slight deficit irrigation with almost no water lost to deep percolation. This farming company uses an in-house irrigation manager scheduler.

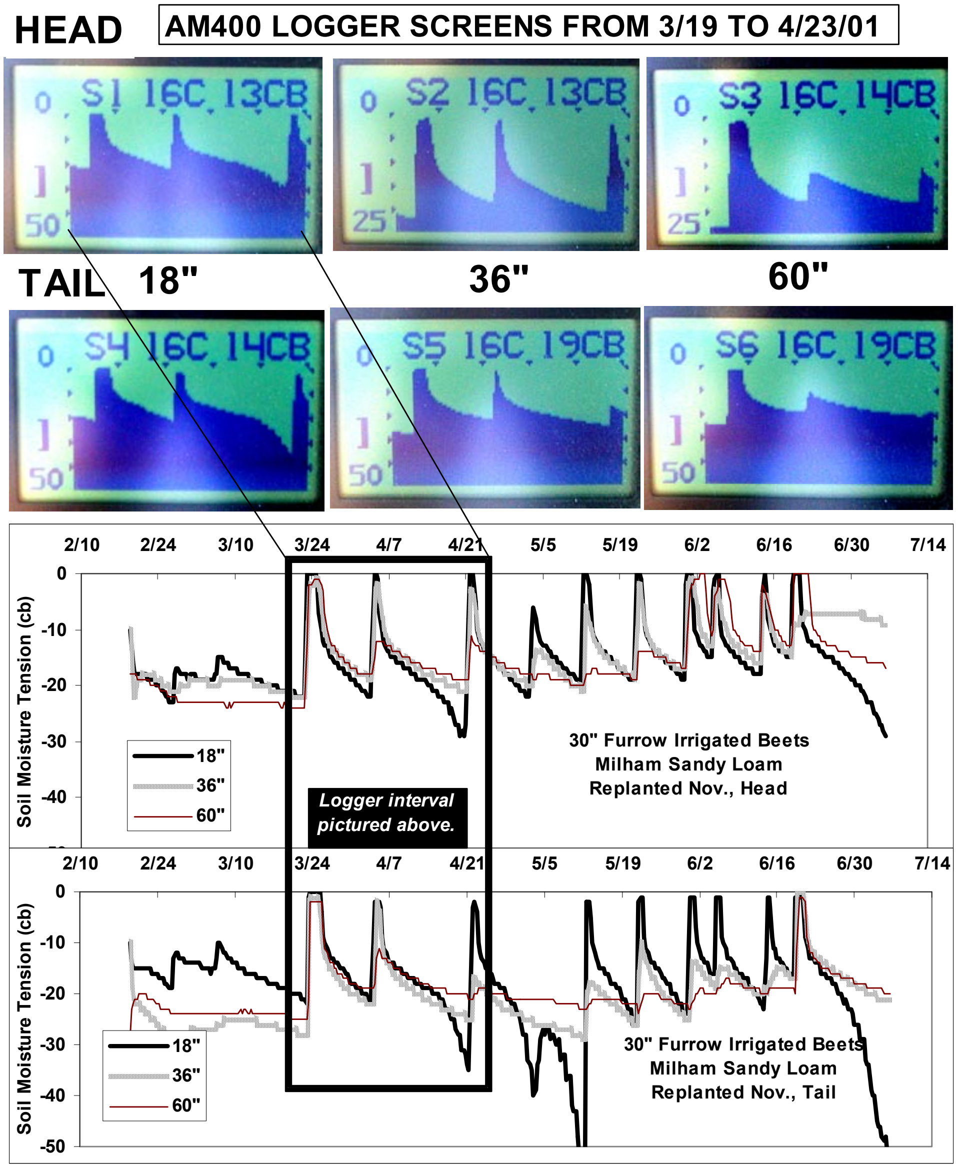


Fig. 3. Logger screen displays (top) for all Watermark sensors for 3/19-4/21/01. This monitoring period is bracketed in the season-long charts shown below. Total applied water was 38" with actual ET estimated @ 31". Alternate furrow irrigation using siphons on a 1280 foot run.

Contrast Figure 2 with Figure 3, furrow irrigated sugarbeets on a Milham sandy loam. The top part of the figure shows the screens as they appear on the logger just as a grower would view them while looking at the field. The charts below are created from a download of the logger at the end of the season. The value of real-time continuous monitoring is perfectly illustrated by this figure. The sharp peaks up to 0 cb indicate transitory saturation during irrigation at the 18, 36 and occasionally 60" depths. These are followed by a quick falloff down to about -10 cb with a slower, more even decline starting about 2 days after irrigation that represents actual crop water use. These figures clearly indicate that the irrigation schedule is too frequent – causing a significant amount of deep percolation (the sharp peaks). Weekly, 'one-shot' observations of soil moisture can not provide as clear a picture of this dynamic (and wasteful) water movement. This grower wanted to "keep the beets wet and leach the nitrate out of the rootzone to get better sugar" … and had to add water-run N fertilizer in April. Even with personal consultations he saw little need to change what he was doing in 2001 or 2002.

Calibration to actual water content and consistent performance of soil moisture sensors are the two biggest concerns always raised with these devices. Hanson, et al. (2000) in looking at 5 different soils found correlation coefficients of determination (r^2 values) of 0.67 to 0.83 for calibration curves developed for the NP by volumetric soil sampling. This degree of variation is often due more to volumetric sampling errors and natural soil variability than the instrument itself. The average correlation coefficient relating the NP water content to WM readings of soil 'tension' (an instrument to instrument comparison) was 0.87 with a standard deviation of 0.13. Even though the WM calibration is supposed to align with tensiometer readings, Hanson reported 66% of tensiometer readings were higher than WM readings.

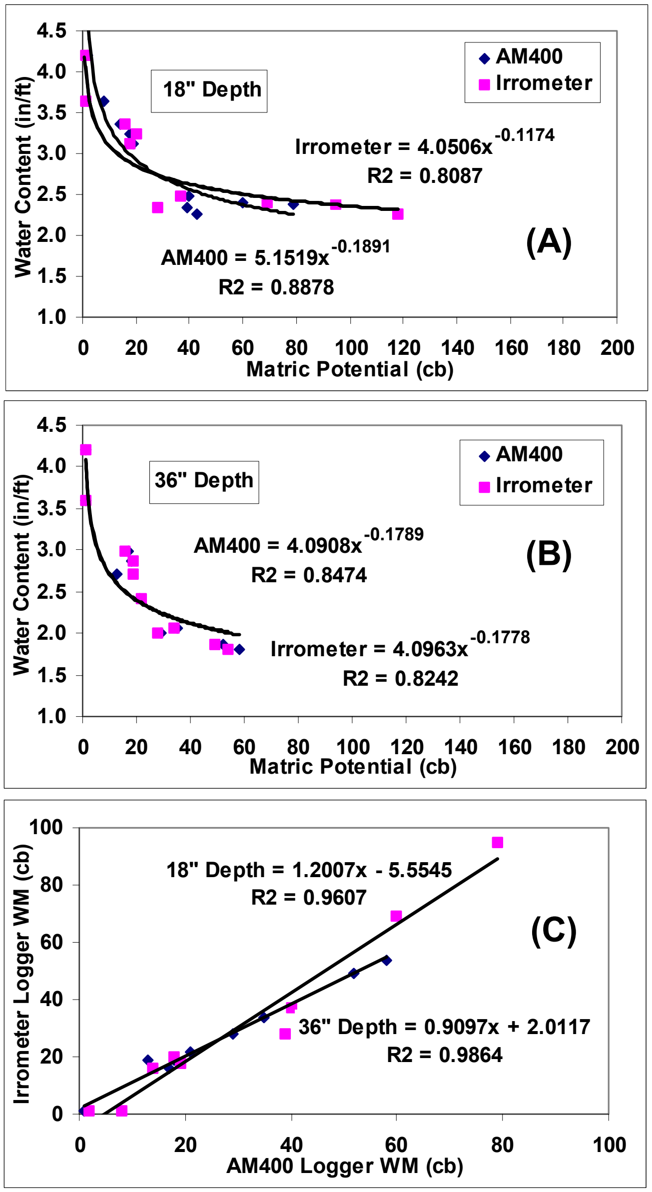


Fig. 4. Soil moisture release for a Lerdo complex clay loam in winter wheat (spring 2003) with water content decline as a function of matric potential as estimated by Watermark blocks attached to two different loggers (a), (b). Relationship of paired WM readings at the 18 and 36" depths (c).

These figures are similar to what we've seen in one area of the Kern Demonstration Project. In a comparison of the AM400 logger to a beta version of the Irrometer logger in wheat in 2003 we found an average r^2 value of 0.86 with a standard deviation of 0.036 for six WMs in a Lerdo clay loam (Figure 4). However, a very strong difference in soil moisture release can be seen between the 18 and the 36" depths due to a slightly higher sand content @ 36".

Problems with Absolute Numeric Thresholds and Accurate Sensor Calibration

Figure 4c. shows excellent correlation of WM sensors at the same depth for the two different loggers (>0.96), but close examination reveals the difference in predictive slopes is about 30%. Is this a difference in loggers or WM quality control? Probably not! In this case, the paired WMs that are correlated against each other are installed to the same depth (one set @ 18" and another set @ 36") and are only 4" apart. Even over this small distance it is possible to have enough soil textural/root density changes to significantly change what should be a 1:1 relationship. This difference clearly shows the limitations of exact calibration and using absolute numeric thresholds of soil tension and/or water content for deciding when to irrigate.

The problem is further underscored by the correlations with tensiometer and WM readings from our first year of the project. Using 7 fields with tensiometers installed at the 18 and 36" depths with 2 WM sensor groups and NP access tubes we ended up with 28 pairs of instruments to compare. Soil textures ranged from coarse loamy sand to sandy clay loam. A slurry of finer soil was added into the installation holes on the coarse textured soils. For determining tensiometer values as a function of WM readings the average of all regression slopes was 0.95 with a mean intercept of 10.5 and a mean r^2 of 0.645. Not bad in general, but the standard deviation of the slope and r^2 values was 0.61 and 0.23, respectively.

Table 1, following, lists the average season-long matric potential at the 5 foot depth, along with two estimates of irrigation efficiency and project rating characteristics by irrigation system, soil texture and crop for the 2001 and 2002 seasons.

Table 1. Various soil moisture, calibration, irrigation efficiency and project rating characteristics by irrigation system, soil texture and crop for the 2001 and 2002 seasons. 2003 data has not been collated.

Criteria	No. Fields	[1]Avg. 5' WM (cb)	[2]Mean Soil Moisture Release R^2 Best	Worst	[3]Irrigation Efficiency Estimate CIMIS	Meas.	[4]Sensor Performance	[4]Grower Use Ratings Logger	Faxed Sched.	Consultation	[4]General Efficiency Rating Original Grower	Demo Program
IRRIGATION SYSTEM												
Border	11	-39	0.62	0.15	100%	92%	2.0	2.0	1.7	1.8	2.3	2.4
Drip	21	-63	0.64	0.22	94%	97%	2.9	2.4	1.9	2.0	2.7	2.9
Drip SDI	1	NA	NA	NA	NA	NA	3.0	1.0	1.0	1.5	2.5	2.5
Drip Tape	3	NA	NA	NA	NA	NA	2.7	1.9	1.7	1.6	2.4	2.5
Fanjet	28	-59	0.70	0.18	98%	99%	2.7	2.2	1.6	1.9	2.8	2.9
Furrow	29	-20	0.79	0.21	90%	88%	2.8	1.3	1.4	1.8	1.3	2.1
Sprink/Furrow	1	-20	0.97	0.39	100%	100%	1.5	2.0	1.5	1.5	2.0	2.5
Sprnk-Big Gun	5	-30	0.47	0.05	99%	100%	2.2	1.0	1.0	1.5	2.3	2.3
Sprnk-Hnd Mv	7	-37	0.84	0.10	100%	92%	2.6	1.0	1.3	1.5	2.5	2.5
	Average	**-38**	**0.72**	**0.18**	**97%**	**95%**	**2.5**	**1.6**	**1.4**	**1.7**	**2.3**	**2.5**
SOIL TEXTURE												
C	2	-17	0.47	0.03	96%	92%	3.0	1.8	2.0	2.0	1.5	2.5
CL	14	-11	0.83	0.35	90%	89%	3.0	1.2	1.4	2.0	1.1	2.2
SiL	3	-30	NA	NA	91%	86%	2.3	2.0	2.3	2.0	2.7	2.5
SCL	16	-49	0.78	0.23	99%	97%	2.7	1.5	1.4	1.6	2.4	2.5
L	27	-48	0.71	0.12	98%	94%	2.5	1.7	1.4	1.8	2.6	2.6
csL	4	-13	0.75	0.07	87%	100%	3.0	1.4	1.3	1.1	2.3	2.4
fSL	5	-69	0.91	0.49	100%	97%	2.6	1.7	1.3	1.8	1.8	2.4
SL	25	-52	0.63	0.15	96%	96%	2.6	2.1	1.7	1.9	2.5	2.7
csSL	4	-29	0.50	0.23	83%	100%	2.6	2.5	1.5	2.3	2.4	2.6
LS	5	-44	0.71	0.30	90%	96%	2.7	2.3	1.7	1.9	2.3	2.5
csLS	1	-32	0.55	0.17	100%	100%	2.5	3.0	2.5	2.5	3.0	3.0
	Average	**-36**	**0.68**	**0.21**	**94%**	**95%**	**2.7**	**1.9**	**1.7**	**1.9**	**2.2**	**2.5**
CROP												
Alfalfa	6	-28	0.50	0.07	99%	100%	2.1	1.1	1.0	1.5	2.3	2.3
Almond	32	-59	0.69	0.18	98%	99%	2.6	2.1	1.7	1.9	2.8	2.9
Citrus	3	-13	0.75	0.07	87%	100%	2.8	2.5	1.5	2.3	2.2	2.7
Cotton	21	-27	0.83	0.19	95%	91%	2.9	1.1	1.4	1.9	1.6	2.4
Grape	14	-53	0.59	0.23	96%	92%	2.6	2.5	2.0	2.2	2.4	2.7
Melons	1	-39	0.52	0.01	100%	73%	1.0	2.0	1.0	1.5	2.5	2.5
Peppers	1	NA	NA	NA	NA	NA	3.0	1.5	NA	0.5	2.5	2.5
Pistachio	10	-62	0.66	0.14	96%	92%	2.8	2.0	1.6	1.7	2.9	2.8
Snap Beans	1	NA	NA	NA	NA	NA	3.0	1.5	NA	0.5	2.5	2.5
Sugar beet	7	-18	0.69	0.10	89%	89%	2.9	1.6	1.7	1.6	1.9	2.3
Tomatoes	3	-20	0.97	0.39	100%	100%	2.5	2.0	1.5	1.3	1.8	2.2
Wheat	8	-4	0.95	0.32	82%	79%	2.7	0.5	1.0	1.4	1.0	1.6
	Average	**-32**	**0.71**	**17%**	**94%**	**92%**	**2.6**	**1.7**	**1.4**	**1.5**	**2.2**	**2.4**
	***Project Means**	**-46**	**0.69**	**0.18**	**96%**	**95%**	**2.7**	**1.8**	**1.5**	**1.8**	**2.3**	**2.5**

[1] Season long average matric potential at a 5 foot depth as recorded by a WM sensor.

[2] Mean correlation coefficient R2 for paired WM and NP water content readings. Does not include 2003 data.

[3] Water use efficiency estimated by 1) dividing a CIMIS weather station season long crop ET by the applied water and 2) dividing the Project measured water content depletion by the applied water for the season.

[4] Sensor Performance, Grower Use Ratings and General Efficiency Ratings are anecdotal estimates by project staff and cooperators on the degree of use/benefit of various project aspects. "0" is no use/benefit, with "3" being high.

For most project fields, regressions of WM readings with NP data have yielded more than one usable soil moisture release curve. The mean “Best” R^2 value given in Table 1 is the mean value of the best curve fit from each field. The “Worst” value is the mean of the worst of the field curve fits. In general, results are fairly similar for all three categories. The notable exception being that of furrow irrigation and cotton. These reveal the greatest improvements in general efficiency going from a 1.3 to a 2.1 rating for furrow irrigation and attaining an 88% water use efficiency.

CONCLUSION

The point is that the perfect installation and highly calibrated instrument reading is seldom going to occur in large production field settings. Grower’s “sense” abilities are quick to grasp this fact. We have made some progress in increasing these abilities during the last three years of field work. Some growers have simply changed the frequency on their calendar scheduling, but this is still and improvement. A few others have embraced the idea have “push button information” on soil moisture. The following points should be emphasized:

1. Growers need access to a consultant or farm advisor to help navigate the maze of monitoring technology.
2. Even with experienced help for installation, soil and crop rooting variability make exact calibration nearly impossible. Tracking the ‘relative’, dynamic changes in soil moisture is most easily done by continuous data logging and graphical presentation of real-time data.
3. Growers will only take advantage of this data if they can understand the presentation and access these charts quickly, reliably, and probably for less than $10 to $15/acre.
4. The most significant gains to be made by this type of monitoring are in annual, furrow irrigated row crops. These are also the tougher locations to install (and subsequently remove) monitoring equipment.
5. Out of nearly 500 Watermark installations only 3 sensors were unresponsive. Only one logger out of 80 was found to be defective and was quickly replaced by the manufacturer. The Watermark/AM400 logger systems can last for at least 3 years.
6. Average water use efficiency for Kern County Demonstration Fields has proven to be quite high. Benefits of soil moisture monitoring and scientific irrigation scheduling will likely come in the form of higher crop yields and NOT WATER SAVINGS.

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Precise Irrigation Scheduling Using Soil Moisture Sensors

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The efficient use of irrigation water requires several kinds of information. One element of an efficient irrigation scheduling is monitoring the soil to assure that the crop irrigation goals are being met. Various soil moisture measuring devices have been tested for irrigation scheduling in silt loam and sandy loam. Aquaflex, Gro-Point, Moisture-Point, neutron probe, tensiometer, Watermark soil moisture sensor and Gopher probes were compared. Several sensors were tested as read automatically by a datalogger and read manually with a hand-held meter. Practical suggestions are provided to use soil moisture sensors to the benefit of crop production and water conservation.

Introduction

Precise irrigation scheduling is necessary to optimize marketable yield of high value crops while conserving water and protecting water quality. Irrigation scheduling is greatly facilitated by any soil moisture sensor which can provide timely and responsive information on soil water or soil water potential status. For a particular sensor to be useful for a particular crop and soil, it needs to respond rapidly and reliably to the range of variation of water status in that soil which is important for marketable yield. Several sensors were tested for their responsiveness and usefulness for irrigation scheduling in soils typical of the Treasure Valley of the Snake River Plain of Oregon and Idaho.

Materials and Methods

Experiment 1. Six soil moisture sensors were compared by their performance in response to wetting and drying in a micro sprinkler irrigated hybrid poplar plantation at the Malheur Experiment Station in Ontario, Oregon.

The trees had been planted in April 1997 on Nyssa-Malheur silt loam soil on a 14-ft by 14-ft spacing. The tree rows are oriented to the northwest. The trees are irrigated using a micro sprinkler system (R-5, Nelson Irrigation, Walla Walla, WA) with the risers placed between trees along the tree row at 14-ft spacing. The sprinklers delivered water at the rate of 0.14 inches/hour at 25 psi and a radius of 14 ft. The area used for the sensor performance trial was managed to receive two inches of water whenever the soil water potential at 8-inch depth reached -50 kPa.

Two Aquaflex sensors (Streat Instruments, Christchurch, New Zealand) were installed on September 14, 2000. Each sensor was installed at 8-inch depth along the tree row and between two trees. The two Aquaflex sensors were connected to an Aquaflex datalogger. On July 23, 2001, six types of soil moisture sensors were added to the study. One sensor of each type was installed in four groups adjacent to the existing Aquaflex sensors. The position of each sensor was randomized between groups. The sensors in each group were installed in a line parallel to and approximately 8 inches from the Aquaflex sensors. The sensors were installed at 8-inch depth. Each Aquaflex sensor had a group of sensors on each side. The sensors added to the study were tensiometer (Moisture Indicator, Irrometer Co., Riverside, CA), Watermark soil moisture sensor model 200SS (Irrometer Co. Inc., Riverside, CA), Neutron Probe model 503 DR hydroprobe (Boart Longyear, Martinez, CA), Moisture Point (Environmental Sensors Inc., Escondido, CA), Gro Point (Environmental Sensors Inc., Escondido, CA), and Gopher (Cooroy, Queensland, Australia). The four Gro Point sensors were connected to two Gro Point 3 channel data loggers. The Watermark sensors were connected to an AM400 Soil Moisture Data Logger (M.K. Hansen Co., East Wenatchee, WA). All other sensors were read manually at 9:00 a.m. from Monday through Friday. The tensiometers and Watermark sensors measure soil water potential. The other sensors use various techniques to measure volumetric soil water content.

The tensiometer and Watermark sensors required that a hole in the soil be made with a standard 7/8-inch diameter soil auger for installation. The tensiometers required regular resetting due to the column of water breaking suction around -60 to -70 kPa. The Gro Point sensor was relatively compact and was easy to bury. The neutron probe and the gopher required the installation of PVC access tubes for each monitored location. The Moisture Point used a 3-ft probe permanently installed at each location to be monitored. The Moisture Point probe required a hole made with a probe provided by the company for installation. The neutron probe, Gopher, and Moisture Point allowed measurement of soil moisture at different depths at each location. The Aquaflex was 10 ft long and was installed horizontally, requiring a 10-ft trench dug to the depth of installation.

Both the neutron probe and Gopher required site specific calibration. One undisturbed core soil sample was taken in each instrument location during sensor installation. The soil samples were immediately placed in tin cans and weighed, then oven dried at 100°C for 48 hours and weighed again. Volumetric soil moisture content was calculated for the soil samples using the gravimetric method. After the sensors were installed, 2 inches of water was applied. On July 25, another set of soil samples was taken and volumetric soil moisture content was determined as before. The sensors were read at the same time as the soil samples were taken. The neutron probe was read as counts during 32 seconds. The volumetric soil water content determined from the soil samples was regressed against the neutron probe and gopher readings. The coefficient of determination (r^2) for the regression equation for the neutron probe was 0.93 at $P = 0.01$. The regression equation was used to transform the neutron probe readings to volumetric water content. A calibration for the Gopher sensor was not possible due to a lack of correlation between the gopher readings and the volumetric soil water content determined from the soil samples. The average soil moisture data from the neutron probe and from the tensiometers was compared using regression against the average soil moisture data for each of the other sensors.

Experiment 2. Six soil moisture sensors were compared by performance in their response to wetting and drying in a drip-irrigated potato field at the Malheur Experiment Station in Ontario, Oregon. The sensors were Aquaflex, Gro Point, Moisture Point, Neutron Probe, tensiometer, and Watermark. The Watermark sensor was tested as read automatically by a datalogger and read manually with a hand-held meter, model 30 KTCD-NL (Irrometer Co., Riverside, CA), as previously calibrated (Shock et al., 1998).

Potato seed of cultivar 'Mazama' was planted on April 26, 2002 in rows spaced 36 inches apart. The potato seed pieces were spaced 9 inches apart in the row. The soil was an Owyhee silt loam with a pH of 8.1 and 2 percent organic matter. Drip tape (T-tape, T-systems International, San Diego, CA) was laid at 4-inch depth between two potato rows. The drip tape had emitters spaced 12 inches apart and a flow rate of 0.22 gal/min/100 ft. The crop was irrigated daily to replace the previous day's evapotranspiration. Potato evapotranspiration (Et_c) was calculated with a modified Penman equation (Wright 1982) using data collected at the Malheur Experiment Station by an AgriMet weather station. From July 15 to July 25 and again from July 30 to August 7, the crop was not irrigated to evaluate sensor performance under variable soil moisture, during both wetting and drying conditions.

In mid-June the sensor study was installed along one of the potato rows. Six types of sensors were installed between the drip tape and the potato row. The sensors were installed 8 inches from the drip tape and 10 inches from the potato row. The sensors were centered at 9-inch depth. The experimental design was a randomized complete block design with four replicates. These instruments were installed, managed, and calibrated as in experiment 1 above.

Experiment 3. The response of Watermark soil moisture sensors to irrigation events and the termination of irrigation was read automatically using an AM400 Hansen datalogger and an Irrometer Watermark Monitor (Irrometer Co.).

Automated reading of Watermark soil moisture sensors was done in a furrow-irrigated Greenleaf silt loam planted to onions. The sensors were installed with their centers 8 inches deep directly below the onion plants. The sensors were installed in the lower part of the field where the furrow irrigations were less effective at wetting the soil. Six Watermark soil moisture sensors and a temperature probe were connected to an AM400 Hansen datalogger which read the sensors three times a day. Data was recovered from the AM400 using a palm computer as previously described (Shock et al. 2001).

Seven Watermark soil moisture sensors and a temperature probe were connected to the Irrometer Watermark Monitor. A computer and the WaterGraph program (Irrometer Co., Inc.) was used to set the sensor data collection frequency at 15 minutes. Data was recovered from the Irrometer Watermark Monitor using a laptop and the WaterGraph program.

All experiments. All trials reported here benefited from simultaneous crop evapotranspiration irrigation management information (Wright, 1982) available from a US Bureau of Reclamation AgriMet station on site.

Results and Discussion

Experiment 1. The tensiometer, Watermark, neutron probe, Gro Point, and Aquaflex responded to the wetting and drying cycles of the soil (Figure 1). The neutron probe and Aquaflex sensors seemed to be less responsive to the soil drying between irrigations than the Gro Point sensor. Lower responsiveness of the neutron probe is not surprising since neutrons radiate deep into the soil were drying does not proceed as quickly. Then slower neutrons can bounce back to the neutron probe sensor. All sensors showed correlations ($r^2 > 0.7$) to the neutron probe and correlations ($r^2 > 0.5$) to the tensiometer except the Moisture Point sensor (Figures 2 and 3). The Moisture Point estimates of soil water were substantially lower than the neutron probe data (Figures 2 and 3).

Experiment 2. The tensiometer, Watermark sensor, and neutron probe responded to the wetting and drying cycles of the soil (Fig. 4). The Gro Point responded, but the amplitude of the response was less than that of the neutron probe. The Moisture Point was the least responsive to the wetting and drying cycles of the soil compared to the other sensors, probably due to the soil pulling away from the sides of the probe. For undetermined reasons, the Aquaflex datalogger only collected 3 days of data; this did not allow for a graphic display.

The watermark sensor measured with the AM400 datalogger and the 30 KTCD-NL meter showed close correlations to the tensiometer (Fig. 5). The AM400 and the 30 KTCD-NL readings of different Watermark Sensors were fairly closely correlated to each other; both instruments used similar equations to convert Watermark sensor electrical resistance to SWP (Shock et al. 2001).

All sensors showed correlations ($r^2 > 0.6$) to the neutron probe except the Moisture Point sensor (Fig. 6). The Aquaflex and Gro Point estimates of soil water were often lower than the neutron probe (Fig. 4). The Moisture Point estimates of soil water were substantially lower than the neutron probe, Aquaflex, and Gro Point.

Experiment 3. The automated collection of Watermark sensor data by an AM400 Hansen datalogger and an Irrometer Watermark Monitor (Irrometer Co.) provided similar interpretation of wetting and drying cycles (Fig. 7). Watermark sensors responded to irrigation within one hour. Small differences in calibration equations can be noted (Fig. 7 D) and slight differences in the interpretation of soil water potential near saturation are evident (Fig. 7 C).

The AM400 was convenient for following and scheduling irrigation events in the field due to its graphic display. Irrometer Watermark Monitor was convenient for setting the data logger reading frequency, easy retrieval, and automatic interpretation of the data. The operation, advantages, and limitations of Watermark soil moisture sensors are described elsewhere (Shock 2003).

Acknowledgments

Technical assistance of student employees Scott Jaderholm, Kendra Nelson, and Autumn Tchida is greatly appreciated. Funding for sensor comparison trials was made available by the Agricultural Research Foundation at Oregon State University, Corvallis, Oregon.

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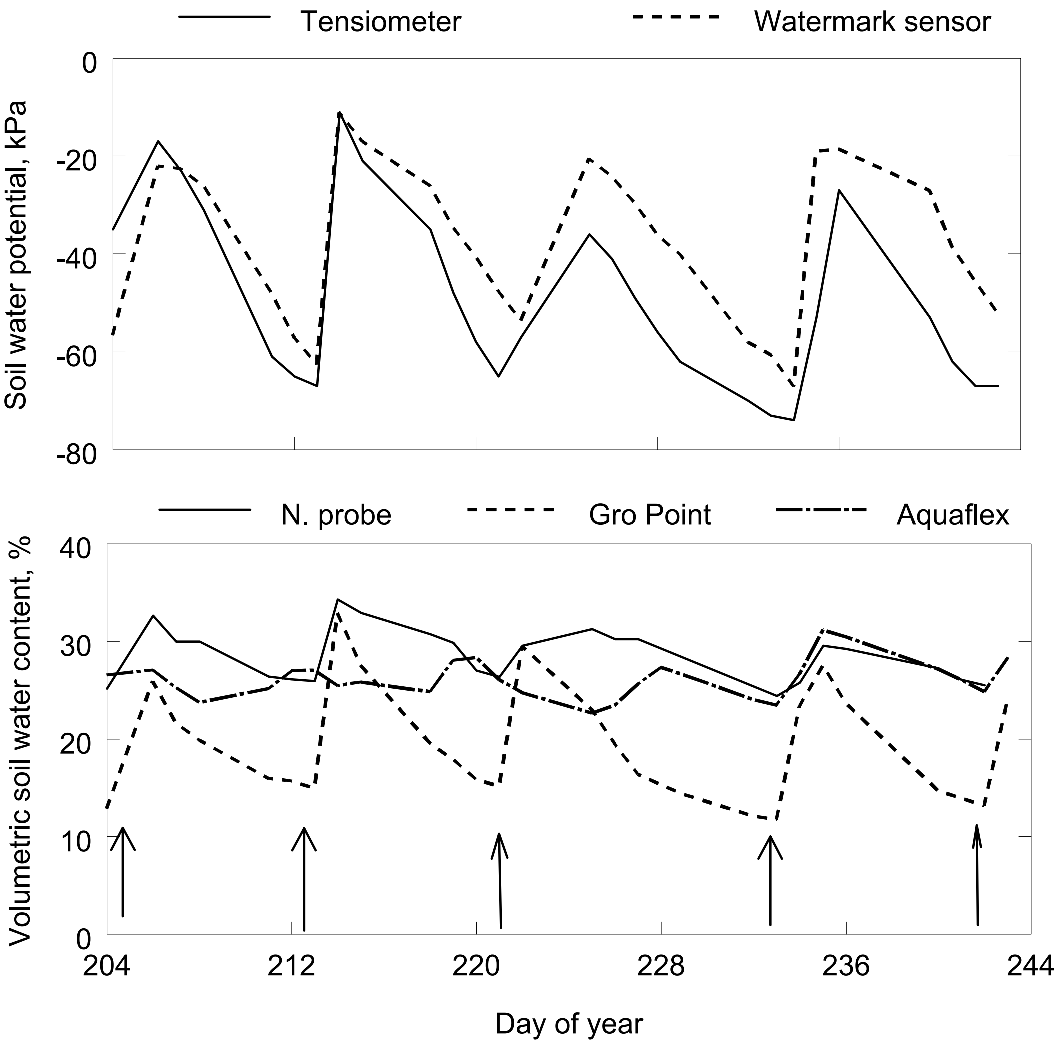


Figure 1. Soil moisture data over time for five types of soil moisture sensors in Experiment 1. Arrows denote irrigations with approximately 2 inches of water applied. The Moisture Point sensor was not available during this time due to repairs being made. Malheur Experiment Station, Oregon State University, Ontario, OR.

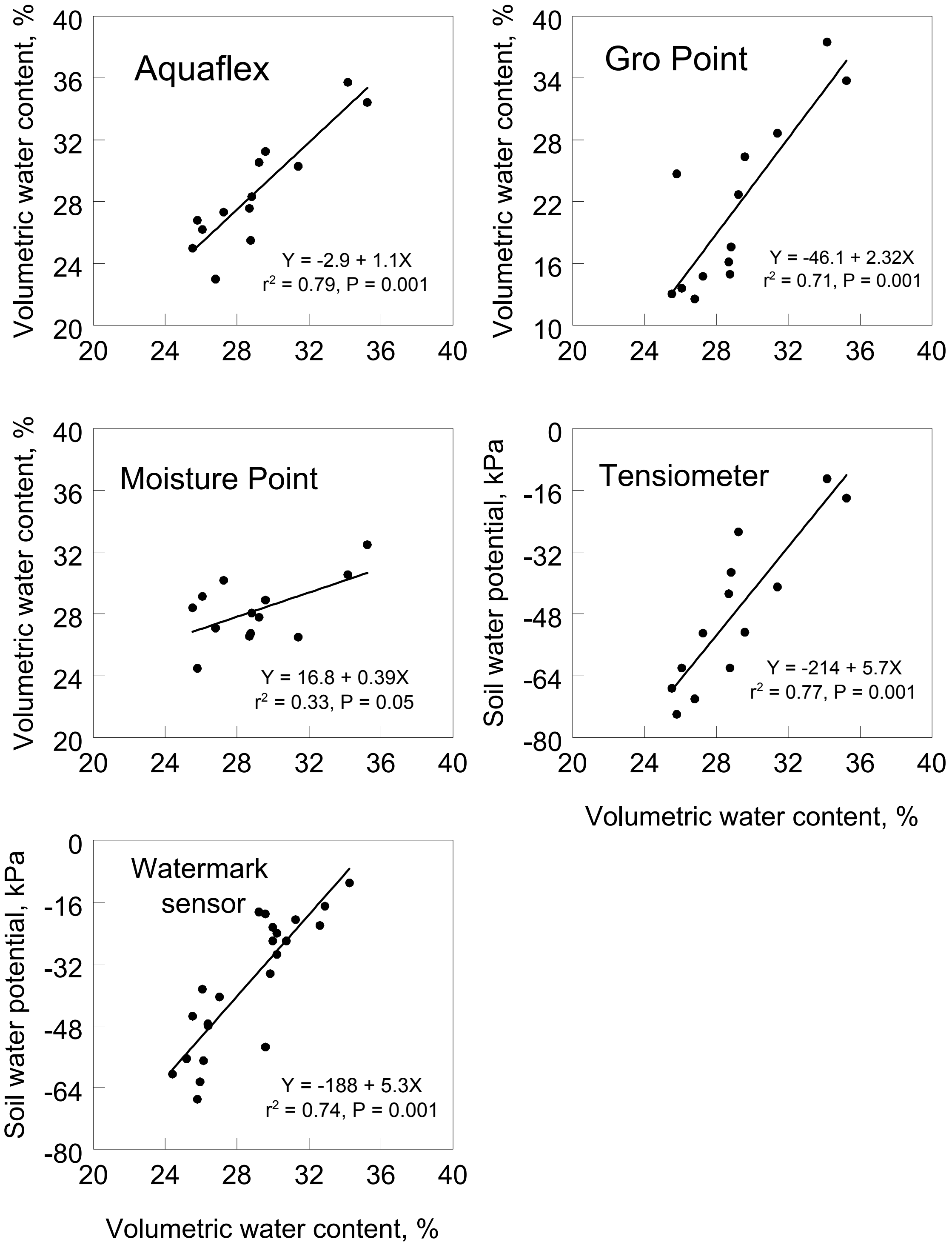


Figure 2. Volumetric soil water content measured in Experiment 1 by a neutron probe (X axis) regressed against soil moisture data (Y axis) measured by 5 types of soil moisture sensors. Data points for the Aquaflex sensor are the average of two sensors. Data points for the other sensors are the average of four sensors. Malheur Experiment Station, Oregon State University, Ontario, OR.

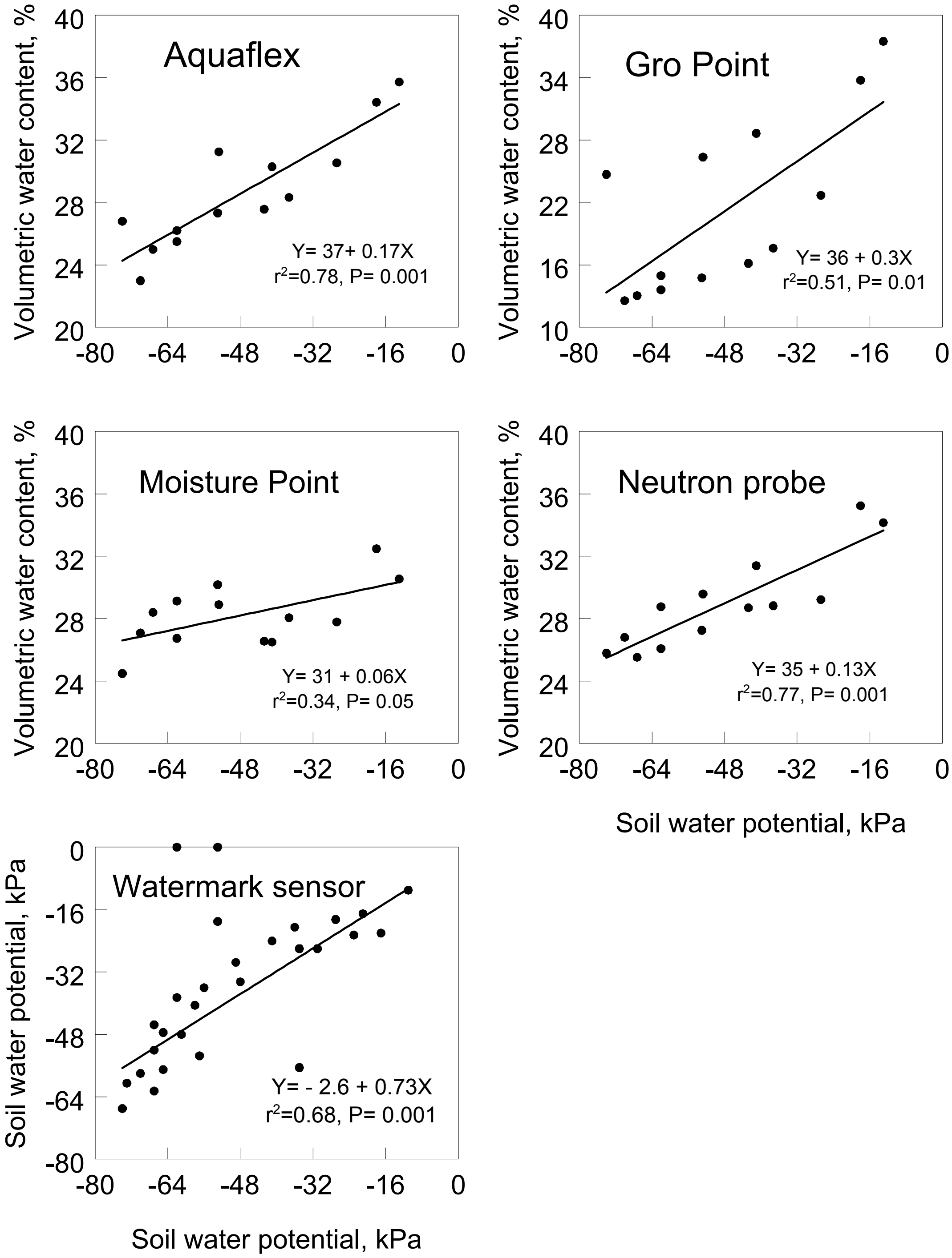


Figure 3. Soil water potential measured in Experiment 1 by tensiometers (X axis) regressed against soil moisture data (Y axis) measured by 5 types of soil moisture sensors. Data points for the Aquaflex sensor are the average of two sensors. Data points for the other sensors are the average of four sensors. Malheur Experiment Station, Oregon State University, Ontario, OR.

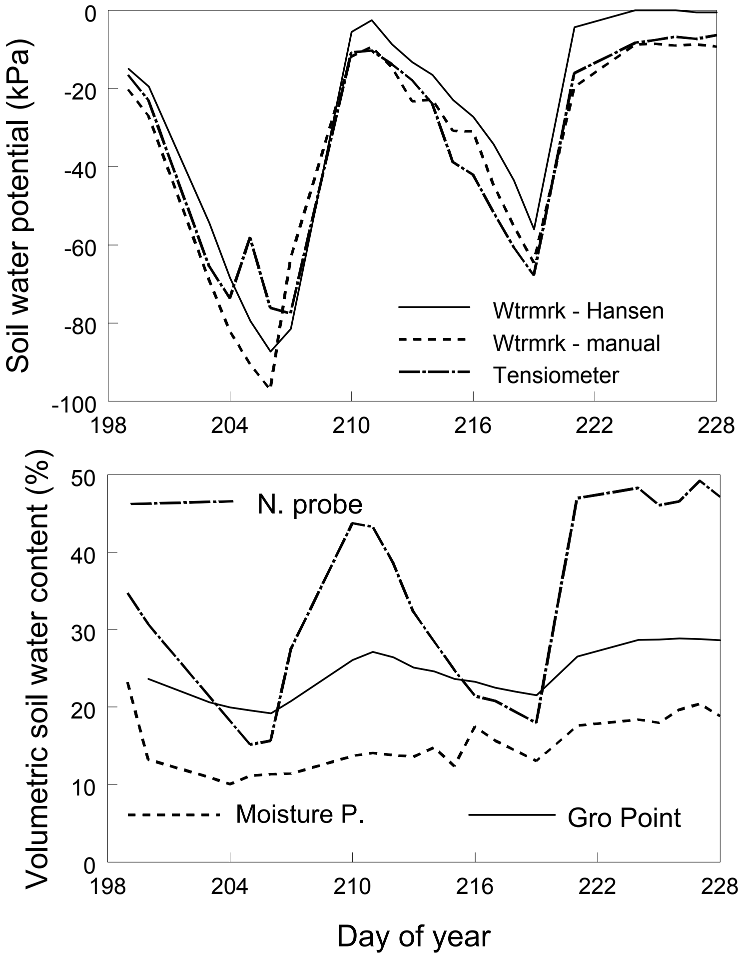


Figure 4. Soil moisture over time for five types of soil moisture sensors in Experiment 2. Malheur Experiment Station, Oregon State University, Ontario, OR, 2002.

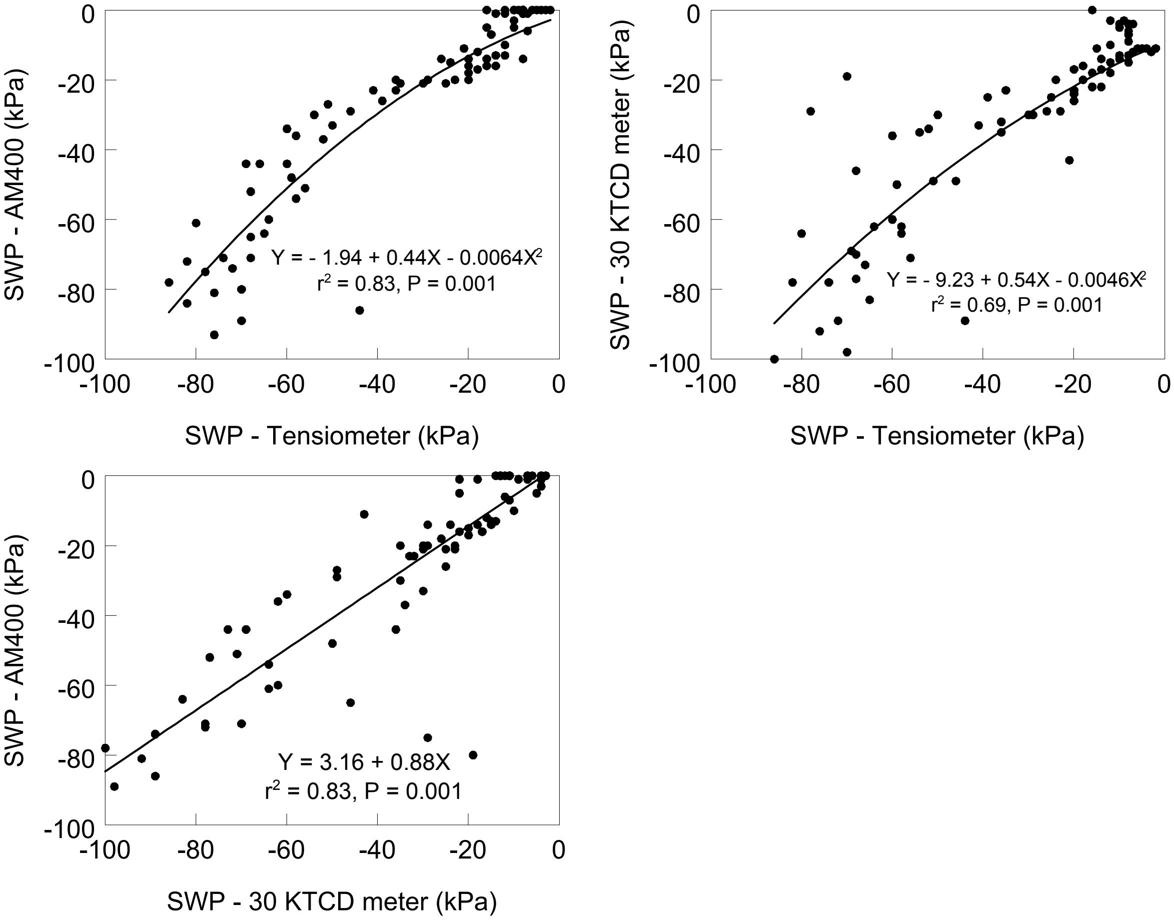


Figure 5. Regressions of soil water potential (SWP) measured in Experiment 2 by three instruments. Malheur Experiment Station, Oregon State University, Ontario, OR, 2002.

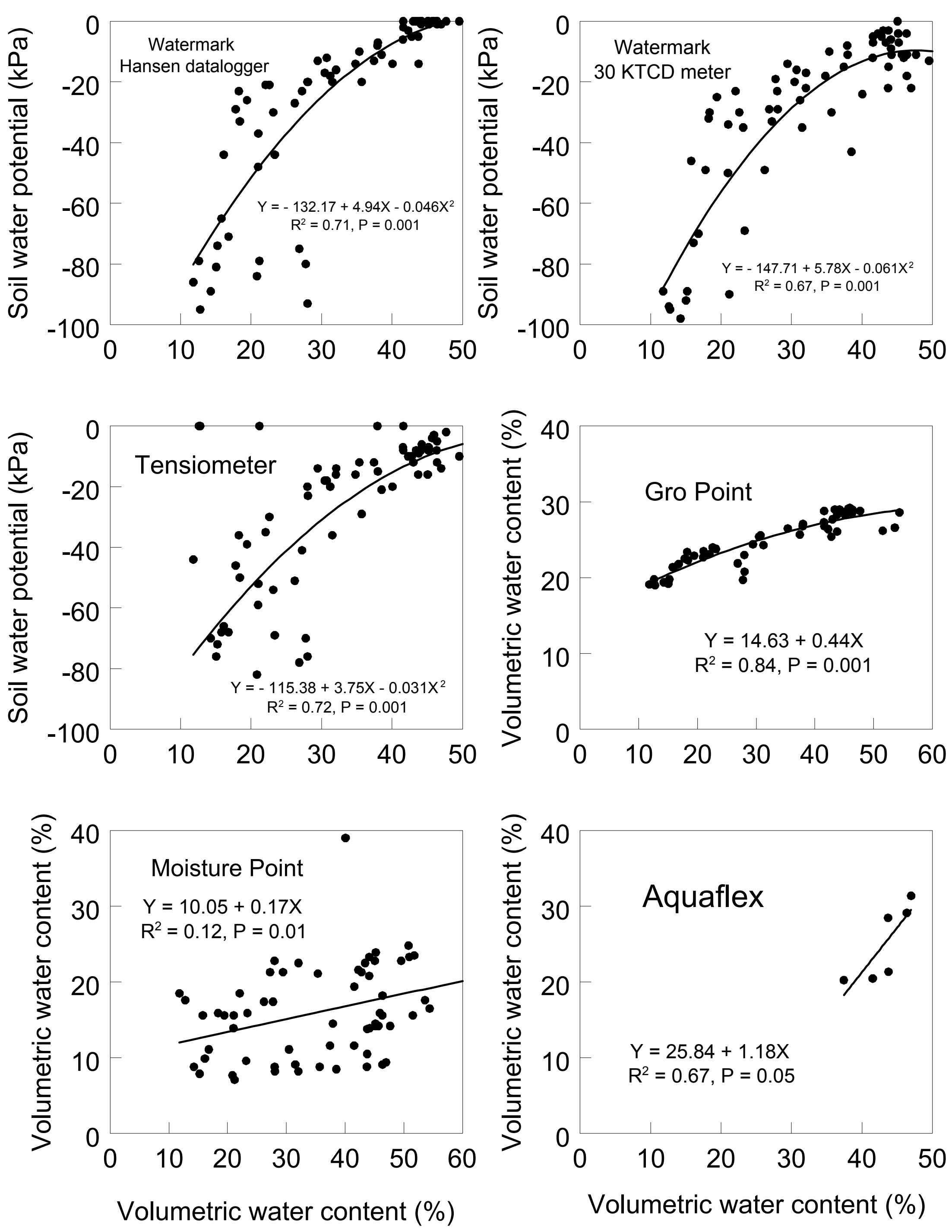
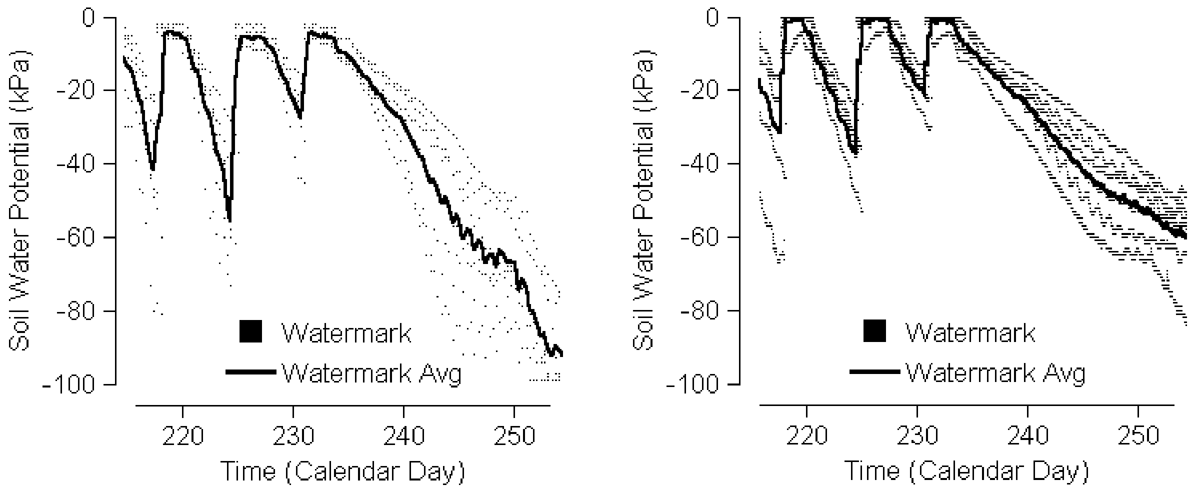


Figure 6. Volumetric soil water content measured in Experiment 2 by a neutron probe (X axis) regressed against soil moisture data (Y axis) measured by 6 types of soil moisture sensor. Malheur Experiment Station, Oregon State University, Ontario, OR, 2002.

A. Time vs AM400

B. Time vs Watermark Monitor



C. Comparison over time

D. Watermark Monitor vs AM400

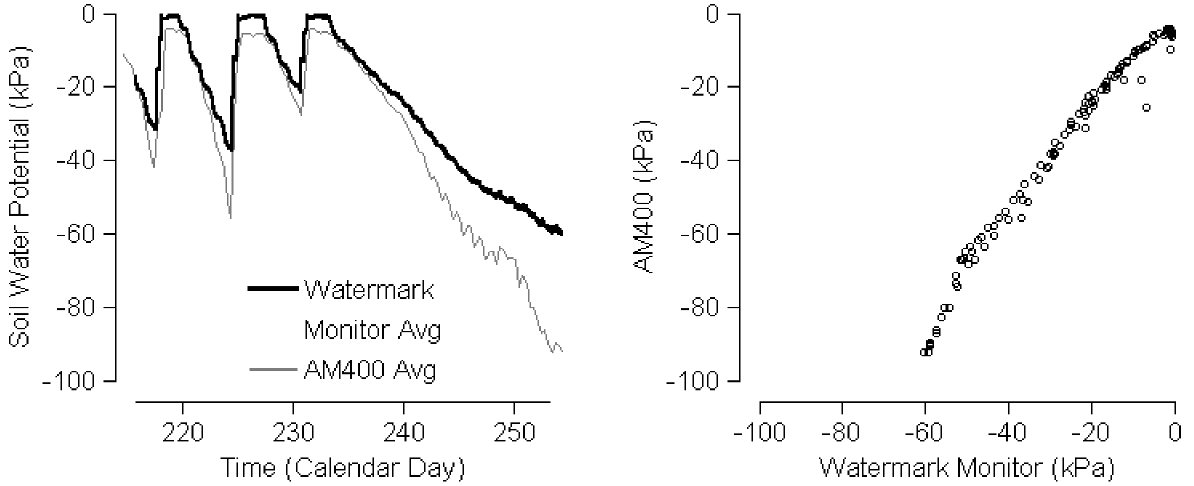


Figure 7. Response of Watermark soil moisture sensors to irrigation events and the termination of irrigation as measured by an AM400 Hansen datalogger (A) and an Irrometer Watermark Monitor (B). The average readings of the an AM400 Hansen datalogger and an Irrometer Watermark Monitor are compared over time (C) and over the measured range of soil water potential (D).

DETECTING CANAL SEEPAGE USING THE ELECTROMAGNETIC INDUCTION METHOD

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SUMMARY

Many water districts in California are faced with important water losses and reduced irrigation efficiency due to canal seepage. Thus, it is necessary to identify tools that can help detect potential leakages along canals in an effort to conserve irrigation water. The goal of this study was to apply the electromagnetic induction (EM) technology to detect potential seepage in a section of canal located at the Lost Hills Water District, CA. A mobile system comprising of an EM-31 sensor, GPS, and soil sampler, was developed to conduct the survey. Potential canal seepage was assessed when the canal was open (August) and then closed (October). Data calibration was performed following soil sampling at 0-8 ft. Contour maps indicated that soil water content was lowest near the surface (0-3 ft) with values ranging from 20-30%. For all depths, water content was greater in the canal mid-section. After the canal had been closed in October, water content remained high in the mid-eastern segment of the canal. Greater water content could be indicative of potential seepage along that part of the canal. Percent soil clay content increased with depth and ranged from 10-50%. The overall results of such study can be useful in improving water management and conservation strategies along irrigation canals.

INTRODUCTION

Seepage from irrigation canals is a serious water management problem in California's San Joaquin Valley (SJV) since more than 600 million cubic meters of water are being lost every year. Seepage reduces irrigation efficiency and its water may contain toxic substances harmful to soils and groundwaters. Additionally, water shortage is becoming a very important problem for California agriculture. Is it is forecasted that, by 2020, California’s population will increase to 47.5 million people and the state will experience water shortages of 2.4 million acre-feet in average years and 6.2 million acre-feet in drought years. These shortages will inevitably result in water reallocation to urban and industrial sectors, thereby posing a significant threat to the agriculture industry. Thus, it is important to identify tools that can help detect potential leakages along canals thereby conserving irrigation water and sustaining crop productivity in the region.

The electromagnetic (EM) induction technology has become a very useful and cost-effective tool to monitor and diagnose soil properties over large areas, because it allows for rapid, aboveground measurements with very limited soil sampling (Hendrickx et al., 1992). However, while the EM technique has been commonly utilized for salinity assessment, its use for seepage investigations is just developing. The principle of the EM technology is as follows: the EM instrument transmitter coil induces an electromagnetic field in the ground, which in turn creates a secondary magnetic field that is measured by the receiver coil. The ratio of both fields provides a measure of the depth-weighted apparent electrical conductivity (EC) in a volume of soil below both coils (McNeill, 1980). Since EC of a soil is a function of its water content, salt content, and texture, use of the EM technique can be very valuable for canal seepage assessment. Recently, researchers in Australia found that EM was useful in detecting canal seepages (Akbar et al., 2000). If the EM technology can effectively be used as a non-invasive mean of measuring soil water content and detecting potential canal seepage, significant water savings should be possible throughout irrigated agriculture in California. Therefore, the objective of this study was to use the EM technology to assess potential seepage along an irrigation canal of Central California.

MATERIALS AND METHODS

The canal seepage surveys were conducted at the Lost Hills Water District in the San Joaquin Valley, Kern County, CA. An unlined section of a canal, about 4000 ft long, was selected for the study. The surveys were performed in August 2001 when the canal was open and susceptible to seepage, and in October 2001 after the canal had been closed. The soil along the canal was clay loam with increasing clay content with depth.

A Mobile Conductivity Assessment (MCA) system was developed at the Center for Irrigation Technology to conduct the canal surveys. The MCA system comprised four basic components mounted on a truck: (1) an electromagnetic (EM) induction sensor, (2) a global positioning system (GPS) receiver, (3) a computer, and (4) a hydraulic soil sampler (Figure 1.). The EM sensor was placed in a plastic carrier-sled attached about 10 ft behind the truck to avoid any interference due to metallic objects. The EM and GPS instruments were connected via digital interfaces to an on-board computer that simultaneously recorded the EM readings along with their geographical locations.

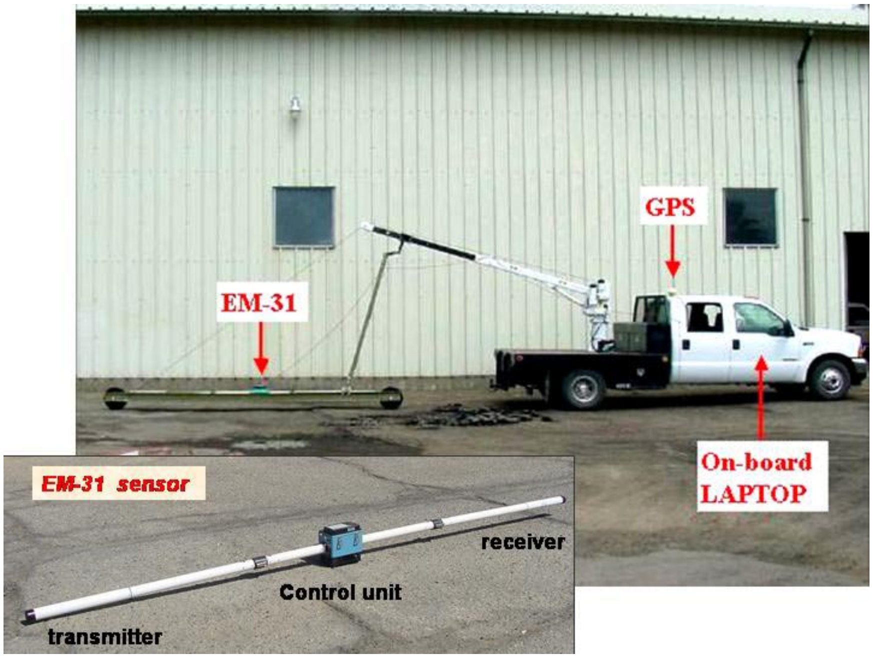

Figure 1. Mobile conductivity assessment (MCA) system used in the canal seepage surveys.

In this study, the EM-31 meter (Geonics Limited, Ontario, Canada) was used to measure soil electrical conductivity and indirectly soil moisture down to 8 ft. The EM-31 operates at a frequency of 9.8 kHz and consists of a transmitter coil and a receiver coil with a control unit in the center. The instrument has a fixed inter-coil spacing of 12 ft, which allows observation measurements down to 10 and 20 ft in the horizontal (meter parallel to the surface) and vertical (meter perpendicular to the surface) dipole modes, respectively.

The EM and GPS data were collected from four traverses parallel to the water flow on each side of the canal. The surveys were conducted at a speed of about 4 mph, with readings taken every 5 seconds. Calibration of the EM data was obtained through soil sampling. For each survey, an optimal sampling plan was generated using the statistical package ESAP (Lesch et al., 1999). This sampling plan consisted of six locations that characterized the spatial distribution of the EM readings along the canal. At these six sites, soil samples were collected in 3-ft increments to a depth of 8 ft using the hydraulic soil sampler. Soil water content, electrical conductivity (EC), and texture were determined on these samples, following standard analytical methods (Rhoades, 1996; Klute, 1986). Estimates of each measured parameter were then obtained for the entire survey area using the statistical software. Contour maps showing the distribution of the three parameters were generated with the ArcView GIS software (Environmental System Research Institute, 1996).

RESULTS AND DISCUSSION

Contour maps showing the distribution of soil moisture, EC, and clay content along the canal at different profile depths in August 2001 are presented in Figure 2. Soil water content was lowest near the surface (0-3 ft) with values ranging from 20 to 30%. The maps also showed that water content increased with depth. The 6-8 ft profile had the highest moisture levels (up to 48 cm^3 cm^{-3}) due to the presence of water table at those depths. In the 3-6 ft soil profile, water content ranged from 20 to 40% with greater percentages found in the mid-section and north-east segment of the canal. Higher soil water content could be indicative of potential seepage. Water loss in those sections of the canal was also observed by the Water District.

In August, soil EC ranged from 0.5 to 9 dS/m throughout the profile. The lowest values (<4 dS/m) were observed at higher depths (6-8 ft). Soil EC was greater in the mid and north sections of the canal at the 3-6 ft depth, with highest values always found on the eastern side of the canal. This pattern was similar to that noted on the soil water content maps.

Results also indicated that percent clay content increased with soil depth and ranged from 11 to 53%. This is indicative of coarser-textured soil and lower water holding capacity at the surface. Throughout the soil profile, higher clay contents (40-53 %) were observed in the mid-section of the canal. However, lower clay percentages (20-30%) were found in the middle-eastern side of the canal at 3-6 ft depth. At that location, soil water content and EC were particularly high, which could suggest potential seepage.

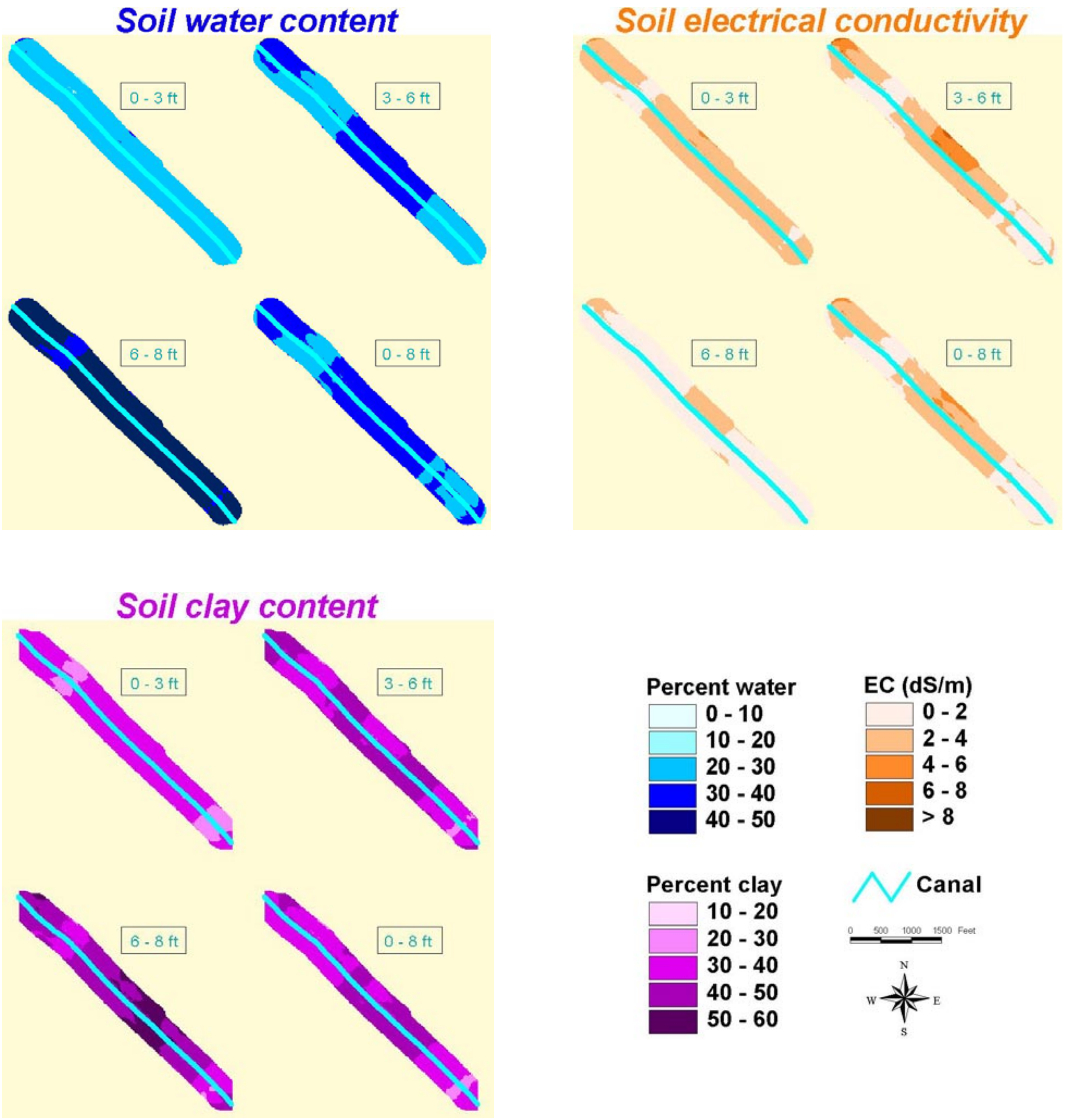

Figure 2. Distribution of soil water content, electrical conductivity, and clay content along the irrigation canal at different depths in August 2001.

Changes in soil water content and EC observed in Octob8er 2001 after the canal had been closed are shown in Figure 3. The maps indicated that water contents were very uniform and low (20-30%) at the soil surface (0-3 ft). Moisture spatial distribution and percentages were comparable to those observed in August, suggesting that seepage is unlikely near the soil surface. In October, low soil water contents were also found at the 3-6 ft depth, except in the mid-eastern section of the canal where values up to 40% were noted. This indicated that water percentages did not decrease in that section after the canal had been closed and could confirm the possibility of seepage at that location and depth. Water content decreased through the 6-9 ft profile in October, although it remained highest than the upper depths due to the presence of water table. Average soil EC increased after closing the canal.

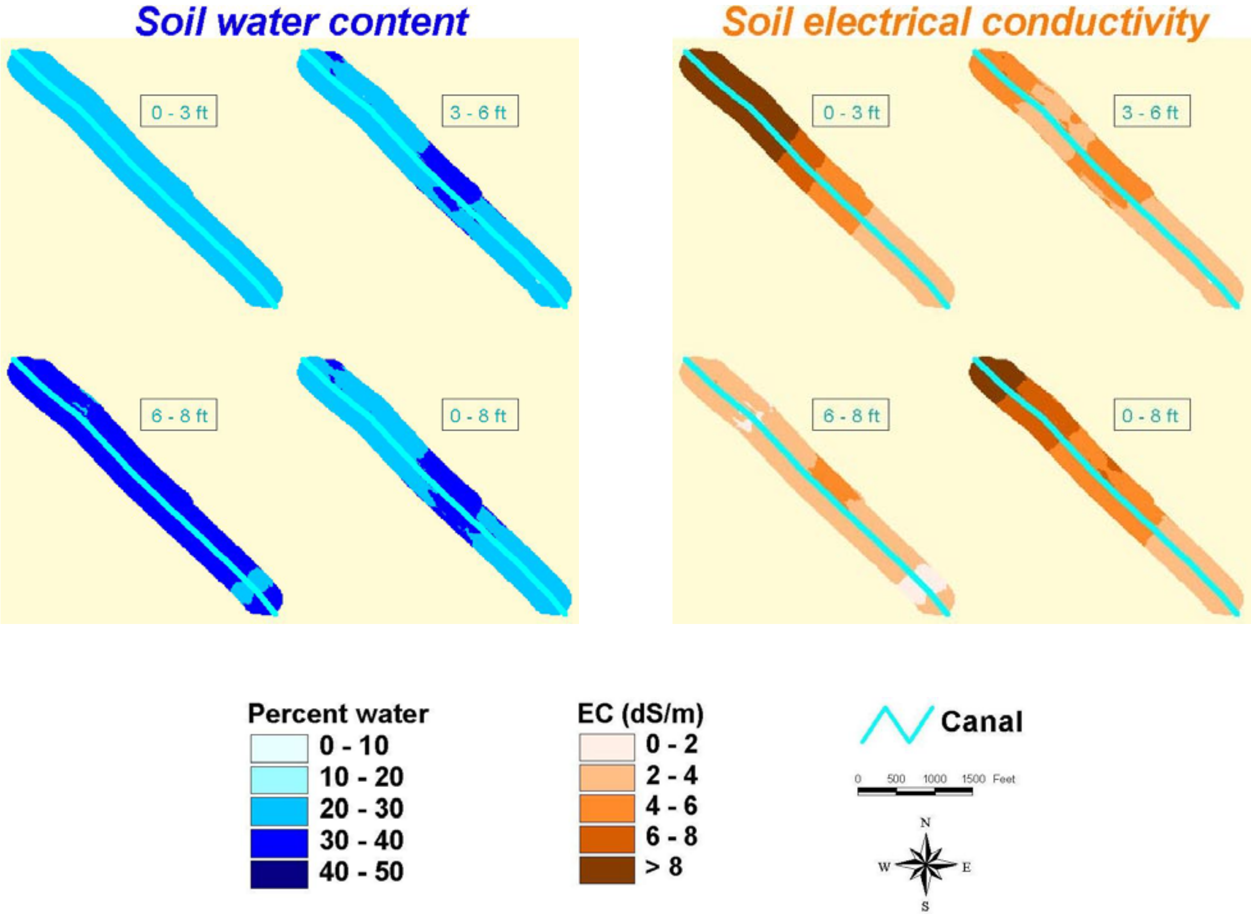

Figure 3. Distribution of soil water content and electrical conductivity along the irrigation canal at different depths in October 2001.

CONCLUSIONS

The purpose of the study was to use the EM technology to detect potential seepage along an irrigation canal of Central California. The surveys demonstrate that the EM technique has great potential for quick evaluation of soil water content over large areas and is a cost-effective alternative to extensive sampling. The overall results of such study and the contour maps indicate that canal seepage assessment using the EM technique can be useful in improving water management and conservation strategies along the irrigation canals. Data obtained from the canal surveys can also aid in financial decision making by providing information on the extent of possible canal seepage and need of canal lining.

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Evaluation of Collector Size for the Measurement of Irrigation Depths[1]

G. A. Clark, E. Dogan, D. H. Rogers, and V. L. Martin[2]

Abstract. Fixed-plate (FP), grooved-disk, sprinkler diffusers provide distinct streams or jets of water that are not easily distorted by wind and minimize evaporative losses. However, these sprinklers provide variable, cyclic, and nonuniform application patterns of applied water that are difficult to accurately measure with collectors that have openings of 10 cm or less. In 1999, 2000, and 2002, field studies were conducted to evaluate the measurement effectiveness of a non-evaporating sprinkler irrigation catch device (IrriGage). The standard IrriGage (IrriGage) has a 10 cm diameter opening, a 20 cm long collector barrel, and an attached storage bottle for collected water. IrriGage collectors were compared to other catch devices that included a 15 cm diameter collector similar to the IrriGage and 43 cm diameter pans (PAN). All collectors were tested under three different sprinkler irrigation packages that included fixed-plate diffusers (FP) with a grooved-disk, spinning-plate diffusers (SP), and wobbling plate diffusers (WP).

In 1999, IrriGage collectors positioned within a corn canopy failed to accurately measure the irrigation depths and sprinkler patterns as compared to the larger diameter PAN collectors. In 2000, IrriGage collectors were lowered and repositioned into a grass buffer. Measured irrigation depths and CU values from IrriGages were significantly ($p < 0.05$) higher and distributed differently than associated data from PAN collectors.

In 2002, IrriGage collector evaluations under all three irrigation packages (FP, SP, and WP) indicated significantly higher irrigation depths and higher variances in collected data than the 15 cm collectors (similar to 2000 results). Measured depth differences between 10 and 15 cm diameter collectors were greatest under the FP sprinkler package. However, while rotating plate diffuser (SP and WP) measured depths with 10 cm IrriGage collectors were 4% to 7% higher than with 15 cm collectors, application patterns were mimicked. These results indicate that 10 cm IrriGage collectors should not be used to measure irrigation depths and uniformities on FP diffuser sprinkler packages. While 10 cm IrriGages may be used for sprinkler packages with rotating plate diffusers, actual irrigation depths may be slightly less than measured values.

Keywords. Uniformity, Precipitation Gauge, Rain Gauge, Irrigation Collector, Sprinklers

Introduction

Sprinkler irrigation system uniformity is an important performance characteristic (William, 1963; Branscheid and Hart, 1968; Vories and von Bernuth, 1986; Heermann et al., 1992; Evans et al., 1995; and Li and

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Kawano, 1996), and should be evaluated based on expected conditions (field conditions) that will exist in the crop field (Volker and Hart, 1968). Since crop growth and yield are dependent on available water, substantially lower uniformity might result in reduced crop yields in the areas receiving less irrigation water.

Fixed-plate (FP), grooved-disk deflector sprinkler irrigation packages have distinct jet streams with large water droplets. Spinning-plate (SP) diffuser and wobbling-plate (WP) diffuser sprinkler irrigation packages produce smaller water droplets and usually evenly distribute irrigation water to the crop fields. In addition, impact and rotating sprinkler designs also have more uniform applications due to the breakup in droplet size and patterns. However, sprayed water from those systems may be more susceptible to wind drift and evaporative losses than low drift nozzle (LDN) type sprinklers (James and Blair, 1983; Hanson and Orloff, 1996; Bilanski and Kidder, 1958).

Marek et al. (1985) indicated that collectors should display characteristics such as sharp edges to separate water droplets, should prevent splash in and out, and should minimize evaporation losses of collected water as well as from droplets on the inner surface. They evaluated the measurement performance of three different collectors: oil cans with a 10.3 cm dia. and a 14.1 cm depth, glass separatory funnels with a 9.02 cm dia., and a fuel funnel with a 4.9 cm diameter. The sprinkler irrigation package had Rainbird model 30 W-TNT series impact sprinklers with a 0.52 cm inside diameter nozzle operated with 244 kPa pressure. Results from the three different collectors were significantly different. The separatory funnels were the most accurate devices, but were expensive. While, oil cans-over estimated irrigation depth by 5%, they concluded that the fuel funnels were unacceptable collectors for uniformity measurements.

ASAE (2001) states that catch devices (collectors) used for uniformity measurements should be identical with a minimum height (h) of 12 cm, and with an opening of at least 6 cm in diameter. For data collection on center pivot systems, two or more sets of collectors parallel to one another should be used with a maximum collector spacing of 3 m between collectors for spray irrigation sprinkler packages. However, Evans et al. (1995) indicated that under field conditions, using two or more catch device rows is not practical during data collection. Further, there should be no obstructions (such as a crop canopy) between the irrigation nozzle or discharged water trajectory and the catch device. If the canopy is higher than the opening of the collection device, then a buffer distance equal to twice the distance between the opening of collector and the height of the obstruction should be cleared.

Clark et al. (2002) developed an inexpensive, non-evaporating in-field precipitation gauge (IrriGage) that might be used not only for rainfall and irrigation depth measurements, but also for evaluation of sprinkler irrigation system uniformities. The IrriGage (IrriGage) device is a 20 cm long, 10.2 cm dia. PVC pipe with a PVC cap glued to the bottom of the barrel. The gauge has a bottle attached to the bottom cap as a water reservoir. The authors concluded that these devices could be used to measure sprinkler irrigation depths with little or no evaporative loss, that they exceed the collector criteria specified in the ASAE center pivot performance test standard (ASAE, 2001), and that they are easy to make and set up in field tests. Because the IrriGages are non-evaporating, collected water amounts do not have to be read immediately following irrigation events.

Field measurements of center pivot irrigation system uniformity (data not currently reported) with 43 cm diameter pans and 10.2 cm diameter IrriGage's (IrriGage) raised some concerns about using IrriGage's on fixed-plate, grooved disk sprinkler packages. The distinct streams of water may or may not be caught by a gauge. Because the volume of water caught by the gauge is averaged over the surface area of the opening, small gauge openings may result in artificially high or low depths based upon the caught or missed streams. In addition, even with the larger catch devices, adjacently measured depths could vary from 10% to over 100%.

Therefore, the objectives of this study were to evaluate the catch accuracy of different irrigation water collectors from above-canopy, fixed-plate and rotating-plate sprinkler devices on a moving irrigation system.

MATERIALS AND METHODS

Catch Device Characteristics

This study evaluated the catch accuracy of the IrriGage (fig. 1) 10 cm diameter collection devices (Clark 2002) for both fixed-plate and rotating-plate sprinkler irrigation packages. Study sites included a linear-move sprinkler irrigation system at the Kansas State University (KSU) Sandyland Experiment Field, St. John, KS (1999 and 2000), a center-pivot system at the KSU Livestock Waste Management Learning Center in Manhattan, KS (2002A), and a linear move sprinkler system at the KSU North Central Experiment Field, Scandia, KS (2002B).

The primary objective of this work was to compare the catch accuracy of the IrriGage collectors to a larger diameter collection device. The 1999 and 2000 studies compared IrriGage collectors to large diameter (43 cm) pans (PAN; fig. 1). The 2002 study sites involved a comparison of the standard 10 cm IrriGage devices with a 15 cm diameter collector constructed very similarly to the IrriGage collectors. The PAN collectors had the shallowest depths (10 cm), slightly less than ASAE criteria (12 cm) (ASAE, 2001). However, the large diameter (d) of the PAN's resulted in a much larger hydraulic radius (R_h= A/C = d/4) than the smaller catch devices. The hydraulic radius provides a relative indication of the potential boundary dimension that could result in splash in/out errors. A large hydraulic radius indicates that the surface area for collection is large compared to the circumference of the boundary region of the collector. Thus, because the PAN's had a R_h of 10.8 cm while the IrriGage collectors had an R_h of 2.5 cm, it was believed that splash in/out would not be a substantial concern with the large diameter PAN collectors.

All sprinkler systems in this study (1999, 2000, 2002A and 2002B) had sprinklers on drops just below the system trusses, and all drops were on a 3.0 m spacing. Discharge rates from the three middle sprinkler nozzles from each treatment zone of the linear sprinkler irrigation systems (1999, 2000, and 2002B) used in this study were measured while on the sprinkler system. A PVC pipe was positioned over each sprinkler nozzle and directed the discharge water into a 20 L bucket. Discharge volumes were measured for 30 seconds, collected water was then weighed, and data were converted to discharge rate units. The middle three nozzles and pressure regulators from both FP and SP sprinkler package test zones on the center pivot irrigation system (2002A) were taken to the Biological and Agricultural Engineering, Kansas State University hydraulic laboratory for discharge rate tests. A test pressure equal to the center pivot inline pressure was used and pressure-regulated nozzle discharge rates were tested three times for one minute each. These tests were used to verify the nozzle consistency and the manufacturer reported nozzle discharge rates.

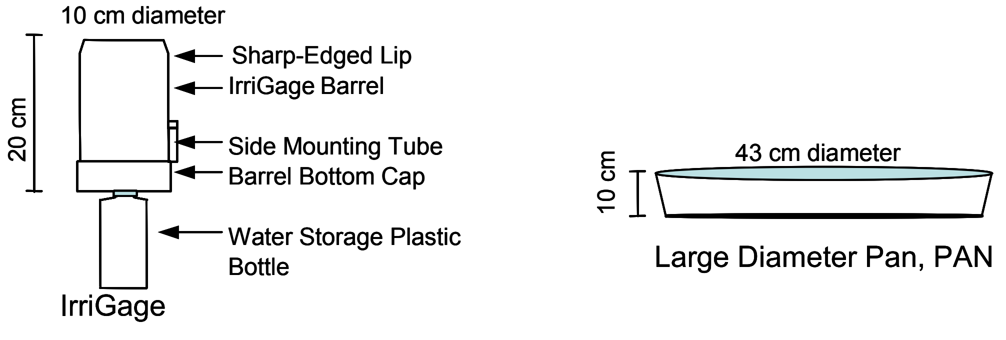

Figure 1. Characteristics of the IrriGage and PAN collectors.

1999 / 2000 Field Evaluations

The 1999 and 2000 studies were used to evaluate IrriGage collectors under three irrigation pressure and nozzle size combinations with fixed plate, grooved-disk deflectors. A linear move sprinkler irrigation system was used with four 49-m long spans that each had 16 flexible hose drops with polyethylene weights to minimize swinging. Sprinklers were positioned at 2.2 m to 2.4 m above the soil surface. The three sprinkler nozzle size/pressure combinations provided the same nozzle discharge rate, but different distribution patterns and application uniformities (Clark et al., 2003).

In 1999, twelve IrriGage collectors were placed within a corn canopy along corn rows that were 76 cm apart. The IrriGage collectors were positioned 1.2 cm above the soil surface using steel support rods. Corn plants within 1.2 m of the IrriGage collectors were removed from all sides of the IrriGage setup area to minimize any effect due to plant canopy. The corn canopy was approximately 2 m tall. Thus, at the corn tassel stage, the ratio of buffer distance to canopy height difference (from the collector opening) was 1.5 and not 2.0 as recommended by ASAE (2001). The IrriGage collectors were left in the field during the entire growing season. Water amounts from irrigation events caught with the IrriGage collectors were measured with a volumetric cylinder and then converted to depth (mm) units and used for graphical and statistical analysis.

For the irrigation testing events, PAN's were placed in a grass buffer area 10.0 to 12.0 m from the IrriGage collectors, about 6.0 m from the corn plants, and in-line with the IrriGage collectors. PAN's were positioned in the grass buffer just before irrigation events and measurements were taken immediately after the irrigation system passed over to minimize evaporative losses. Water collected by the PAN's was weighed with a balance and then converted to depth (mm) units. Those results were used as base values to compare with IrriGage collector measurements. In 1999, IrriGage collectors and PAN's were evaluated using five separate sprinkler events during the growing season.

The IrriGage collectors were also evaluated in 2000 using the same irrigation system as in 1999, but the IrriGage collectors were moved to the same grass buffer strip area where the PAN's were located . This time IrriGage collectors were mounted 60-cm high using metal support rods, located 6 m from the corn plants, and about 1 m from the PAN's. Five irrigation events were also measured in 2000.

Environmental conditions for tests in both years were obtained from a weather station located on the experiment field site. The anemometer was partially protected by a shelter belt located approximately 50 m to the south of the weather station. Reference crop evapotranspiration for that station was obtained from the Kansas State University Weather Data Library which posted modified Penman alfalfa crop ET.

2002 Field Evaluations

In 2002, standard 10 cm IrriGage collectors were compared to 15 cm collectors on two experimental field sites (2002A and 2002B) under three different sprinkler irrigation packages. In the 2002A study, collectors were evaluated at the KSU Livestock Waste Management Learning Center (WMLC), Manhattan, KS. The irrigation system was a new center pivot sprinkler irrigation system with seven, 55 m long spans. The last span of the center pivot irrigation system was used for the collector evaluations. The first nine drops of the last span were installed with a spinning plate (SP) sprinkler package. The remaining eight drops of that system had the FP sprinkler package. Both irrigation packages were operated at 103 kPa pressure. Sprinkler drops were about 1.4 m above the soil surface.

Three sets of twelve IrriGage collectors and one row of the 15 cm collectors were set up under the sprinkler packages (figure 2). Collectors within rows were 0.75-m apart All 10 cm IrriGage and 15 cm collectors were mounted on metal rods such that the openings were at a 60 cm height. Collectors were tested using three irrigation events that were each set to apply a gross depth of 19 mm of water. IrriGage collectors were set up as "Single", "Side-by-Side", and "Inline" (figure 2) in order to evaluate different arrangements of IrriGage collectors to accurately measure sprinkler irrigation depths and application patterns.

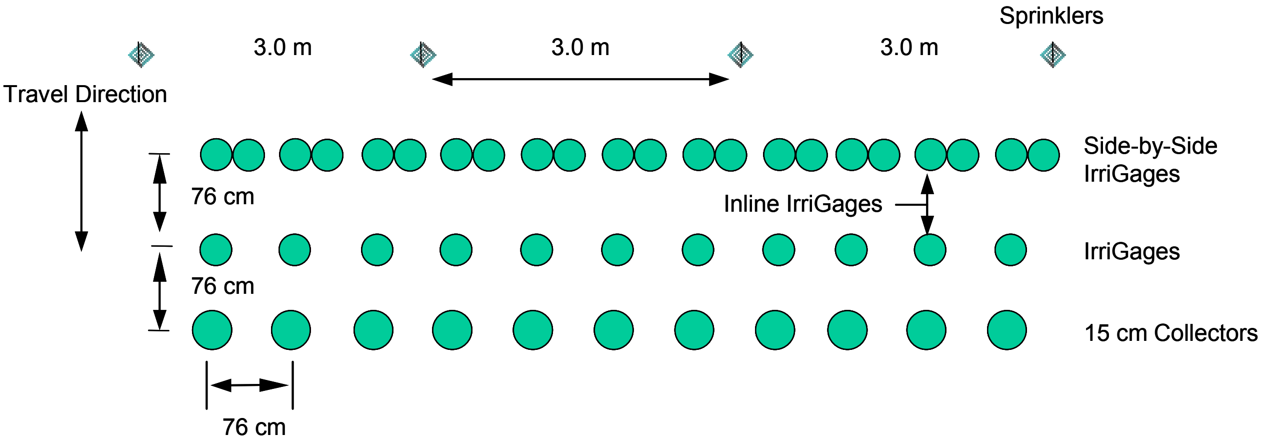

Figure 2. Set up of collection devices used in the 2002 tests.

In the 2002B study, IrriGage collectors were evaluated at the KSU North Central Experiment Field, Scandia, KS. The irrigation system was a new linear move irrigation system with five, 55-m long spans. The last two spans of the linear irrigation system were used for collector evaluations with wobbling plate (WP) sprinklers (Senninger Wobblers[3]) operated at 103 kPa pressure. Irrigation drops were 2.0 to 2.3 m above the soil surface. Collector set up was identical to the 2002A study with twelve sets of collectors that were positioned under each span. The irrigation system was set to apply 19.0 mm of water and move with a speed of 24.7 m/h. The linear irrigation system was operated twice during the same day.

Coefficient of Uniformity (CU) values were calculated for the 1999 and 2000 data sets using ASAE (2001) standard methods for center pivot and linear move irrigation systems. Irrigation depths and CU values were analyzed using ANOVA and T-Test statistical procedures and graphical analysis.

Environmental conditions for the 2002A and 2002B field tests were obtained from weather stations located an adjacent experiment field sites. Reference crop evapotranspiration for those stations were determined using the Penman-Monteith grass reference crop equation (Smith et al., 1996; Allen et al., 1998).

RESULTS AND DISCUSSION

Environmental conditions (air temperature, relative humidity, wind speed, and grass reference evapotranspiration) during catch device evaluations for all three years were hot and dry. Average daily wind speeds often exceeded the 3.6 km/h (1 m/s) testing threshold recommendation in the ASAE center pivot evaluation standard (ASAE, 2001), but never exceeded the 18 km/h (5 m/s) upper threshold recommendation. Field tests were performed in the early morning or evening hours when actual wind speeds and evaporative demands were lower.

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[3] Mention of specific products or trade names does not imply endorsement by the authors or Kansas State University

1999 Results

Average irrigation depths and corresponding CU values from each set of twelve collectors for all 5-test events under the fixed plate sprinklers operated at 42 kPa (FP42), 103 kPa (FP103), and 138 kPa (FP138) measured with IrriGage and PAN collectors are presented in table 1. Irrigation depths collected with IrriGage collectors under the FP42 sprinkler package averaged 8.3 mm, while FP103 and FP138 sprinklers had average irrigation depths of 10.3 and 10.0 mm, respectively. However, PAN collectors had significantly higher ($p < 0.05$) average irrigation depths of 13.7, 13.0, and 12.5 mm, respectively (table 1). Because the diameter of the PAN collector opening (43.0 cm) was greater than the IrriGage collectors (10.2 cm), irrigation depths from the PAN's were considered to be more accurate and representative of actual irrigation depths and patterns.

Low pressure sprinkler distribution patterns were variable but were consistent with results reported by Clark et al. (2003). The PAN collectors showed a consistent cyclic distribution pattern under the lower pressure (42 kPa) sprinklers, and a consistently uniform distribution under the higher pressure (138 kPa) sprinklers. However, IrriGage collectors recorded consistently lower amounts of water under the higher pressure sprinklers, and provided quite variable and inconsistent results under the lower pressure sprinklers. Coefficients of uniformity (CU) from IrriGage collectors for FP42, FP103, and FP138 sprinkler packages averaged 42.3, 79.1, and 80.4, respectively, while CU values from PAN's were significantly higher ($p < 0.05$) at 77.5, 90.5, and 92.5, respectively (table 1). Furthermore, standard errors from PAN's were smaller than from IrriGage collectors. Differences in both irrigation depths and CU values in 1999 were attributed in part to the height of the IrriGage collectors and possible corn canopy interference with the irrigation patterns.

Table 1. Average irrigation depths and CU values for the IrriGage and PAN collectors from the 1999 and 2000 sprinkler irrigation uniformity tests.

Year: Sprinkler		Average Depth (mm)			Coefficient of Uniformity (CU)		
Package		IrriGage	PAN	Signif.	IrriGage	PAN	Signif.
	FP42	8.3	13.7	*	42.3	77.5	*
1999	FP103	10.3	13.0	*	79.1	90.5	*
	FP138	10.0	12.5	*	80.4	92.5	*
	FP42	17.1	14.5	*	79.9	79.5	NS
2000	FP103	20.2	14.4	*	72.3	90.6	*
	FP138	16.9	13.8	*	77.1	91.3	*

Data were analyzed using ANOVA procedures. * Significantly different at 0.05 level. NS = Not significant.

2000 Results

In 2000, irrigation depths from IrriGage collectors averaged 17.1, 20.2, and 16.9 mm for the FP42, FP103, and FP138 sprinkler packages, respectively (table 1). However, PAN measured irrigation depths for the same packages were all significantly lower ($p < 0.05$) at 14.5, 14.4, and 13.8 mm, respectively. Thus, IrriGage collector depths ranged from 18% to 40% higher than the corresponding PAN collector depths. Calculated CU values from IrriGage collectors for the FP42, FP103, and FP138 sprinkler packages were 79.9, 72.3, and 77.1, respectively. PAN-based CU values were 79.5, 90.6, and 91.3 for the same sprinkler packages, respectively (table 1). While the FP103 and FP138 CU values from the IrriGage collectors were significantly lower ($p < 0.05$) than PAN-based data, associated CU values for the FP42 packages were not different.

Overall, these differences between the two collector types in both years were not expected, particularly since the IrriGage collectors had a larger opening size (10 cm) than the current ASAE standard (minimum of 5.0 cm; ASAE, 2001) for uniformity measurements from center pivot sprinkler packages. Year to year (1999 vs. 2000) differences in measured irrigation depths from low pressure fixed plate sprinklers using IrriGage collectors were attributed to: collector opening size, collector height, and possible crop canopy effect on the discharged water trajectory patterns.

2002 Results

Mean irrigation depths from all 2002 collectors and arrangements with corresponding data set variance values under the FP, SP, and WP sprinkler packages are presented in table 2. Average irrigation depths from the FP package using 15 cm and single IrriGage collectors were significantly different at 14.4 and 17.4 mm, respectively (table 2). The single row of IrriGage collectors consistently over-estimated irrigation depths by 20.8% similar to the results in 2000 under another fixed plate sprinkler package. In addition, data collected with IrriGage collectors were also significantly more variable (table 2) than with the 15 cm collector and did not mimic the individual 15 cm collector results (data not shown).

Differences in measured depths and associated variances under the rotating plate sprinkler packages (SP and WP) were consistent with one another (table 2). Measured irrigation depths from all collector arrangements under the SP and WP sprinkler packages followed similar trends with relatively close measured mean depths and low variability in the data from IrriGage and 15 cm collectors. However, single row IrriGage-based depths under SP and WP sprinklers were still significantly higher than 15-cm collector depths by 7.0% and 4.1% respectively. The associated variance in the 15 cm collector data sets from the under the SP sprinklers (0.025) and WP sprinklers (0.027) was relatively low and was significantly lower than the associated single row IrriGage variance (0.103 and 0.100) from those same two sprinkler packages. Yet, the 10 cm IrriGage collectors provided good pattern representation from individual collectors as compared to 15 cm collectors under both spinning plate and wobbling plate sprinklers (data not shown). These sprinkler packages have greater droplet breakup and smaller droplets as compared to the fixed plate sprinklers.

Coefficient of uniformity (CU) values from 10 cm IrriGage collectors were lower than corresponding CU values from the 15 cm collectors (table 6) under all three sprinkler packages. However, an analysis of variance (ANOVA) showed that CU value differences were not significant within any of the sprinkler packages from the various collector arrangements. CU values under the fixed plate sprinkler were substantially lower than those under the other sprinklers and correspond to the large variances in data associated with that sprinkler package (table 3). This typically due to the distinct jets of water that are common with those types of sprinklers. Those jets can result in application patterns with a harmonic pattern that has relatively large amplitude variations (Clark et al., 2003), which can be difficult to accurately measure with a collector that has a relatively small opening.

The addition of another set of 10 cm IrriGage collectors either as a Side-by-Side set or as another Inline set did not improve depths or variability in measured data (table 2), or CU values (table 3). Measured results were very similar to those from the single row of 10 cm IrriGage collectors. Therefore, it appears that size of an individual collector is more important than an increase in total surface area by using multiple collectors.

Table 2. Average irrigation depths and variances for the collectors evaluated under the fixed plate (FP), spinning plate (SP), and wobbling plate sprinklers in 2002.

Sprinkler Package: Collector Size / Arrangement	Mean Depth (mm)[£]	Difference from 15 cm Gage (%)	Variance (mm2)[§]	Coefficient of Variation
Fixed Plate – 2002A:				
15 cm	14.4	--	33.3	0.40
10 cm Single	17.4 ***	20.8	62.8 **	0.45
10 cm Side-by-Side	17.3 ***	20.1	58.0 **	0.44
10 cm Inline	17.5 **	21.5	78.6 ***	0.51
Spinning Plate – 2002A:				
15 cm	14.2	--	2.5	0.11
10 cm Single	15.2 *	7.0	10.3 ***	0.21
10 cm Side-by-Side	15.1 **	6.3	6.2 ***	0.17
10 cm Inline	15.4 **	8.5	5.7 ***	0.16
Wobbling Plate – 2002B:				
15 cm	19.6	--	2.7	0.08
10 cm Single	20.4 *	4.1	10.0 ***	0.16
10 cm Side-by-Side	21.1 ***	7.7	11.1 ***	0.16
10 cm Inline	21.1 ***	7.7	12.5 ***	0.17

[£] Mean depths for a specific sprinkler package were significantly different (paired t-test) from the 15 cm collector values at the 10% (*), 5% (**) or 1% (***) level of significance.

[§] Calculated variances for a specific sprinkler package were significantly different (F-test) from the 15 cm collector variances at the 10% (*), 5% (**) or 1% (***) level of significance.

Table 3. Average coefficient of uniformity (CU) values for the collectors evaluated in 2002 under the fixed, spinning and wobbling plate sprinklers.

Collector Size / Arrangement	Fixed Plate	Spinning Plate	Wobbling Plate
15 cm	66.6	94.2	90.8
10 cm Single	58.9	88.2	87.2
10 cm Side-by-Side	61.6	89.7	85.5
10 cm Inline	61.9	90.5	85.6
Significance[£]	NS	NS	NS

[£] Data were analyzed using ANOVA procedures; NS = Not significant..

SUMMARY AND CONCLUSIONS

In 1999, 2000, and 2002, field studies were conducted to evaluate the measurement effectiveness of a non-evaporating sprinkler irrigation catch device (IrriGage). In 1999 and 2000 IrriGage collectors were compared to 43 cm diameter pans (PAN). Tests in 2002 compared different arrangements of 10 cm IrriGage to15 cm diameter collectors. All collectors were tested to measure sprinkler irrigation system depths and uniformity under different sprinkler irrigation packages. Sprinkler irrigation packages tested included fixed-plate diffusers (FP) with grooved-disks, spinning-plate diffusers (SP), and wobbling plate diffusers (WP) with different nozzle and pressure combinations. FP sprinkler packages had distinct water jet streams with larger water droplets, while SP and WP sprinklers had smaller water droplets that appeared to be evenly distributed.

In 1999, IrriGage collectors positioned within a corn canopy failed to accurately measure the irrigation depths and sprinkler patterns. Even with higher irrigation pressures (103.0 to 138.0 kPa), IrriGage collectors did not reasonably measure irrigation depths or patterns as compared to PAN collectors. In 2000, even though the IrriGage collectors were lowered and repositioned into a grass buffer, measured irrigation depths and CU values were significantly ($p < 0.05$) higher than associated data from PAN collectors. In addition, irrigation application patterns from the IrriGage collectors under the FP sprinkler package with different pressure combinations did not match the PAN results.

In 2002, IrriGage collector evaluations under fixed plate (FP), spinning plate (SP), and wobbling plate (WP) irrigation packages indicated greater irrigation depths and lower CU values than 15 cm collectors, similar to 2000 results. Additionally, IrriGage collector results did not accurately measure nor mimic the FP irrigation patterns as compared to the 15 cm collectors.

The results of this work indicate that further work is needed to determine an appropriate collector size (and perhaps shape) for the measurement of irrigation depths from center pivot and linear move irrigation machines with lower pressure sprinkler packages. This is particularly needed for the fixed plate, grooved disk sprinklers that provide distinct jets of water with little pattern breakup.

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Moderately Priced SCADA for Mutual Irrigation Companies

by

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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 to consider is a Supervisory Control and Data Acquisition System (SCADA), which can provide for 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.

SCADA systems were once perceived to be too costly for most mutual irrigation companies or small irrigation districts but the hardware is decreasing in cost and becoming much more affordable for agricultural situations. The opportunity, the costs, and the benefits of SCADA for mutual irrigation companies are explored in this paper.

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 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 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 chart recorder

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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. SCADA can provide smaller companies a lot of bang for the buck including improved canal operations and can even be a factor in protection of the company's decrees.

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.

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 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 three differentiating levels of SCADA implementation can be described by their respective function and utility to the canal company.

- ☐ Monitoring (only)
- ☐ Remote manual operations
- ☐ 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.

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 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 gate which is integrated with SCADA.

A Case Study: 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 just 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) 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 four 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.

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. 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.

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.

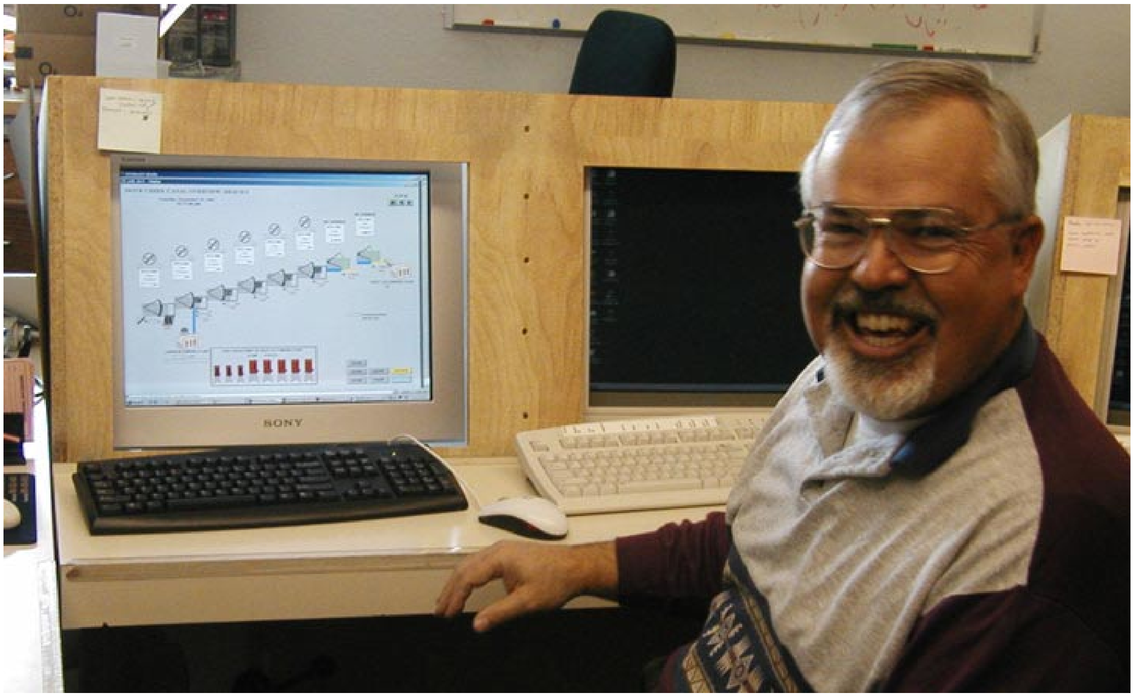

Figure 2. Chuck Lurvey, district engineer for the Delores Project in Cortez, Colorado, is sitting in front of the SCADA central computer. Radial gate icons on the HMI screen indicate the water surface level in the canal and the gate positions of the radial gates at checks along the canal.

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 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.

Water Measurement Options in Low-Head Canals and Ditches

by

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September 2003

Measuring water in open-channel water-ways with low available head continues to challenge engineers and water managers. Over the past few years improvements and adaptability of fixed canal devices, such as the ramp flume, have become a popular tool of water measurement. However, in situations when backwater (from moss buildup or from canal operations) submerges structures or when there is not sufficient head for a standard device, an operator is left with very few options.

1. BACKGROUND

In the mid-1990s, engineers and technicians developed an ultrasonic device to determine, using profiling Doppler principles, the flow of liquid waste moving through sewers in New York City. The instrument was located on the bottom of the sewer pipe and contained a depth sensor. It combined velocity readings with the cross-sectional area of the channel (programmed into the device) to produce a flow rate. This profiling Doppler flow meter proved successful in several tests, but it carried a substantial price tag, over $20,000. It was only cost-effective to use in larger-volume canals (500 cfs and above) where a fixed structure for such data-gathering would be even more expensive or where a flow rate was desperately needed to ensure efficient canal operations.

In the late 1990s, a series of less-expensive ultrasonic Doppler measurement devices, the “StarFlow” line, was engineered by an Australian firm, Unidata. These instruments use continuous Doppler to determine average velocity and flow. The price of one model of the Unidata instruments ($1,500) suggested the device could be cost-effective in several water-measurement situations, including those for smaller canals.

The potential cost benefits of the StarFlow warranted investigation of its performance under field conditions. In 2003, the Water Conservation Center of the Bureau of Reclamation’s Pacific Northwest Region conducted demonstrations of the StarFlow at two sites, one in Oregon and the other in Idaho. These sites were chosen based on canal configuration, range of flow, and the interest and cooperation of the two water districts.

2. THE INSTRUMENT

The Unidata ultrasonic Doppler instrument chosen for this demonstration was the StarFlow Model 6526C (for water less than 2 meters in depth). It is 11 inches in length, 2½ inches in width, and 1 inch in height (see Photograph 1). The instrument contains a pressure transducer and two sensors that measure velocity. It transmits an ultrasonic signal that when measured for Doppler shift and read with other data derives volume. The instrument is designed to be installed on the bottom of the canal with a signal cable leading to the surface data logger.

The StarFlow measures water velocity within a 15 degree "field of view" looking forward and upward. This velocity is then applied to a cross-sectional area determined by the measured depth and a user-specified cross-section configuration entered into the device during set-up. In wider channels, it is possible that the velocities measured within the device's field of view would not be representative of the average velocity for the entire cross-section. In theses cases, it is necessary to adjust the "measured velocity" value. This is done by making a proportional adjustment in the "speed of sound in water" parameter in the StarFlow set-up parameters.

Photograph 1. *The Unidata StarFlow ultrasonic Doppler flow meter contains a pressure transducer and two velocity sensors. The instrument is 11 inches in length, 2½ inches in width, and 1 inch in height. It can be installed facing upstream or downstream.*

3. SMALL CANAL DEMONSTRATION

The Talent Irrigation District is served by Reclamation's Rogue River Basin Project in southwestern Oregon. Its Crooked Creek Siphon on the Talent Canal (near Medford) was chosen for the first demonstration site. Flows in the Talent Canal range from 2 cfs to 15 cfs and enter the siphon just downstream from the measurement site (see Photograph 2).

The canal in this area has a flat gradient and little freeboard. The site was surveyed for the installation of a ramp flume designed to operate in all flow ranges and conditions. The ramp flume design would require that additional freeboard be established upstream of the measurement site. A bypass/overflow gate which can route canal flows to Crooked Creek is located next to the downstream siphon entrance. Because of the variability of the siphon and bypass structure, a rated section with a staff gage would not be consistent.

Photograph 2. *View is looking upstream in the Talent Canal at the Crooked River Siphon entrance. The StarFlow instrument was installed upstream of the wooden bridge. This section of canal experiences backwater when the spill to the river is not operated. The canal capacity is about 15 cfs.*

At the Talent Canal site, a data logger (Campbell Scientific Model CR10X) was used as part of the demonstration. The separate data logger allowed additional parameters to be added to the demonstration. A separate float well was installed so that the data from a float-operated depth sensor could be compared against the data from the internal pressure transducer (Photograph 1). The data logger was connected to a dial-up phone system so that the data could be downloaded by and monitored at the irrigation district's office.

The cross-sectional area of the channel was measured and programmed into the data logger. Using the velocity from the demonstration instrument and the cross-sectional area for a given flow depth the flow rate is calculated by the data logger. The demonstration instrument was installed and the canal flows were turned on. Once the instrument was operating, a current meter measurement was made and an average velocity was calculated (see photograph 3).

The average velocity calculated from the current meter measurement was approximately 25 percent lower than the velocity reading from the demonstration instrument.

To compensate for this difference, a “velocity shift” was programmed into the data logger to use in the flow-rate calculation. On later flow checks using the current meter, the flow rate indicated by the demonstration instrument were within 3 percent of the current metered flows.

Photograph 3. *At the Talent Canal site current-meter measurements were made to provide data which were used to calibrate the velocity readings from the StarFlow instrument. Calibration was required at each demonstration site.*

The pressure transducer worked exceptionally well when compared with the depth data from the float well. Figure 1 shows the correlation of the depth versus depth plot is 99.7 percent. Figure 2 shows that 99 percent of the time the pressure transducer was within 0.01 feet of the float well reading.

Photograph 4. *This view of the site on Talent Canal shows the equipment cabinet containing the data logger and dial-up equipment. The technicians are installing the float well equipment which was used to verify the depths obtained from the pressure transducer in the Starflow instrument.*

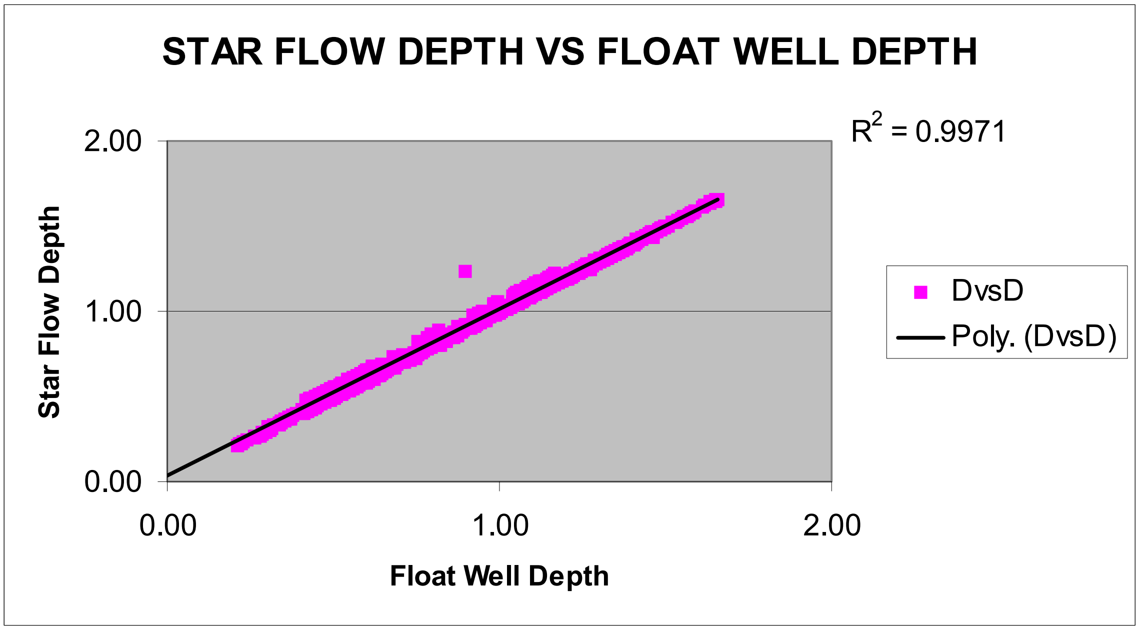


Figure 1. *The float well data at the Talent Canal site agreed very closely with the data from the StarFlow pressure transducer.*

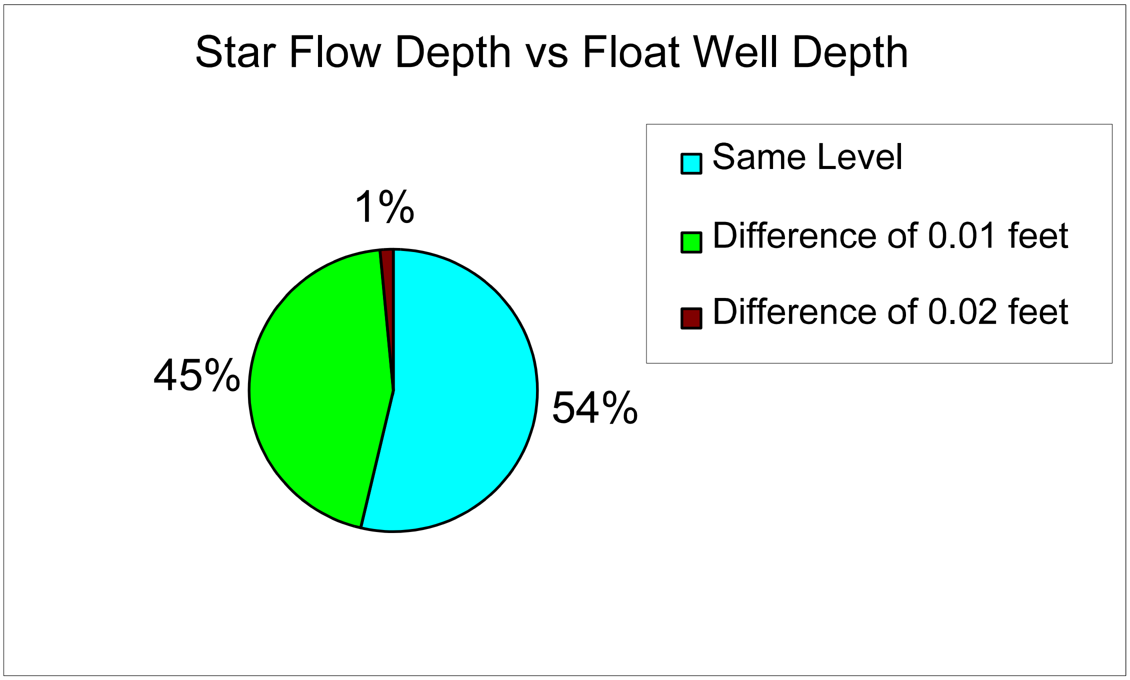


Figure 2. *Depth readings from the two different data sources at the Talent Canal site were within 0.01 foot of each other 99 percent of the time.*

4. LARGE CANAL DEMONSTRATION

The South Board of Control in Homedale (southwest Idaho) is supplied by water delivered through the South Canal from Reclamation's Owyhee Project. The canal carries up to 500 cfs and is operated and maintained by the South Board of Control. The measurement site in the South Canal was located at the terminus of a rock tunnel; this site has been used for flow measurements for several years. The site is a trapezoidal section of concrete lining with a foot bridge to facilitate current metering for the rated section (see Photograph 5). The rated section functions well in the early months of the irrigation season; however; as aquatic growth continues into the late summer periods, water is backed into the rated section and the rating table becomes inaccurate.

***Photograph 5**. The view is looking downstream at the South Canal measurement site. The StarFlow instrument was installed in the concrete section. Canal capacity is approximately 500 cfs. This site was chosen because there is a well-defined, stage-discharge curve which could be compared with the data gathered from the demonstration instrument.*

Flows at this site are up to 5.5 feet deep (see Photograph 6). It is a long-term measurement site and there is a well established stage-discharge curve to compare against values obtained by the demonstration instrument. At this site, the data were recorded by the StarFlow data logger purchased with the demonstration instrument. The stage-discharge curve was checked using a current meter at different times during the summer. The current meter measurements correlated very well with the stage-discharge curve.

The pressure transducer depths were compared with visual staff gage readings each time the station was visited. The two readings were never more that 0.01 feet different on any of the visits.

The demonstration instrument was installed on May 22, 2003 in the center of the concrete-lined section at the measurement site. The demonstration device was operated 20 days before the first calibration was made. Figure 3 displays the flow data gathered by the data logger compared with calculated flows from the stage-discharge curves for the recorded depths. It shows that the demonstration instrument was indicating a flow about 9 percent higher than the stage-discharge curve.

After the first adjustment, the instrument was operated 9 days. A review of the data indicated that the earlier adjustment had been excessive. The data indicates that the demonstration instrument was indicating a flow about 4 percent lower than the stage-discharge curve (see Figure 4). Another calibration adjustment was made.

The demonstration instrument was then operated from June 20 to July 24, 2003. The flow rate data collected by the demonstration instrument was within 1 percent of the flow rate calculated from the stage-discharge curve (see Figure 5).

The flow depths at this site were up to 5.5 feet. The velocity measurements from the demonstration instrument fluctuate up and down which creates a wide plot line. The average of the data, however; correlates well with the stage-discharge curve calculations. The data seem to indicate that the deeper the flow the wider the range of fluctuation.

***Photograph 6**. At the South Canal site, flow depths varied from 3.5 feet to 5.5 feet during the 2003 irrigation season. Current meter measurements were made from the foot bridge.*

With a correlation of greater than 99 percent, no calibration adjustments were made on the July 24th visit.

On September 4, 2003 data were again downloaded as the water district was near the end of its irrigation season. The data plot (see Figure 6) indicates that for a short period in mid August the flow rate calculated from the stage-discharge curve was nearly 50 cfs higher than the flow rate recorded from the demonstration instrument. It appears that the demonstration instrument was able to adjust for a backwater situation and plot a more reliable flow rate during the backwater period.

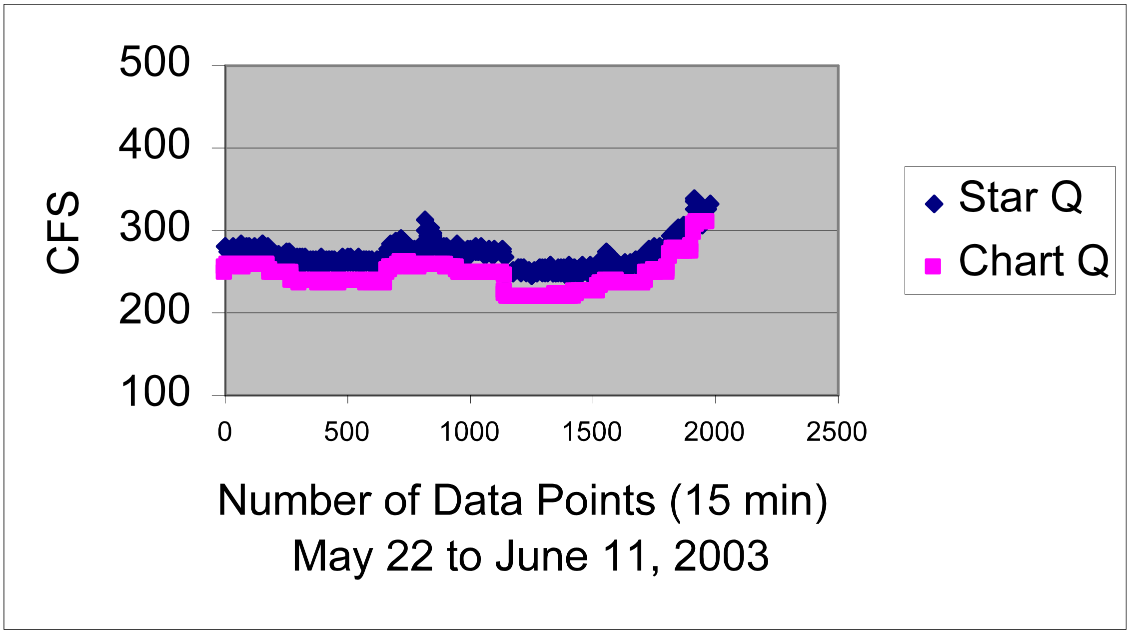


***Figure 3. South Canal Site** — For the South Canal site, the plot shows that before any calibration was attempted, the StarFlow was reading approximately 9 percent higher than the stage-discharge curve.*

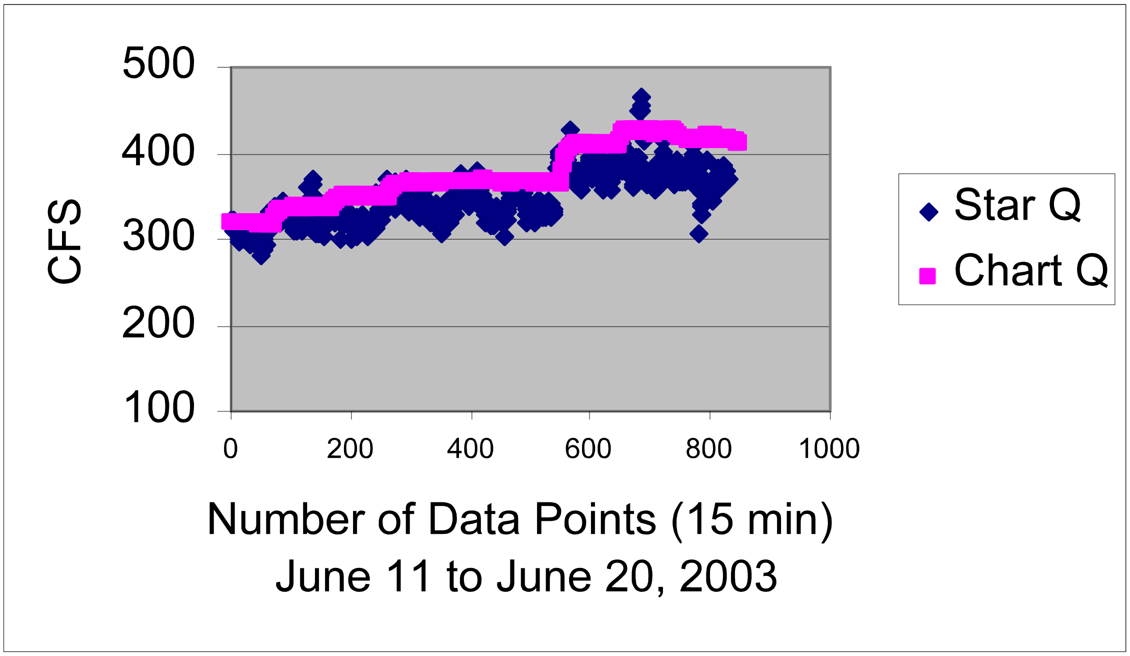


***Figure 4. South Canal Site** — The plot shows that the calibration adjustment was excessive as the StarFlow readings are approximately 4 percent lower than the stage-discharge curve.*

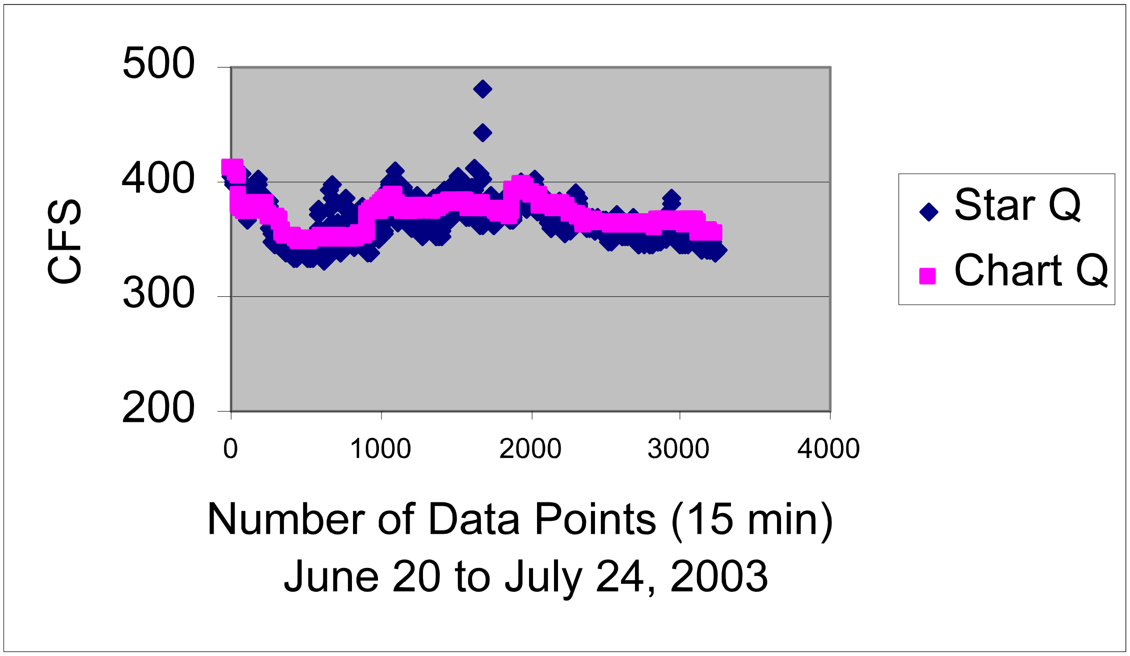


Figure 5. South Canal Site *— The second calibration adjustment brought the average of the StarFlow flow readings to within 1 percent of the stage-discharge curve tabulations.*

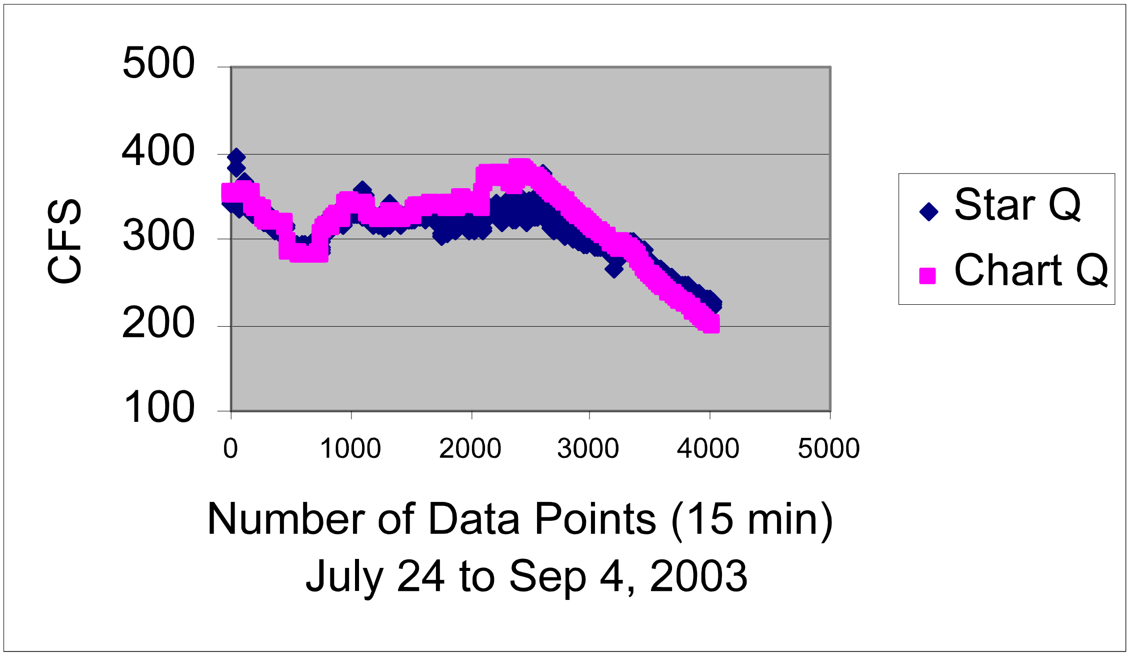


Figure 6 – South Canal Site *– The StarFlow data tracked the stage-discharge until mid August when aquatic growth backed water into the measurement site. The StarFlow instrument senses the slower velocities in a backwater situation and calculates accordingly. In contrast, a stage-discharge curve inaccurately shows more flow in a backwater situation.*

5. OBSERVATIONS AND CONCLUSIONS

- The water depths indicated from the pressure transducer of both demonstration units proved to be reliable when compared with staff gage readings and float well data.

- The demonstration instruments had to be calibrated after installation. Whether or not additional calibrations are needed at different flow ranges was not determined.

- The equipment stayed up and functioned during the entire demonstration period. The data loggers recorded properly with no malfunction or missing data.

- The irrigation district operating the Talent Canal used the telephone dial-up to obtain instantaneous data on the canal status. The district operators then used the flow data and canal-depth data to make operating decisions. The water district is pleased with the demonstration results and is looking for other locations to install additional instruments.

- In the Talent Canal, with a maximum flow rate of 15 cfs, the real-time data was very useful to the irrigation district in making daily water management decisions.

- At the South Canal site, with larger flows and a larger cross-section, there was too much variability in the instantaneous flow measurements to be of real-time use to system operators, particularly at higher flows. Over longer periods, however, the accumulated flow totals were generally within 1 percent of total calculated using the stage-discharge curve.

- The demonstration instrument may prove to be very useful in small canals with limited head. More demonstrations need to be made in larger canals and in canals with significant turbulence.

Canal Velocity Indexing at Colorado River Indian Tribes (CRIT) Irrigation Project in Parker, Arizona using the SonTek Argonaut SL

Authors: Dr. Stuart Styles P.E., Mark Niblack, Beau Freeman

Abstract

An index velocity rating was developed for a SonTek/YSI Argonaut Side-Looking (SL) ultrasonic Doppler flow meter installed in the Main Canal of the Colorado River Indian Tribes (CRIT) Irrigation Project in Parker, Arizona. Velocity data collected concurrently with the ultrasonic flow meter and conventional current meter were compared using linear regression techniques. The rating equation for this installation provides a reasonably accurate means of computing discharge. This project was completed by the Irrigation Training and Research Center (ITRC), California Polytechnic State University, San Luis Obispo, working under a technical assistance contract for the Water Conservation Office, United States Bureau of Reclamation (USBR), Yuma, Arizona.

The procedure used in the evaluation included multiple measurements over a range of low, medium, and high flows. This approach verified the validity of discharge measurement through analysis of coefficients of determination and by comparison of discharges computed from the ratings to measured discharges.

Introduction

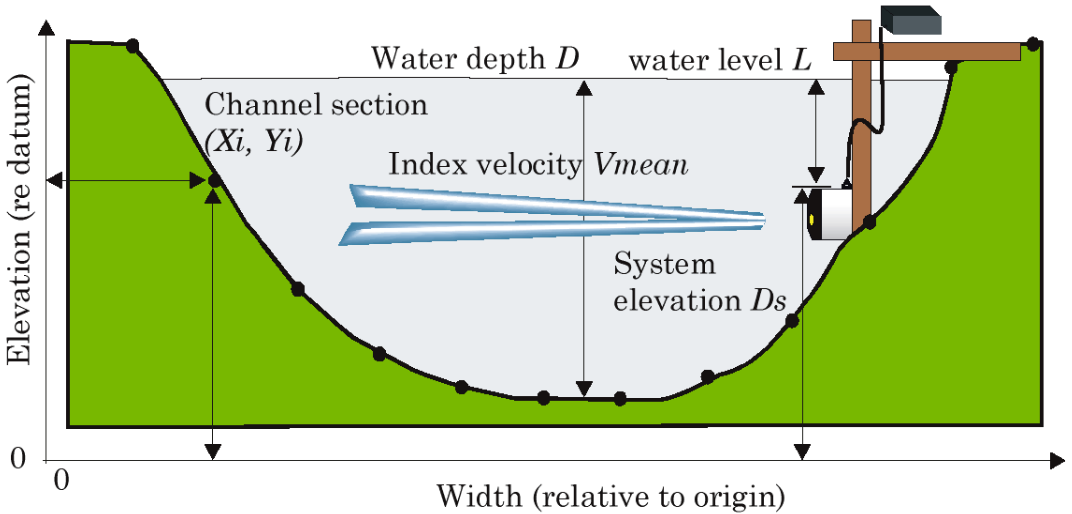
This paper is a summary of an application of the Index Velocity Rating Procedure for a SonTek/YSI Argonaut™ Side-Looking (SL) 1.5-MHz acoustic Doppler current meter. The Argonaut SL has the ability to perform internal discharge computations as the product of mean channel velocity and cross-sectional area. The index coefficients for establishing the empirical velocity relationship in a channel are determined through regression analysis. Computing flow with the internal flow algorithm requires the user to input a specific velocity equation and the channel geometry defined by up to 20 cross-sectional points (x-y pairs).

The discharge and velocity measurements presented in this paper were collected in the Colorado River Indian Tribes (CRIT) Main Canal. Current metering was done following procedures established by the USBR in their Water Measurement Manual (USBR 2001). The actual Argonaut SL measured velocity values are used to illustrate the index velocity rating technique and the development of an equation to accurately produce discharge records using hydroacoustic instruments. The process discussed in this paper is a modification of the procedure outlined by the USGS for indexing (USGS 1998).

Utilizing electronic flow rate measurement equipment that can cost less than 10 percent of a large concrete flume is attractive economically. However prior to the use of this indexing procedure, there was much uncertainty of the overall accuracy in the use of a flow meter such as the Argonaut SL in some irrigation canal applications.

Basic Operation Principle

The SonTek/YSI Argonaut SL measures 2-dimensional horizontal water velocity in an adjustable location and size of the sampling volume using the physical principle termed the Doppler shift. The Argonaut transducers measure the change in frequency of a narrow beam of acoustic signals in order to compute along-beam velocity data. Beam velocities are converted to XYZ (Cartesian) velocities using the known beam geometry of 25° off the instrument axis.



source: SonTek/YSI Argonaut
Operation Manual

Figure 1. SonTek/YSI Argonaut SL channel geometry for internal flow computations

Basic Deployment Instructions

To determine an index velocity rating, concurrent mean channel velocity and Argonaut SL measured velocities are required. The following steps outline the basic procedures one follows in collecting velocity and stage data for developing an index velocity rating. The result is a dataset comprised of i) a mean velocity, ii) average Argonaut SL velocity, and iii) average stage.

1. An Argonaut SL is installed with the appropriate deployment settings and mounting bracket. Site selection is an important consideration and the diagnostic guidelines provided in the manufacturer's technical documentation should be carefully observed. These diagnostic parameters include an assessment of the signal strength and standard deviation for a given set of operating conditions.

2. The channel is accurately surveyed and a stage-area rating is developed. Elevations for the cross-section points are in terms of stage referenced to the station datum.

3. Discharge measurements (Price AA current metering or comparable device) are made near the Argonaut SL site while the instrument is sampling velocity.

4. The average stage during the discharge-measurement period is recorded.

5. Mean channel velocity is derived for each individual discharge measurement by dividing the measured discharge by the channel area computed from the stage-area rating.

6. For each discharge measurement, Argonaut SL measured velocities are averaged for the discharge-measurement period. For the Argonaut SL, the velocity x-component or the computed velocity vector can be used for the measured velocity.

7. Each discharge measurement yields a computed mean channel velocity and an average Argonaut SL velocity.

8. The index velocity rating procedure recommended by the ITRC requires a wide spread in the measured discharge (a 2:1 ratio), usually at least 10 measurement values over the entire range of flows. The regression coefficient (r^2) must be better than 0.96 to assure confidence in the results.

This discussion does not attempt to provide a detailed description of all the technical issues involved with the deployment of the instrument for a desired level of accuracy. The performance of the Argonaut SL depends on considerations such as the influence of boundary interference, proper alignment with the flow, appropriate settings of the averaging and sampling intervals, and cell size. A further limitation in the operation of the Argonaut SL is the aspect ratio, which is defined as the ratio of the measurement range to height. Range is horizontal distance from the instrument and height is the vertical distance to the surface or bottom. It is strongly recommended to use the Argonaut SL for aspect ratios greater than 5:1. It is not recommended for aspect ratios less then 5:1. A bottom-mounted unit looking toward the water surface is recommended for those applications.

Measurement Results

A total of eight discharge measurements were collected in the CRIT Main Canal. The measured stage, computed mean channel velocity determined by current meter, and the Argonaut SL measured velocity are summarized in **Table 1.**

Table 1. CRIT Main Canal Current Meter and Argonaut SL Velocity Measurements

No.	Stage, feet	Current Meter Velocity, fps	Argonaut SL Velocity, fps
1	11.80	1.19	1.29
2	12.20	1.19	1.39
3	11.30	2.05	2.08
4	11.30	1.97	2.09
5	11.80	3.00	2.95
6	11.80	2.97	3.06
7	10.50	1.48	1.42
8	10.50	1.47	1.42

Index Velocity Rating Development

An index velocity rating is developed in this section to relate the mean channel velocity to the velocity measured by the Argonaut SL in the CRIT Main Canal. For some operating conditions, the index velocity relation may be linear, while in other situations the relation may be best expressed as curvilinear or a compound curve (USGS 2002). In each instance, the user should assume that stage might be a significant factor in the accurate prediction of mean channel velocity. This situation where the relationship between mean velocity and Argonaut measured velocity is affected by stage is handled by performing a multiple linear regression.

If the relation between the mean channel velocity and the measured Argonaut SL velocity is linear, it can be represented by a linear equation as follows:

$$V_m = xV_{SL} + C$$

where,

V_m = computed mean velocity
V_{SL} = average measured Argonaut SL velocity during one measurement period
x = velocity coefficient
C = constant

The first step in determining whether a linear relation exists is to plot mean velocity (y-axis) and Argonaut SL velocity (x-axis). **Figure 2** is a graph of the velocity dataset for the CRIT Main Canal in **Table 1**.

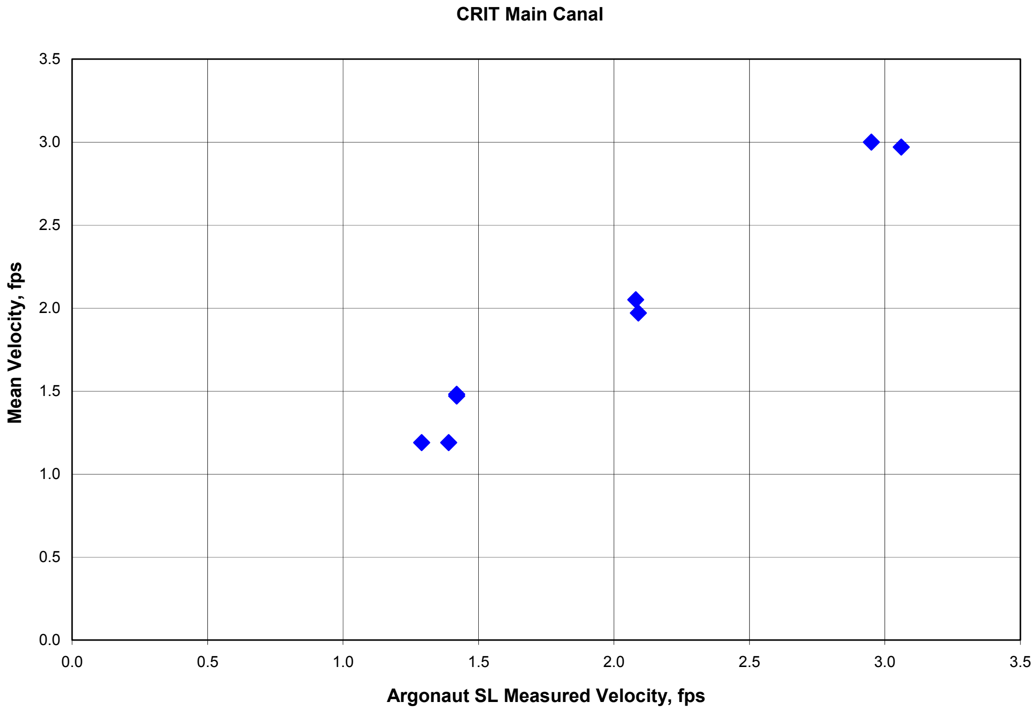


Figure 2. Mean velocity and Argonaut SL velocity from discharge measurements in the CRIT Main Canal

The next step is to derive the linear equation and compute the coefficient of determination (r^2). The r^2 value indicates what percentage of the variation in mean velocity can be explained by the variation of Argonaut SL velocity.

A simple method for determining the equation coefficient and constant along with the r^2 value is the linear regression tool in Excel® spreadsheets.

The linear index velocity rating equation determined for the CRIT Main Canal dataset in **Table 1** is shown below:

$$V_m = 1.015V_{SL} - 0.077$$

Figure 3 shows the index velocity rating from least-squares regression. The r^2 value of 0.98 indicates that 98 percent of the variation in the mean velocity can be explained by the variation in the Argonaut SL velocity.

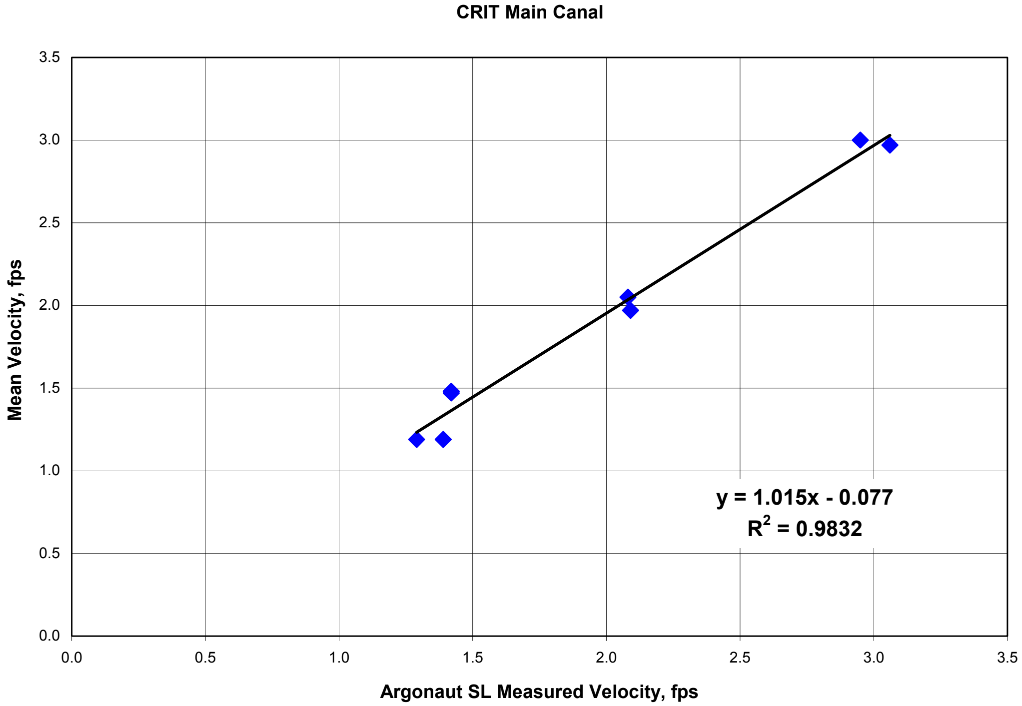


Figure 3. Index velocity rating using simple linear equation ($r^2 = 0.98$)

The above analysis assumed that the Argonaut SL measured velocity is the only parameter to consider when determining the index velocity rating. However depending on the site's hydraulic conditions, stage may be a significant factor in the prediction of mean channel velocity using a side-looking acoustic Doppler velocity instrument.

An equation that relates both the Argonaut SL velocity and stage to mean velocity is:

$$V_m = V_{SL}(x + yH) + C$$

where,

V_m = computed mean velocity
V_{SL} = average measured Argonaut SL velocity during one measurement period
x = velocity coefficient
y = stage coefficient
H = stage
C = constant

The values of the coefficients and constant in the index velocity equation can be determined from the multiple linear regression analysis where mean velocity is the dependent variable and the independent variables are the Argonaut SL measured velocity and the product of measured velocity and stage.

Using multiple regression analysis, the equation and r^2 value determined for the CRIT Main Canal dataset in **Table 1** assuming that stage is a factor is:

$$V_m = V_{SL}(1.995 - 0.080H) - 0.192$$
$$r^2 = 0.99$$

Figure 4 shows the relationship between the mean velocity and the computed index velocity using multiple linear regression.

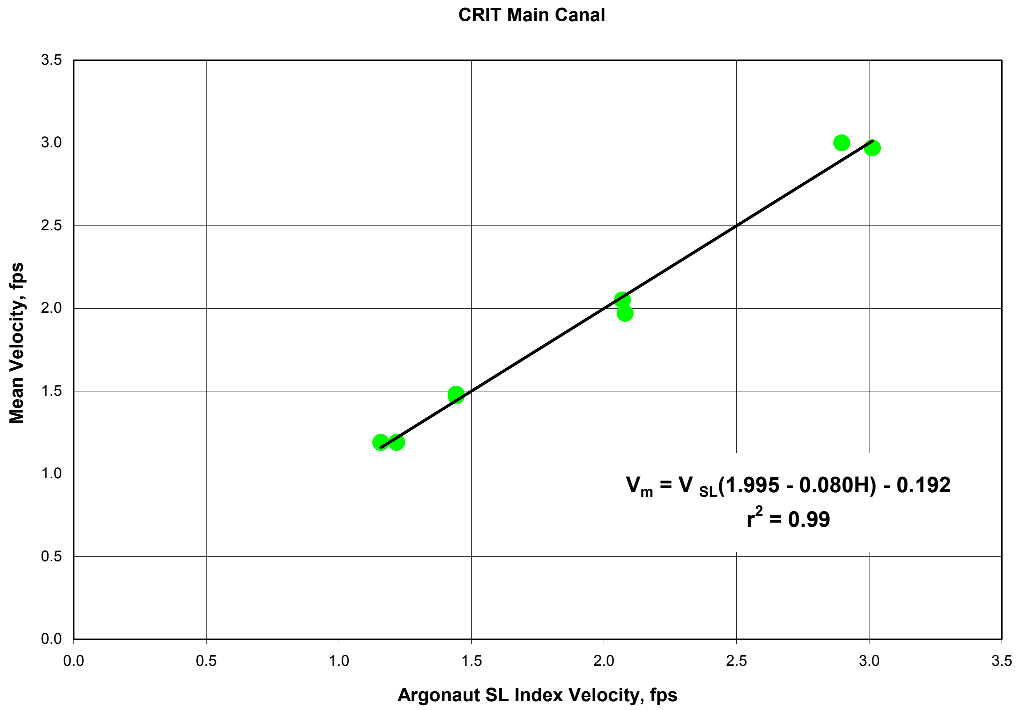


Figure 4. Index velocity rating using multiple regression equation

Results

Table 2 summarizes the computed discharge using both index velocity equations and the percent error relative to the current meter measurements. The flow rate (Q = VA) was computed using the index velocity and channel area based on the measured stage and a bottom width of 25 ft and side slope of 1:1.

Table 2. Discharge (cfs) and percent error using simple linear regression and multiple regression with stage

No.	Current meter discharge, cfs	Simple linear equation no stage		Multiple regression with stage	
		cfs	% error	cfs	% error
1	514	535	4.1%	503	-2.1%
2	540	605	12.1%	553	2.4%
3	841	834	-0.8%	849	0.9%
4	805	839	4.2%	853	6.0%
5	1318	1267	-3.9%	1258	-4.6%
6	1304	1315	0.9%	1308	0.3%
7	562	509	-9.5%	538	-4.3%
8	547	509	-7.0%	538	-1.7%

Conclusion

The index velocity rating determined using the multiple linear regression analysis with stage is generally closer to the discharge measured with a current meter. The percent error of the index velocity for the simple linear equation and the multiple linear regression equation is approximately ±10% and ±6%, respectively. In other words, the inclusion of stage as a factor in determining the index velocity rating for this particular dataset improved the accuracy by about ±4%. It is recommended to always include stage in the development of an Index Velocity Rating Procedure. The final equation can be readily programmed into the instrument for use with the internal flow computations option.

Figure 4. SonTek/YSI Argonaut SL installed in a canal

Due to the inherent problems in using current metering as the reference flow rate, future evaluations will be done using other rapid measurement techniques. The issues with current meters include; poorly defined cross-sections, fluctuating flow rates, moss hanging on meter, etc. Potential technologies include using the portable Doppler meters that can be mounted to boats and rapidly determine the flow rate in a canal.

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Soil Characterization for Fields Irrigated with Recycled Saline Drainage Waters

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Abstract: In California, it is estimated that 4.5 million acres are salt-affected—primarily on the Westside San Joaquin Valley (SJV). In addition to soil salinity, high water tables and boron toxicity are chronic problems for Westside SJV agriculture. Drainage water re-use is considered to be one of the more sustainable and environmentally responsible options for drainage management because the salt, selenium and boron are managed on-farm and do not go off-site to compromise water quality in nearby water bodies. In 1996, an Integrated on-Farm Drainage Management (IFDM) system was developed as a demonstration project at the Red Rock Ranch (RRR) out on the Westside SJV. For the past four years, one focus of our research at the RRR IFDM demonstration project has been the soil characterization of fields at the RRR. The major objective of the soil characterization is to assess the changes in soil salinity of fields subjected to irrigation with recycled saline drainage. Within the last year, we have been conducting infiltration studies in an effort to evaluate the effectiveness of surface applications of gypsum on infiltration rates of the fields receiving the recycled saline drainage water. From soil samples collected down to five feet, it is evident that in the areas receiving relatively better quality canal water, leaching is occurring as indicated by the relatively lower salinity at shallow depths. However, for fields irrigated with the most saline recycled drainage water, there is extreme salt accumulation and sodicity in the top foot of soil. Furthermore, the high degree of spatial variability of soil salinity inferred from non-invasive electromagnetic induction mapping suggests that there is need for more intensive soil management in the fields receiving the relatively higher saline drainage water. Preliminary results have indicated that steady state infiltrability rates averaged at 2.1 cm h^{-1} and 1.7 cm h^{-1} for the gypsum plots in areas receiving canal water and the recycled drainage water, respectively. For the non-gypsum plots, values ranged from 0.7 to 1.0 cm h^{-1} for both areas. Future research should continue to assess changes in the soil chemical and hydraulic properties of the fields at the RRR irrigated with the recycled saline drainage water.

Introduction: Historically, salinity has been a constraint to irrigated agriculture (van Schilfgaarde, 1990). In California, it is estimated that 4.5 million acres are salt-affected—primarily on the Westside San Joaquin Valley (SJV) (Letey 2000). The westside SJV is not in salt balance and the magnitude of the problem is revealed in the estimate of a net import of salt to the Westside in state and federal irrigation water projects (subtracting out natural drainage to the San Joaquin River) of 40 railroad cars daily (San Joaquin Valley Drainage Implementation Program, 1998). Furthermore, the region's soils are derived from alluvium originating from the once submerged coastal mountains and so they contain high concentrations of salts and elements typical of a marine environment (Letey, 2000). In addition to soil salinity, high water tables and boron toxicity are chronic problems on the Westside SJV. The combined Westside acreage that is drainage impacted (groundwater 5 feet or less from the surface) averaged nearly 500,000 acres in the last decade (SJV Implementation Drainage Program, 1998).

Both drainage and salinity compromise the profitability of Westside agriculture not only by reducing yields, but often by limiting crop choices to low value row crops rather than higher value, salt sensitive, vegetable crops. Furthermore, because of political, economical and environmental factors, the west side farmers are not allowed to freely discharge their drainage water. For example, as a result of the high selenium content of the drainage water that was responsible for migratory waterfowl toxicities, the Kesterson Reservoir was closed in 1986, thereby forcing the plugging of drain lines in the Westlands Water District that were contributing drainage flows to the reservoir (Letey et al. 1986).

Drainage water re-use is considered to be one of the more sustainable and environmentally responsible options for drainage management because the salt, selenium and boron are managed on-farm and do not go off-site to compromise water quality in nearby water bodies (Grattan et al., 1999, 1997). In 1996, a sequential drainage water re-use demonstration project, now called IFDM, was initiated at Red Rock Ranch (RRR) to test the feasibility of irrigating salt tolerant crops, forages and halophytes with drainage water so as to reduce its volume prior to discharge into a solar evaporation system. As designed in 1996 (**Figure 1**), high quality canal water (**Table 1**) is used to irrigate **Area A** that is in transition from low value row crops to higher value vegetable crops. Drainage collected from **Area A** plus tailwater is applied to **Area B** ***(1st re-use)*** containing salt tolerant row crops. Drainage from **Area B** is applied to **Area C** ***(2nd re-use)*** where salt tolerant forages are grown. The tertiary drainage (**Table 1**) is applied to **Area D** (***3rd re-use)*** where only halophytes are grown due to the high salinity and boron (ECe 30 - 50 dS/m and boron 25 - 50 mg /kg soil). Finally, the drainage is discharged into a solar evaporation system (1% land area) for rapid evaporation of water and precipitation of the salt.

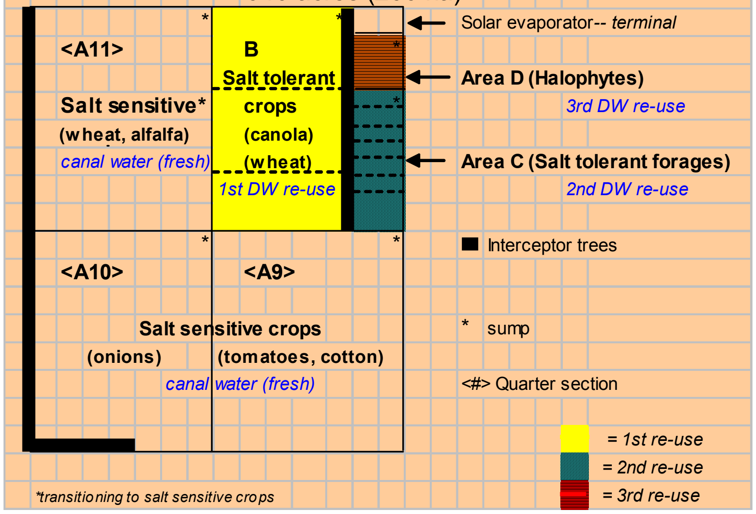
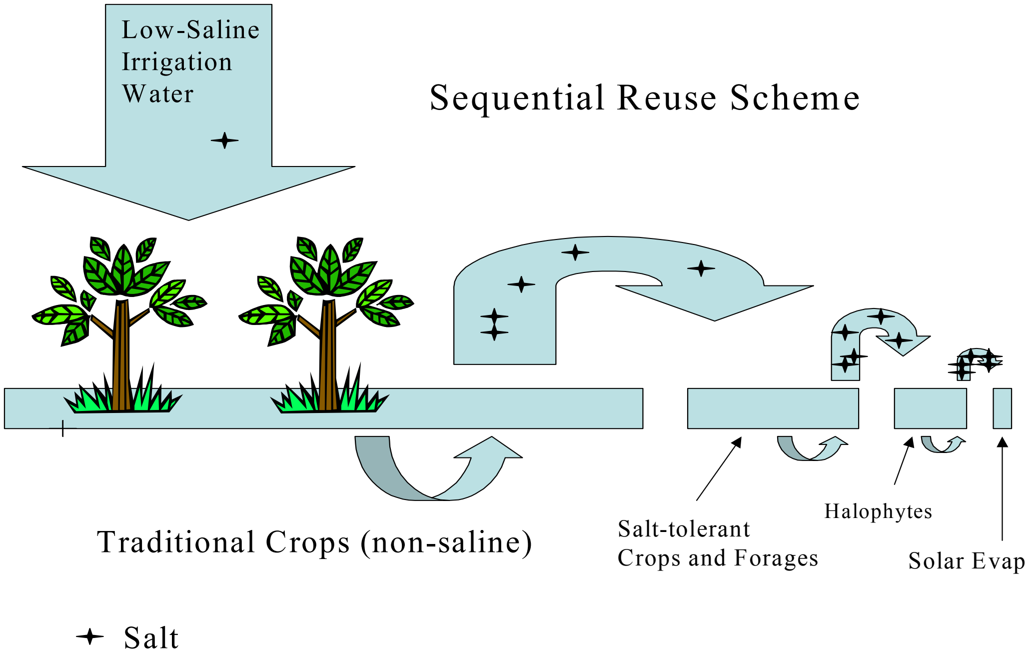


Figure 1. Red Rock Ranch Sequential DW Re-use Demonstration Project as Designed in 1996

Table 1. Typical chemical composition of canal water used to irrigate Area A and concentrated drainage water used to irrigate halophytes in Area D.

Water	EC dS/m	SAR	pH	Na meq/l	Ca meq/l	Mg meq/l	Cl meq/l	SO_4 meq/l	B mg/l	NO_3–N mg/1	Se mg/l
Canal (Area A)	0.57	2.8	7.8	3.1	1.4	1.0	2.0	2.1	0.5	1.3	< 0.1
Drainage (Area D)	15	25	7.9	128	35.8	16.4	15.1	76.5	24	29	1.3

Figure 2. Theoretical function of sequential drainage water re-use.



The RRR IFDM demonstration project is serving as a venue to test the IFDM concept. It is still not proven that the sequential re-use can significantly reduce drainage volumes and that sufficiently high leaching fractions can be maintained at each stage along the sequence to move large amounts of salt and boron into the solar evaporation systems (**Figure 2**). Even though much research is still needed to validate this concept, new IFDM projects are slowly being undertaken by other Westside growers. Consequently, our current research is focused in three critical areas for the testing of IFDM systems:

- Water use (ET) of salt tolerant forages and halophytes that are candidates for IFDM;
- Productivity, and forage quality of the candidate species; and,
- Soil characterization and management for IFDM systems

Information on these topics is urgently needed by Westside growers who are looking to innovative drainage water management and reuse options such as IFDM, as a means of maintaining the profitability and sustainability of their farms.

Objectives: For the purpose of this paper, the focus will be only on our research dealing with the soil characterization and infiltration rate study. The main objectives of this component of our research are to:
1) Assess changes in salinity and ion concentrations in all areas of the IFDM project (A, B, C and D);
2) Assess the spatial distribution of soil salinity in the forage and halophyte areas (C and D); and,
3) Evaluate the effectiveness of surface applications of gypsum on infiltration rates.

Methodology: In order to assess the changes in salinity and chemical composition of the soil, we have been soil sampling (0-5ft, in 1ft increments) twice yearly for the past 3 three years in all areas (A,B,C,D) of the RRR IFDM demonstration project. A hydraulic soil corer (Giddings rig) is used to collect samples at the GPS-referenced locations. In some cases 0-6 inches samples were also collected. Samples were air-dried, sieved through a 2mm (USDA # 10 sieve) and ground for preparation of saturated paste extracts made with distilled water. Soil salinity (electrical conductivity (ECe), pH, boron (B), sodium (Na), calcium (Ca), magnesium (Mg), and sulfate ($S0_4$-S) ion concentrations were measured on the paste extracts and the sodium adsorption ratios (SAR) were calculated. Nitrate (NO_3) and selenium (Se) levels were analyzed on separate extracts. Procedures given in the Western States Laboratory Proficiency Testing Program- Soil and Plant Analytical Methods were used for most of the analyses (Gavlak et al, 1994).

To assess the spatial and temporal variability in soil salinity in Areas C and D, salinity mapping will be conducted each fall using the electromagnetic induction technique ("dual-dipole" EM-38) currently available at California State University- Center for Irrigation Technology (CIT). This technique allows for rapid, high density, aboveground measurements with non-invasive sampling for the determination of depth- averaged (0-2 and 0-4 ft.) soil salinity.

Water infiltration is being measured in Area D (3rd re-use of DW; ECe up to 70 dS/m) where seven years of irrigation with saline-sodic drainage water has degraded the soil structure severely reducing infiltration. For comparison, infiltration is also measured in Area A that has received only freshwater irrigation (canal or wellwater; soil EC $\leq$ 6 dS/m) and is cropped to agronomic plants (e.g. tomatoes, onions, wheat). In Area D, infiltration is measured in plots containing three different halophytic plants (saltgrass, Salicornia, and Atriplex). These differ notably in that saltgrass provides a full vegetative cover over the soil, whereas Salicornia and Atriplex fields have exposed soil. Four replicate plots were established for each area and vegetation type and for each, there are duplicate plots with and without gypsum application (3 ton/acre) for a total of 32 plots.

Results and Discussion:

Figure 3. Red Rock Ranch Sequential DW Re-use Demonstration Project as per Modifications up to July 2003

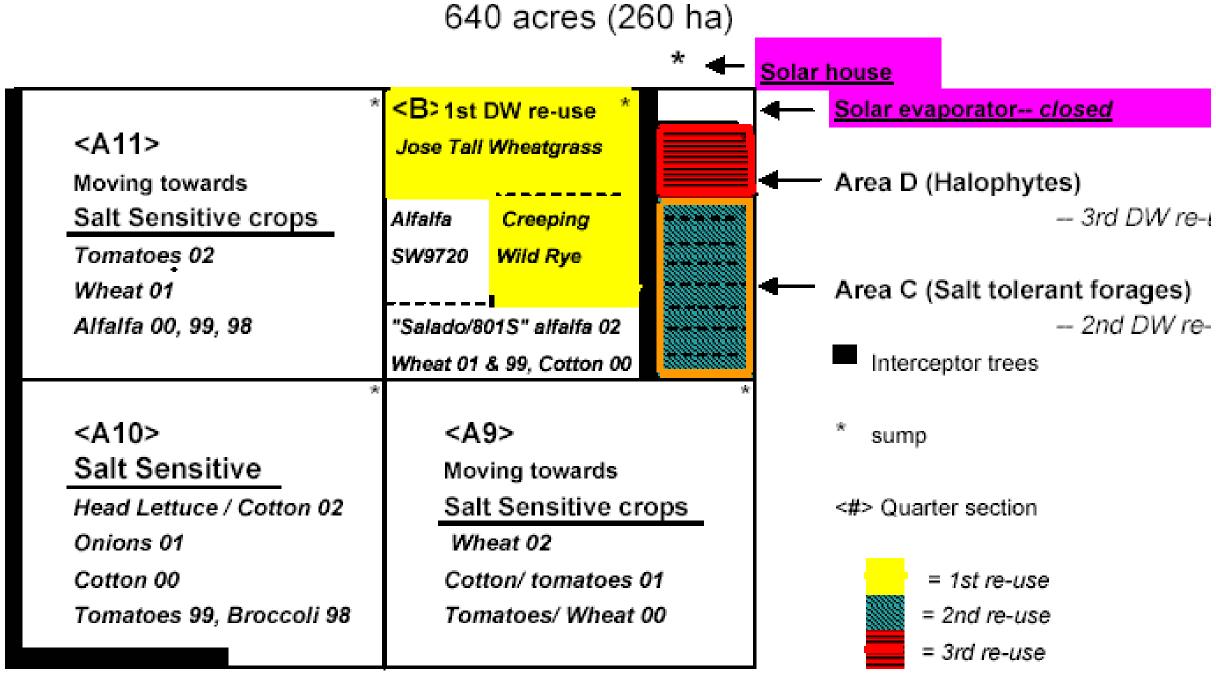


Figure 3 shows the 2003 updated version of the layout of water re-use and crops grown on the RRR IFDM demonstration project. A significant change from the original design showed in **Figure 1**, which may be indicative that the sequential re-use of drainage water is working, is that almost half of the quarter section in Area B is now planted in crops irrigated with fresh canal water. Hence this subsection of the demonstration project can now be re-classified as part of Area A. In 2002 the grower successfully planted head lettuce in subsection A10 which may have only been possible due to the soil improvement achieved with the subsurface drainage system. The other major change from the 1996 design is the closure of the solar evaporator and the testing of a "solar house" and a solar "concentrator". The solar house is an enclosed system which decreases the risk of wildlife access to standing water and allows the collection of clean salt. The solar concentrator is an outdoor system in which enhanced evaporation methods such as nozzles that atomize water are being tested. Markets are currently being sought for the evaporated salt.

Examples of a typical salinity profiles are presented in **Figures 4a** and **b,** along with a summary of the ECe and SAR values for the top foot of soil from fall 2000 to Fall 2002 (**Table 2)**. In Area A, leaching is occurring as indicated by the relatively lower salinity at shallow depths. However, in Area D (3rd re-use of the drainage water), there is extreme salt accumulation (ECe) and sodicity (SAR) in the surface 12 in. of soil (T**able 2**). These extremely high SAR values (>50) represent a sodium-saturated soil, which is prone to severe reductions in water infiltration and permeability (i.e. ponding), particularly when nonsaline winter rains fall (Oster, 2001, 1998). Low soil permeability also contributes to the perched water table which in turn contributes to the inverted salinity profile in Area D.

Table 2. Soil EC and SAR data for the Red Rock Ranch IFDM from 2000 to 2002.

Parameter[††]	Unit	Fall 2000	Fall 2001	Fall 2002	Avg.[†] (2000-2002)
FW-irrigagted acreage					
EC	dS/m	4.6 ± 0.4	4.1 ± 7.4	4.5 ± .7	4.3 ± 2.6
SAR	--	6.6 ± 0.7	2.8 ± 0.3	12.4 ± 1.36	9.1 ± 1.1
Area B (1st re-use of DW)					
EC	dS/m	10.9 ± 2.4	10.4 ± 2.4	10.8 ± 3.5	10.5 ± 2.2
SAR	--	21 ± 4.3	36.6 ± 17.8	20.76 ± 4.74	25.1 ± 5.6
Area C (2nd re-use of DW)					
EC	dS/m	14.2 ± 2.2	15.6 ± .9	16.4 ± 1.1	14.5 ± 1.5
SAR	--	27.2 ± 4.7	14.3 ± 2.6	29.8 ± 1.96	28.1 ± 3.4
Area D (3rd re-use of DW)					
EC	dS/m	55.6 ± 7.6	38.4 ± 2.1	41.5 ± 3.3	40.7 ± 4.1
SAR	--	99.5 ± 11.6	50.8 ± 2.4	79.0 ± 3.9	73.6 ± 5.7

[†] *Average 2000 - 20002 also includes late spring measurements*

[††] *EC, B, Cl, and SO_4 were done on saturated paste extracts and Se and nitrate-N on dry soil.*

Figure 4a: Soil EC (dS/m). Summer 2000

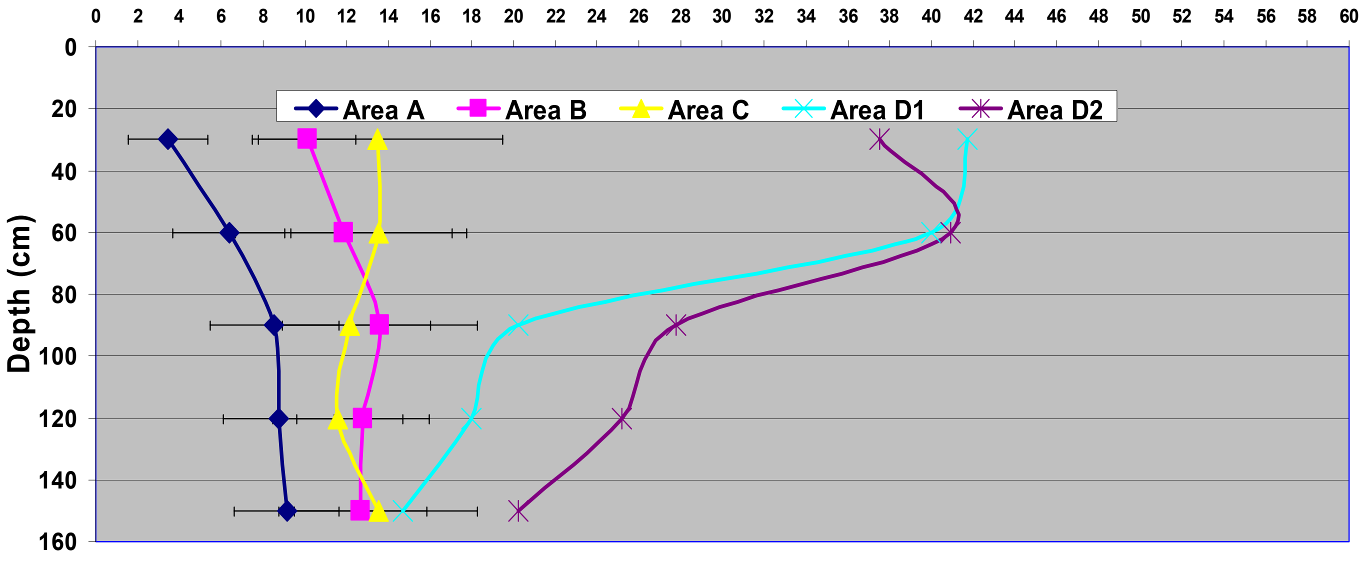
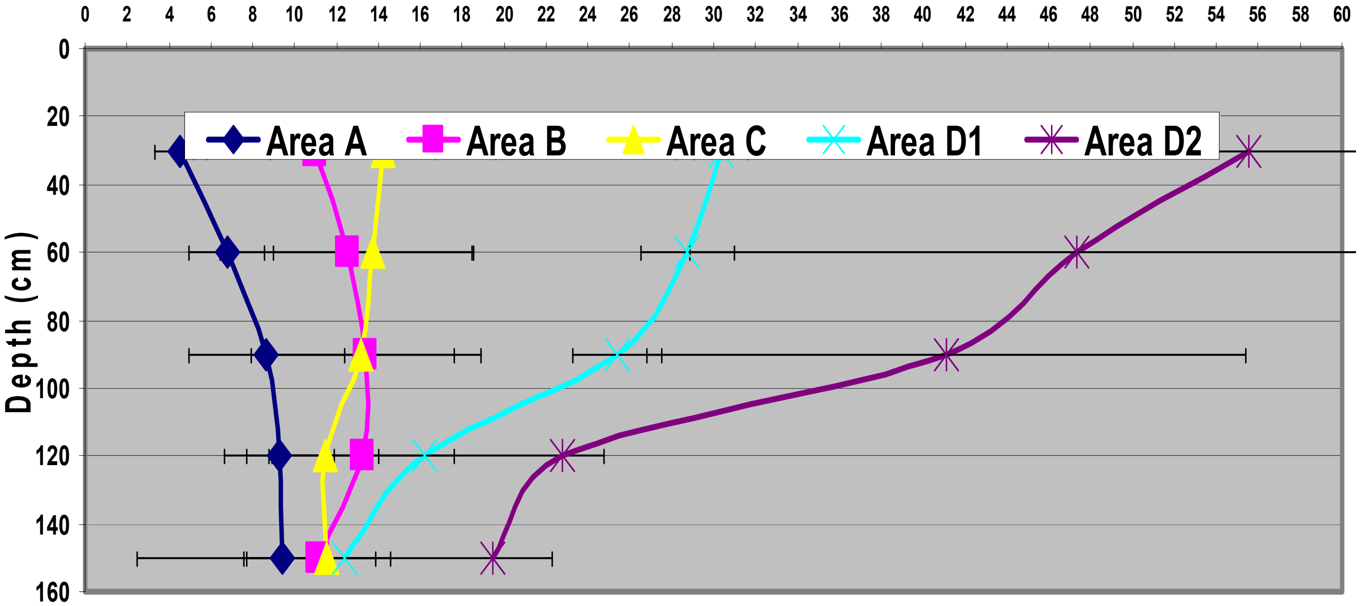


Figure 4b: Soil EC (dS/m). Fall 2000



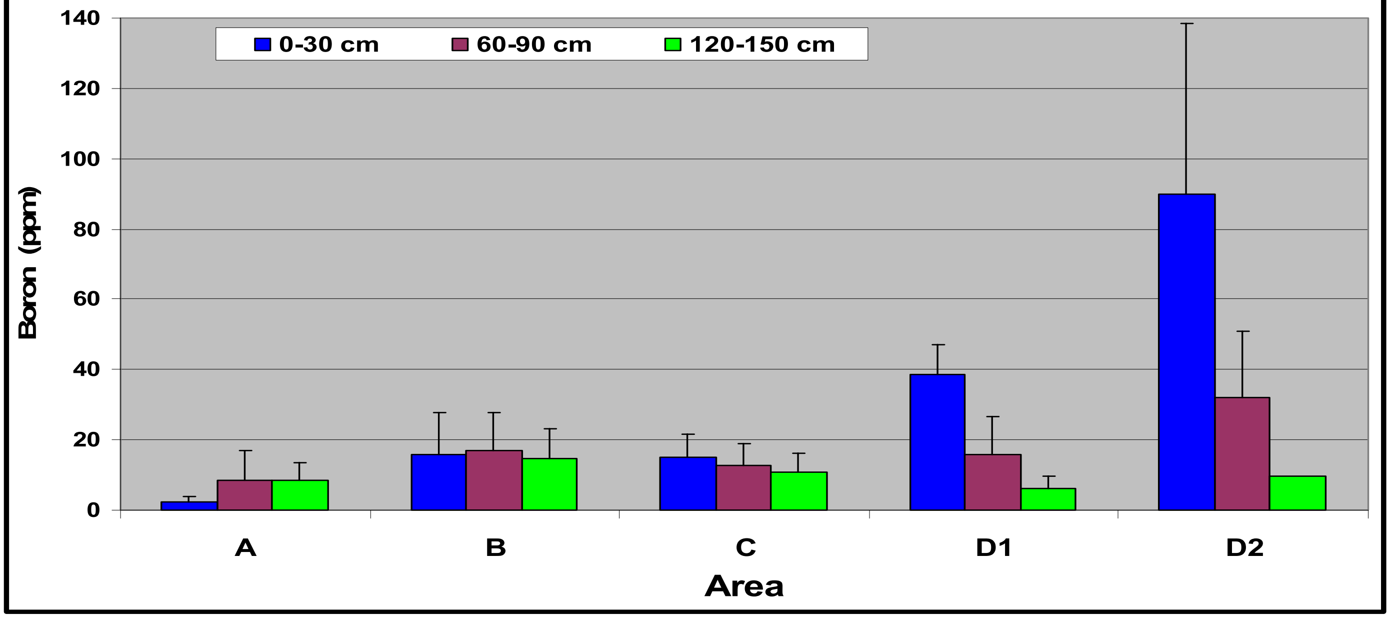


Figure 5: Boron in Soil. Fall 2000.

Similar to salinity, boron concentrations in soil increased with each sequential use of saline drainage water (i,e. Area A<Area B< Area C< Area D). For example, in Fall 2000 (**Figure 5**), in Area A, boron concentrations were lowest in the surface foot of soil indicating leaching. In Areas B and C, boron concentrations were similar at all depths and higher than in A. In Area D, boron in the top foot (30 cm) averaged 38 (D1) and 90 ppm (D2m) for Fall 2000. The higher boron concentration in D2 may be due to increased capillary flow resulting from the open plant canopy for Salicornia as compared to saltgrass.

Table 6: Mean of 2000 and 2001 summer and fall ion concentrations and pH for top 12 inches of soil.

Site	Plant species		Se (ppm)	NO3-N (ppm)	SO4 (ppm)	Cl (meq/L)	Na (meq/L)	Ca (meq/L)	Mg (meq/L)	pH
A	Agronomic	Mean	**0.87**	**22.5**	**939**	**9.4**	**18.8**	**19.0**	**3.4**	**7.6**
	crops	s.e	0.06	8.2	178	2.6	4.2	3.0	0.5	0.1
B	Salt tolerant	Mean	**1.40**	**9.2**	**2261**	**37.7**	**107.4**	**44.1**	**7.4**	**7.4**
	crops	s.e	0.17	4.6	484	10.2	31.9	7.6	1.1	0.2
C	Salt tolerant	Mean	**1.95**	**8.4**	**3319**	**43.2**	**109.7**	**54.1**	**11.3**	**7.9**
	forages	s.e	0.14	5.3	336	10.5	22.0	6.9	1.3	0.1
D1	Halophyte	Mean	**3.78**	**34.0**	**7238**	**186.6**	**338.8**	**99.1**	**21.4**	**7.7**
	(saltgrass)	s.e	0.31	6.0	1418	21.1	9.8	6.4	2.8	0.1
D2	Halophyte	Mean	**7.93**	**30.8**	**8966**	**258.3**	**445.5**	**191.8**	**33.1**	**8.3**
	(Salicornia)	s.e	1.14	14.5	944	59.1	82.4	69.2	7.0	0.1

**EC, B, Cl, SO4, Na, Ca, Mg, pH done on saturated paste extract. Se = total.*

During 2000- 2001, soil pH in the top twelve inches of soil ranged from 7.2 to 8.4 (**Table 6)**. In area A, sodium and calcium levels were similar. However, in areas irrigated with saline-sodic drainage water, sodium levels were more than three times that of the calcium. Generally, calcium levels greater than or at least similar to sodium levels are desirable for soil structure favorable for water percolation and crop growth. Similar increasing trends were observed for chloride and sulfate concentrations in moving from soils receiving fresh canal water in Area A to the soils in Area D with the halophytes (**Table 6).** Selenium concentrations in Area A were less than 1 mg/kg, but in Area D they reached almost 8 mg/kg which poses a significant risk to wildlife when irrigation water ponds in this field. Hence, a current practice is to irrigate sections of Area D, such as the field planted with Atriplex, with a sprinkler system rather than flooding. It is noteworthy that for the period 2000-2001, the fields with the lowest average nitrate concentrations of approximately 9.0 ppm were observed in Areas B and C, which were planted in salt tolerant crops and forages (**Table 6**).

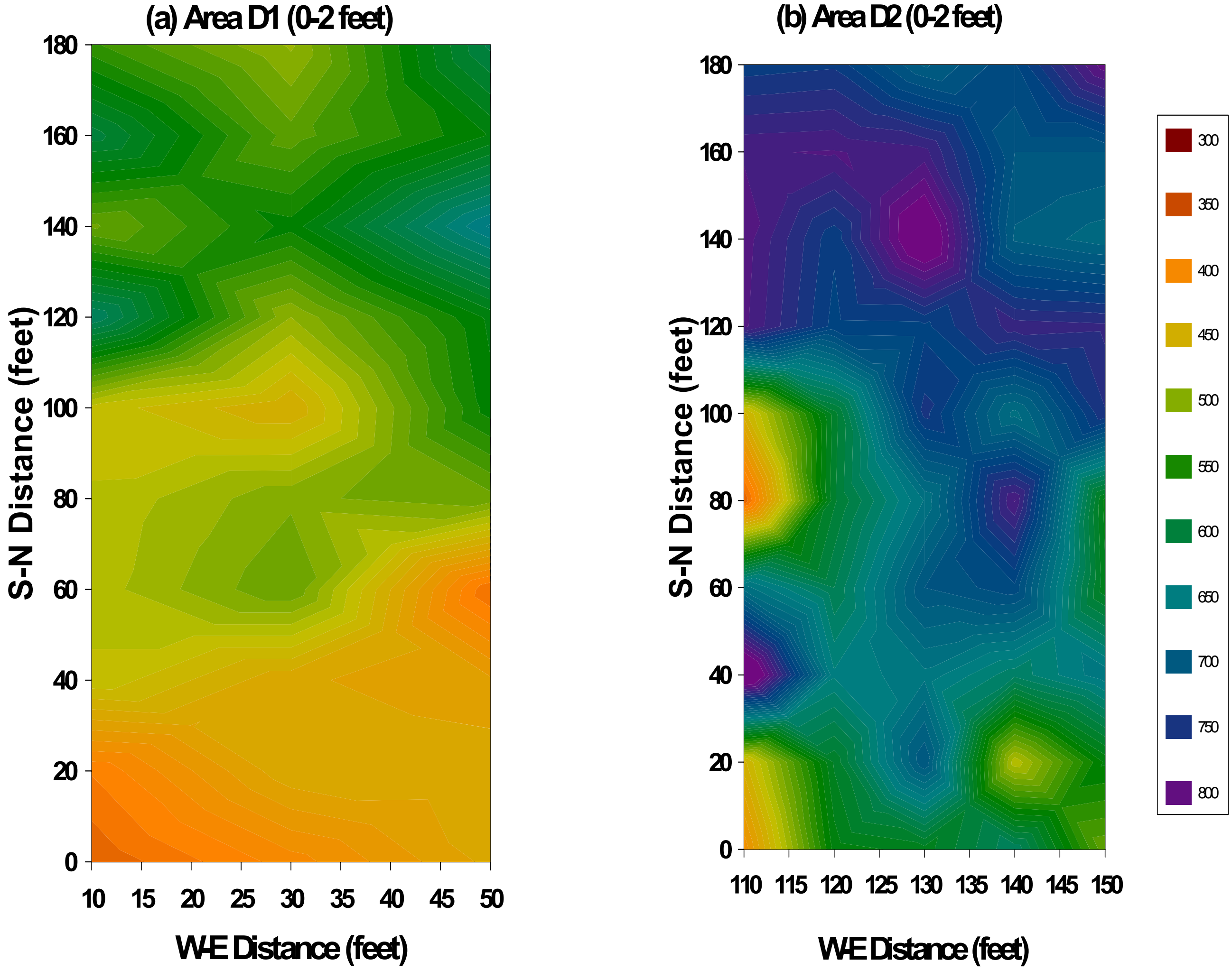
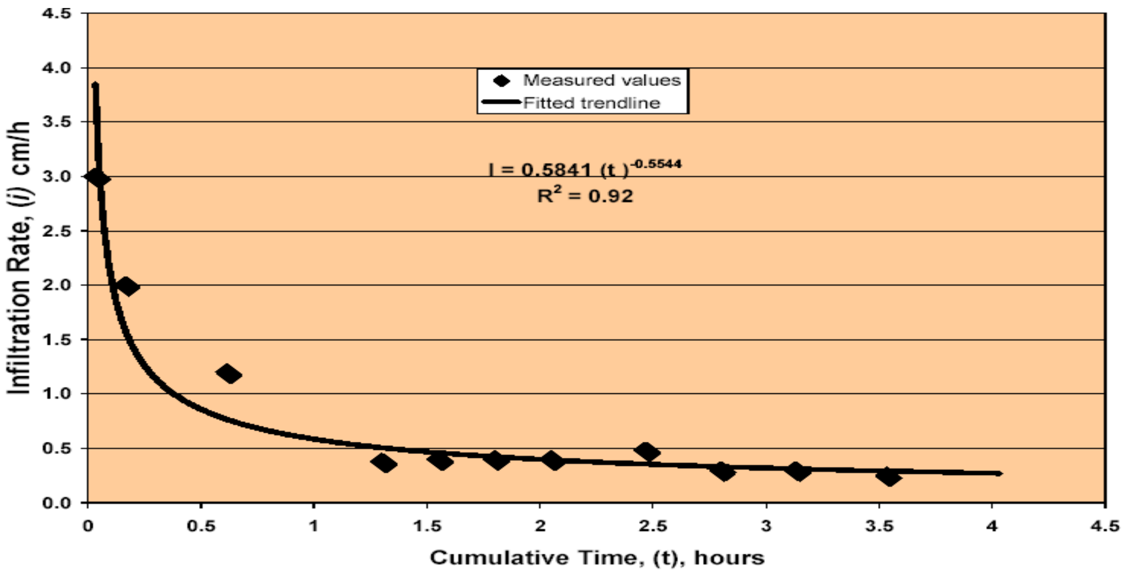


Figure 6. Apparent electrical conductivity (ECa) within the top 2 feet of soil measured with the EM-38 for (a) Area D1 and (b) Area D2. ***Units are in dS/m.***

Salinity maps for fields in Area D, compiled with data from EM 38 measurements, are shown in **Figure 6.** These maps are very useful for monitoring the relative changes in the spatial variability of soil salinity over time. It must be noted that the information depicted in figure 6 is the apparent electrical conductivity (ECa) and as so the influence of soil moisture content, texture and organic matter are incorporated in these values. Hence, unless the data is ground-truthed, a task which has been included as part of research for the next rounds of EM measurements, the maps presented in Figure 6 should be used primarily for comparison of relative, rather than absolute, soil salinity values. Based on this assumption, it would appear that the D2 fields (Salicornia) are relatively more saline than the fields in D1 (saltgrass). More importantly, there is wider range of soil salinity in D2 (**Figure 6b)** than in the D1 fields. Interestingly, both sets of fields have a trend of relatively lower salt concentrations at their southern ends than at the northern ends which is directly correlated to the flow direction of flood irrigation system and the recent conversion to sprinkler irrigation in the entire northern half of the area. This may imply that there is a need for more water at the northern (tail end of the irrigation) end of the field so as to ensure adequate leaching of salts.

Based on the findings from initial infiltration experiments conducted in summer 2001, we have chosen double ring infiltrometers for our field measurements. Currently, we are using various curve–fitting approaches to analyze the time and depth data collected from the ring infiltration measurements in 2002. In our first approach we determine the steady rate infiltration (i_s), also referred to as *steady-state infiltrability* or as the *final infiltration capacity* (Hilllel, 1998). The steady rate infiltrations are examined rather than the initial or "early time" infiltration. Soil infiltrability is relatively high in the early stages of infiltration, particularly where the soil is dry, but then it tends to decrease monotonically and eventually approaches an asymptotic constant infiltration rate (**Figure 7**). Hence, by comparing the "late time" steady rate infiltrations, care is taken to ensure that the values being compared are not influenced by the initial moisture content of the plots or by the differences in the ponding head in the ring infiltrometers. For the infiltration experiments conducted in summer 2002, we found that steady state infiltrability rates (i_s), which generally were attained after 2.5 to 3 hours, averaged at 2.1 cm h^{-1} and 1.7 cm h^{-1} for the gypsum plots in areas A and D, respectively. For the non-gypsum i_s values ranged from 0.7 to 1.0 cm h^{-1} for both areas.

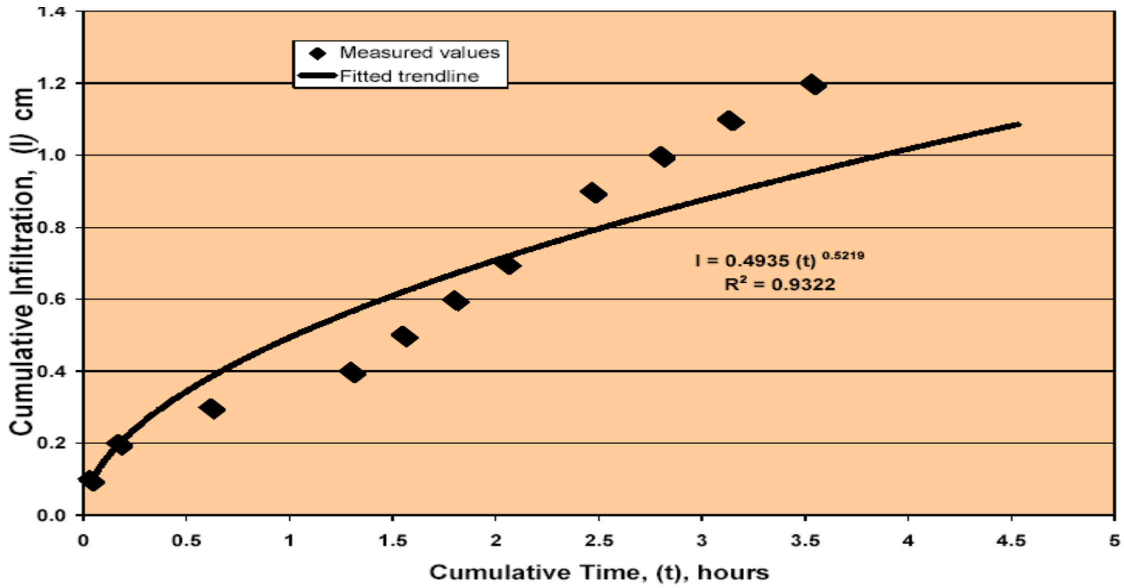
Figure 7. Example of measured infiltration rates with fitted trend line used to determine steady rate infiltration for a non gypsum plot in area A



In our second approach, cumulative infiltration (I) over cumulative time (t) will be determined using (Jury et al., 1991): **I = *a t b*** **Eqn. (1)**

where a and b are empirical constants (**Figure 8**). Derivatives of Eqn. 1 will be taken at 2 and 4 hours to estimate infiltration rates i_2 and i_4.

Figure 8: Example of measured cumulative infiltration with fitted trendline used to determine equation 1 for a non gypsum plot in area A.

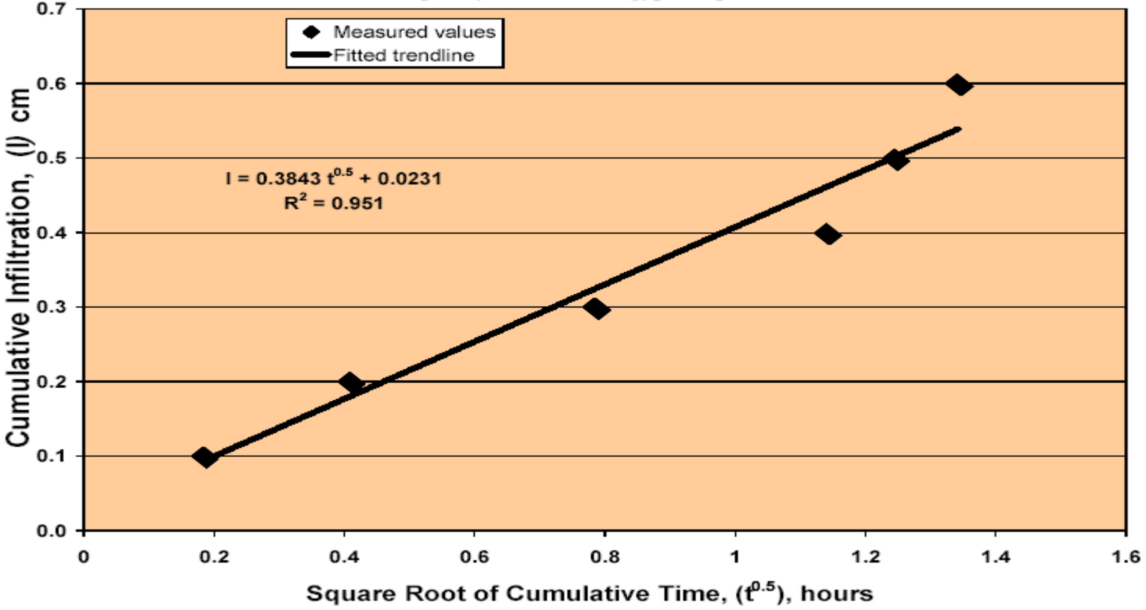


In our final method, we will determine the sorptivity (*S*) of the soil according to (Bower, 1986):

$$I = S\, t\, 0.5 + B \qquad \text{Eqn. (2)}$$

where: *S* is a term that depends on the pore configuration of the soil, the initial water content of the soil, and the ponding head; and *B* is a factor related to the hydraulic conductivity and the elapsed time from water application. Values of *S* will be determined from the infiltrometer measurements by plotting *I* vs. *t*0.5 for the portion of the test where *I* increases essentially linearly with *t*0.5 and *S* is evaluated as the slope of the straight line portion of the curve (**Figure 9**).

Figure 9: Example of measured cumulative infiltration with fitted trend line used to determine Sorptivity, *S* , for a non gypsum plot in area A.



General Comments on the IFDM Demonstration Project

- ***Area A (canal water)*** seems to be benefiting from the use of subsurface drainage. Soil salinity, boron, and SAR are lowest in the surface 30 cm which represents a substantial part of the rooting zone for annual crops.
- ***Areas B and C (1st and 2nd reuse)*** could benefit from more leaching. This could include increased application of tailwater to Area B and in both B and C, increasing the amount of applied water (drainage in the growing season) and fresh water (rain or irrigation) in the winter.
- ***Area D (3rd re-use)*** shows extreme salt accumulation in the surface layer, and little evidence of leaching. Water application is being increased but is limited by poor infiltration in this area. A possible remedy would be to eliminate the 3rd re-use of drainage water and have only two. The first re-use area would have salt tolerant crops, or less tolerant forages; and the second re-use area would have forages of higher salt tolerance, or halophytes, depending on salinity of the drainage water, soil texture, and resulting soil salinity.
- It is our hope that by comparing infiltration rates in the drainage water re-use areas to those under conventional irrigation with non-saline water, we can begin to assess the long term impacts of irrigation with saline-sodic drainage water on soil structure and permeability, and eventually to formulate management plans that utilize gypsum or sulfur, and possibly organic amendments, to minimize soil degradation.

Future Work

- We have reduced our soil core sampling to the just the fall season over the next two years for determination EC, SAR, pH, B, Se, Ca, Mg, Na,NO_3, Cl, and SO_4 in 1ft increments to a depth of 5ft. This is primarily in response to the relatively better depiction of the spatial variability soil salinity available with the EM-38 equipment.
- Data obtained with the EM-38 equipment will be used with “ESAP” software developed by J.R. Rhoades at the USDA Salinity Lab to determine locations for ground-truthing soil sampling, and converting the EM data to absolute soil salinity values
- The infiltration parameters will be monitored twice per year for the next two years.

Acknowledgement

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Projector Director: Sharon E, Benes Ph.D.

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PRESSURE CONTROL IN LAND APPLICATION OF MUNICIPAL WASTEWATER

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INTRODUCTION

The use of waste material for application to farmland as fertilizer has been in practice for centuries. In the past sewage farms were common in locations such as Europe and Australia, however as technology advanced the use of sewage farms became less prominent. The 20th century saw an increase in the use of wastewater for irrigation due to increased pressure on fresh water resources in both developing and industrialized countries. (Johnson 2002).

As population growth continues to put increasing pressure on natural water resources, the search for alternative sources of water has lead to increased use of municipal wastewater. For example, Florida has seen an increase of 26 percent in the number of treatment facilities processing waste water for reuse over a ten year period beginning in 1986. The following chart gives a breakdown regarding reuse application in Florida.

Application use	Percent Breakdown
Landscape Irrigation	40 percent
Groundwater recharge	20 percent
Agriculture Irrigation	18 percent
Industrial Application	15 percent
Wetland and other minor applications	7 percent

(York & Coleman 1999).

Increased attention on municipal wastewater as a resource for irrigation has led to additional focus on the impact that it has on the public health, environment, and the economic return on investment. One of the key elements to a successful project that can address these issues of concern includes a well designed system. The components of a well designed irrigation system can be broken down into the following four categories:

1. Control equipment
2. Water conveyance system
3. Water distribution system
4. Pumping system.

A deficiency in any one area can result in long term problems (Smajstrla, 1994).

PURPOSE

The purpose of this paper is to discuss the water distribution system, specifically sprinkler application and how it is affected by changes in pressure. Pressure changes in the system can result in variable application rates and poor uniformity, thus negatively affecting the overall performance, longevity and economic return on investment of the irrigation system (Smajstrla, Zazueta, Haman 1989).

PRESSURE IMPACT ON APPLICATION RATE

Causes of pressure variations in a system include examples such as changes in elevation, flow differences, (such as different size zones, corner system and or end gun activation on a center pivot), management practices and under-sized laterals. It is suggested that there should be no more than 20% variation in sprinkler operating pressure within a zone. The impact of changes in pressure is more dramatic for systems utilizing low pressure emitters versus higher operating pressure sprinklers. This can be demonstrated by the following equation:

Flow versus Pressure Relationship: % Flow change = % Pressure change / 2

For example, a solid set field with impact sprinklers irrigating municipal wastewater for hay production that is designed to operate sprinklers at 50 psi with a flow rate of 9.66 gpm on a spacing of 60 x 60 ft. yielding an application rate of .25 inches per hour over a defined area of 350 ft. x 350 ft. The infiltration rate of the soil has been determined to be .25 inches per hour. However, one of the laterals has developed a leak and is shut off for repair but the zone is still activated resulting in an increase in pressure of 20 percent which translates into 10 percent increase of sprinkler flow rate, thus raising the application rate to .29 inches per hour. This exceeds the soil infiltration rate resulting in potential runoff.

PRESSURE IMPACT ON UNIFORMITY

Another important definition is Distribution of Uniformity. This can be defined as how uniformly the water is being applied across the area of application (Burt 1995).

DU=Minimum amount applied /Average amount applied x 100

Uniformity can be affected by spacing of the sprinklers, flow and pressure. As discussed above changes in pressure impacting sprinkler flow rate result in variable application rates within the defined area. Irrigation systems should be designed at or below the minimum infiltration rate to avoid runoff (Scherer 1999). A system designed with uniformity as one criteria can help achieve this goal.

The following example looks at the impact of uniformity on the volume of municipal water required to irrigate an agricultural crop. Corn grown in Minnesota requires a typical range of 9 to 11 inches of seasonal net irrigation application, based on ten year average in addition to natural rainfall (Scherer 1999). The design parameters of this example include 100 acres using impact sprinklers on a center pivot with a system Distribution Uniformity of 70%, and a net irrigation requirement of 11 inches per year.

Plant requirement / Uniformity =Irrigation Requirement
Irrigation Requirement x 27,154 gallons x acres = Gallons of water for crop requirement

Plant Requirement	**Uniformity**	**Irrigation Requirement**	**Gallons per Acre Inch**	**Irrigated Acres**	**Gallons/ year**
11 inches	70%	15.7 inches	27,154	100	42,631,780
11 inches	85%	12.9 inches	27,154	100	35,140,470

(Thompson 2002)

The information listed in the chart above indicates that an 18 percent decrease in water use is achieved by increasing uniformity from 70 to 85 percent. This example demonstrates that higher uniformity results in less water required to irrigate the crop, lower pumping costs, reduced risk of leaching chemicals, and runoff in areas where over-watering may have occurred.

FLOW CONTROL NOZZLE VS. PRESSURE REGULATION

Systems with operating sprinkler pressures that see differences of 20 percent or greater than design pressure are candidates for regulation or flow control. The flow rate of the sprinkler is controlled by two components, the size of the orifice and the operating pressure of the sprinkler. Sprinkler flow rate can be controlled by the use of flow control nozzles or if the nozzle is fixed then pressure regulators can be used to control pressure.

Flow Control Nozzles operate using a flexible disk with an orifice that changes shape based on pressure. As pressure increases the disk orifice becomes smaller due to outward flexing of the disk (Kranz 1988). However, activation of the flow control device does not usually occur until upstream pressure exceeds a threshold pressure. Threshold pressure for 1-5 gpm ranges from 20 to 40 psi and 35 to 50 psi for flows greater than 6 gpm (Van der Gulik 1983). This can be a limiting factor for application of low pressure sprinklers, which operate below these ranges (Kranz 1988). There is also a change in droplet size as the orifice changes shape in response to pressure fluctuations which can result in the distortion of sprinkler profile, thus adversely affecting system uniformity.

In-line pressure regulators are designed to maintain a preset outlet pressure. Flow enters the regulator through the inlet side and travels past a fixed seat and through a hollow cylinder (throttling stem) that moves up and down in response to changes in back pressure. The opening between the fixed seat and the throttling stem can be described as a modulating valve that opens or closes in response to changes in inlet pressures, thus maintaining preset outlet pressure. The desired opening for a given outlet pressure is maintained by equalizing back pressure against an internal compression spring. Regulators are generally available in preset operating pressures in 5 psi increments up to 60 psi depending on flow requirements. Activation of the regulator requires an inlet pressure of 5 psi above the preset outlet pressure rating. For example a 30 psi regulator will need 35 psi inlet psi for regulation to occur. A pressure regulator is chosen based on flow rate and operating pressure requirements of the sprinkler.

CONCLUSION

Availability of land for application of municipal wastewater is often limited and may be slated for areas where site development is too expensive due to elevation changes. The use of pressure regulators for application of municipal wastewater is an important tool to address issues such as uneven application rates and poor uniformity. A well designed system with the right nozzle selection, pressure regulation and spacing will achieve application rates at or below infiltration rates resulting in an irrigation system that is environmentally safe, publicly supported and good a return on investment.

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Chlorination dose and response for biological effluent used for drip irrigation

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Abstract. *Control of biological growth within subsurface drip irrigation (SDI) systems is important to keep the system operating properly for many years. The traditional method of control is through the injection of chlorine into the SDI system. Little is known about the effectiveness of chlorine injection into livestock effluent (wastewater) used with SDI systems. This project measured the residual chlorine concentration and coliform count after treatment with chlorine at concentrations between 10 and 120 mg/L and at pH levels of about 8.0 (approximately the unadjusted pH in most effluents), 7.5, and 7.0. Effluent was sampled at four beef cattle feeding facilities (feedlots), two dairies, and two swine feeding facilities. Chlorine and coliform responses varied considerably. The residual chlorine concentrations in effluent from three sites were nondetectable even at chlorine addition of 120 mg/l. At two of those sites, coliforms grew in abundance at all tested Cl concentrations while coliform growth was prevented at 120 mg Cl/l in effluent from the third site. In effluent used in previous SDI research, coliform growth was prevented with a pH adjustment to 7.0 and addition of 10 mg Cl/l.*

Introduction

Management of biological effluent (wastewater) resources from animal feeding operations in the Midwest and Great Plains of the USA is an important issue. This resource represents a potentially important source of nutrients for crops. Because the nutrients are so concentrated, the effluents- if mismanaged- also represent a pollution threat.

One method of effluent utilization is application to field crops via irrigation systems. Proper management of irrigation with effluent fosters the efficient use of nutrients and water components of the effluent. Traditionally, effluent utilization is accomplished with sprinkler (most often center pivot) or furrow irrigation systems.

Subsurface drip irrigation (SDI) with effluent has been shown to be technically feasible (Trooien et al., 2000). Some potential advantages for the use of effluent through SDI systems include (Trooien et al., 2000): reduced human contact; reduced odor; reduced potential for runoff; reduced potential for phosphorus runoff into surface waters; greater uniformity of application resulting in better control of water, nutrients, and salts; reduced irrigation system corrosion; reduced application constraint by weather (winds and temperatures); and increased flexibility in matching field and irrigation system shapes and sizes.

The SDI system must be economically feasible or these advantages are of no consequence. The key to economic feasibility of SDI systems lies in getting many years of efficient operation from the installed system, thus amortizing the initial investment over many growing seasons (O'Brien et al., 1998). To maintain efficient system operation for many years, one must keep the driplines and emitters free from clogging by bacterial and algal growth because emitter clogging is a major problem associated with microirrigation systems (Nakayama and Bucks, 1986). In freshwater SDI systems, biological growth is often controlled with occasional or continuous injection of chlorine. The question that must be asked is, "How can I use effluent through my SDI system and still keep the driplines and emitters free from bacterial and algal clogging using the traditional chlorination approach?"

To address this question, we initiated the research reported here. Our objective was to measure the residual chlorine content and number of coliform colonies in response to treatment of livestock effluent with various concentrations of chlorine at three different pH levels. Coliforms were used as an indicator of potential for emitter clogging and because of the health issues associated with human exposure to coliforms.

Methods

Effluent samples from eight livestock facilities were used in this study. Four sites were beef cattle feeding facilities (feedlots), two were dairies, and two were swine feeding facilities. All facilities except one were located within 200 km of Brookings, SD. The exception was the effluent obtained from the beef feedlot in southwest Kansas used for previous research with SDI and effluent (Trooien et al., 2000). Samples were collected from the effluent containment ponds (sometimes called lagoons) at each site.

Samples were collected by placing an intake about 3 m from the pond bank and about 0.3 m beneath the pond surface. Effluent was pumped from the pond and through a 200 mesh disk filter prior to placement in sample bottles. The samples were kept cool until delivery to the laboratory, usually less than one hour after sampling. One sample required overnight transport so it was stored in a cooler at 4°C until delivery to the laboratory.

The following parameters were measured shortly after receipt of the sample in the lab: pH, alkalinity, biological oxygen demand (BOD), electrical conductivity (EC), total suspended solids (TSS), and total dissolved solids (TDS), and total coliform count. Ammonia concentration was measured for effluent from sites 3 through 8.

Chlorine dose/response testing took place at three different pH levels- unadjusted (generally near 8, Table 1) and adjusted to 7.5 and 7.0. After pH adjustment, chlorine was added at concentrations between 10 and 120 mg/l. Concentrations of added chlorine varied among samples. After one hour of contact time, the residual free and total chlorine concentrations were measured using the amperometric titration method (American Public Health Association, 1998). Residual free chlorine concentration of 1 to 2 mg/l is generally recommended for disinfection of effluent (Feigin et al., 1991).

After the 60 minutes of chlorine contact, 100 ml of sample were dechlorinated with sodium thiosulfate. Dechlorinated sample volumes of 1, 2, and 5 ml were each added to 1.5 ml of total coliform broth. Coliform incubation followed the ASTM standard. Coliform colony counting also followed the standard ASTM procedure. For compactness of presentation, all coliform counts greater than 1000 colonies/100 ml are presented as 1000. For the same reason, all nondetectable concentrations of residual chlorine (free or total) are charted as a value of 0.

Results

Effluent chemistries varied widely from site to site (Table 1). All had pH greater than 7.45 and six were 7.75 or greater. The four beef feedlots had the four highest pH values. Of the eight tested sites, three had ammonia concentrations greater than 400 mg/l. Effluent from seven of the sites had EC greater than 3 dS/m, making them very high salinity hazard for use as irrigation water. Even the lowest-salinity effluent, with EC of 1.89 dS/m, would be classified as high salinity hazard irrigation water (Richards et al., 1954). Total suspended solids content varied tenfold, from 208 mg/l to 2044 mg/l. Also, BOD values varied more than tenfold, from 218 to 3140 mg/l. Finally, coliform variation was even greater. Site 8 had a very low coliform count of 13 while site 5 had a coliform count of nearly 500,000.

Table 1. Selected characteristics of the sampled sites.

Site	Type	pH	Alk	Ammon	EC	TSS	TDS	BOD	Colif
			mg/l as $CaCO_3$	mg/l	dS/m	mg/l	mg/l	mg/l	#/100ml
1	Beef	7.98	584	NA	1.89	260	1311	235	8976
2	Dairy	7.45	1122	NA	3.63	208	3267	240	237
3	Beef	8.07	1094	40	3.13	338	2465	218	8862
4	Beef	7.87	3694	412	10.10	2044	8990	>1870	55000
5	Swine	7.59	5044	823	12.23	675	3880	2320	477493
6	Dairy	7.80	3558	587	7.98	1162	7360	3140	7746
7	Swine	7.75	2398	9	6.25	453	2944	751	81872
8	Beef	8.02	1730	164	5.13	394	3289	<700	13

NA: Not analyzed, Alk: alkalinity, Ammon: ammonia, EC: electrical conductivity,
TSS: total suspended solids, TDS: total dissolved solids,
BOD: biochemical oxygen demand, Colif: coliform count.

The effluent from site 1 grew no coliforms when treated at any concentration of chlorine at any of the three tested pH levels (Fig 1). Total chlorine residual concentration and free residual chlorine concentration behaved similarly for site 1 so they are discussed interchangeably. Residual chlorine was greater than 1 mg/l (which should control bacterial growth, Feigin et al., 1991) at addition of 10 mg Cl/l when the pH was adjusted to 7.0. At pH levels of 7.5 or 8 (the unadjusted level), additions of chlorine at concentrations of 20 to 25 mg/l were required to attain residual chlorine concentrations of greater than 1 mg/l.

Effluent from site 2 required greater additions of chlorine to attain any measurable residual chlorine concentration. At pH of 8, addition of 75 mg Cl/l was required to attain any measurable residual chlorine (Fig 2). When the pH was adjusted to 7, however, addition of 25 mg/l resulted in total residual chlorine of 0.75 mg/l and no coliform growth, even though no measurable free residual chlorine was detected.

Site 3 had effluent similar to site 1 in that no coliforms grew in any of the chlorine dose/response treatments (Fig 3). At the unadjusted pH (8.07), addition of chlorine at 45 mg/l was required to attain detectable free residual chlorine and total residual chlorine greater than 1 mg/l. At pH of 7, only 35 mg Cl/l were required to achieve the same result.

Effluent samples from sites 4, 5, and 6 all had high chlorine demand. No residual chlorine was detected at any treatment up to 120 mg Cl/l and any pH (Figs 4 and 5). Additionally, effluent from site 6 grew numerous coliforms at all chlorine levels. Effluent from site 4 grew no coliforms when chlorine was added at a concentration of 120 mg/l, even though no detectable residual chlorine was found (Fig. 4). Effluent from Site 6 had high ammonia content (Table 1), which reduced the effectiveness of the chlorine disinfection. Even addition of chlorine at the rate of 120 mg/l did not completely control coliform growth (Fig. 5). Sites 4 and 5 also had high ammonia concentrations and they also had high initial coliform counts (Table 1). The effluent from Site 5, although treated with chlorine concentrations of 90 to 120 mg/l, showed no residual chlorine and coliform counts were all greater than 1000 colonies per 100 ml (data not shown).

The effluent sampled at site 7 grew numerous coliforms when chlorine was added at concentrations less than 30 mg/l (Fig 6). Total residual chlorine concentrations were greater than 1 mg/l at additions of 30 mg Cl/l or greater, except at the Cl breakpoint. The residual chlorine data from Site 7 illustrate the chlorine “breakpoint” addition/concentration curve although the free residual chlorine concentration does not increase with increasing Cl addition. When the addition concentration is increased from 30 to 40 mg/l, chloramines are oxidized and the residual chlorine in solution is reduced (Feigin et al., 1991). No free residual chlorine was detected at any chlorine addition concentration and any pH.

Decreasing the pH level decreased the amount of chlorine required to increase residual chlorine content and coliform growth in the effluent from site 8 (Fig 7). At the unadjusted pH of 8.02, addition of 30 mg Cl/l resulted in a detectable total residual chlorine concentration and no coliform growth. Addition of chlorine at 20 mg /l stopped coliform growth at pH of 7.5, while at pH of 7.0, even the addition of chlorine at 10 mg/l prevented coliform growth. The initial coliform count in the effluent from Site 7 was low (Table 1) and the coliform counts, if non-zero, after all treatments were also low.

Summary

Responses of residual chlorine concentrations and coliform growth in livestock effluent were variable. Addition of chlorine to one effluent (swine) with high coliform counts and high ammonia concentrations resulted in no residual chlorine and no coliform control while addition of chlorine to another effluent (beef) resulted in no residual chlorine for any treatment but no coliform growth at addition of 120 mg/l. Addition of chlorine to effluent with high coliform count and low ammonia concentration resulted in measurement of residual total chlorine (except at the Cl breakpoint) and complete control of coliform growth at addition concentrations of 30 mg/l or greater.

Acknowledgements

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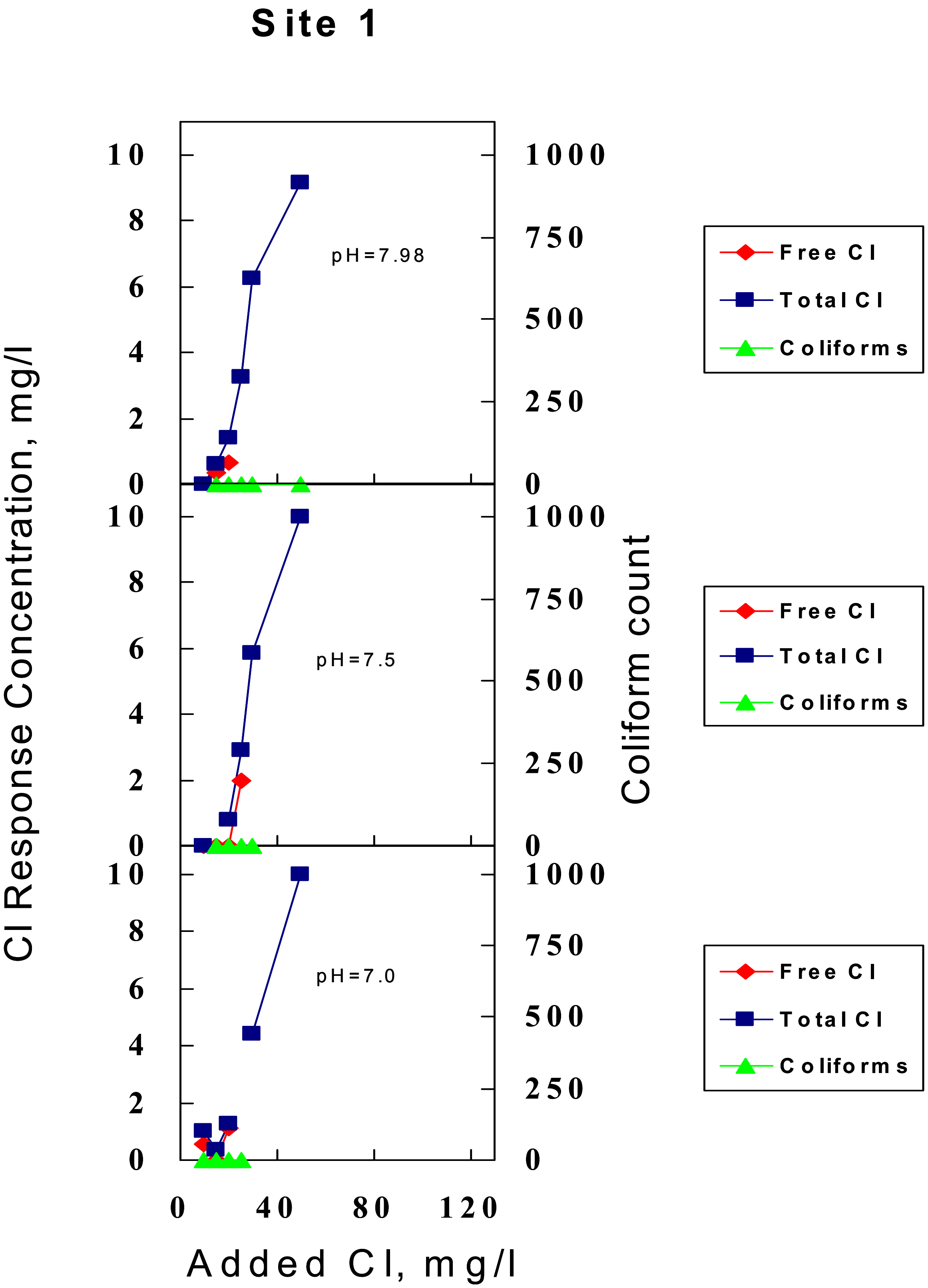

Figure 1. Chlorine dose/response for effluent from Site 1.

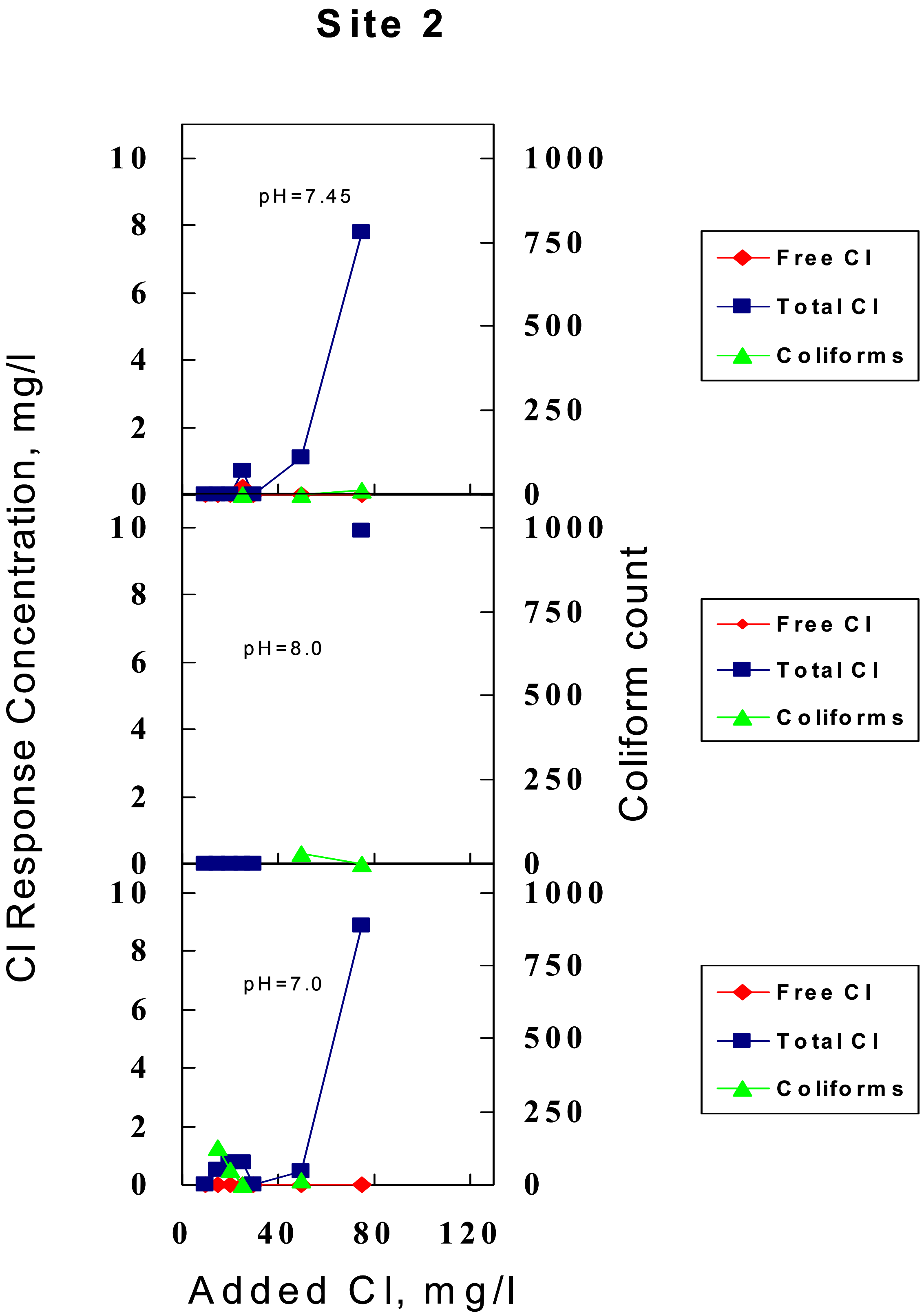

Figure 2. Chlorine dose/response for effluent from Site 2.

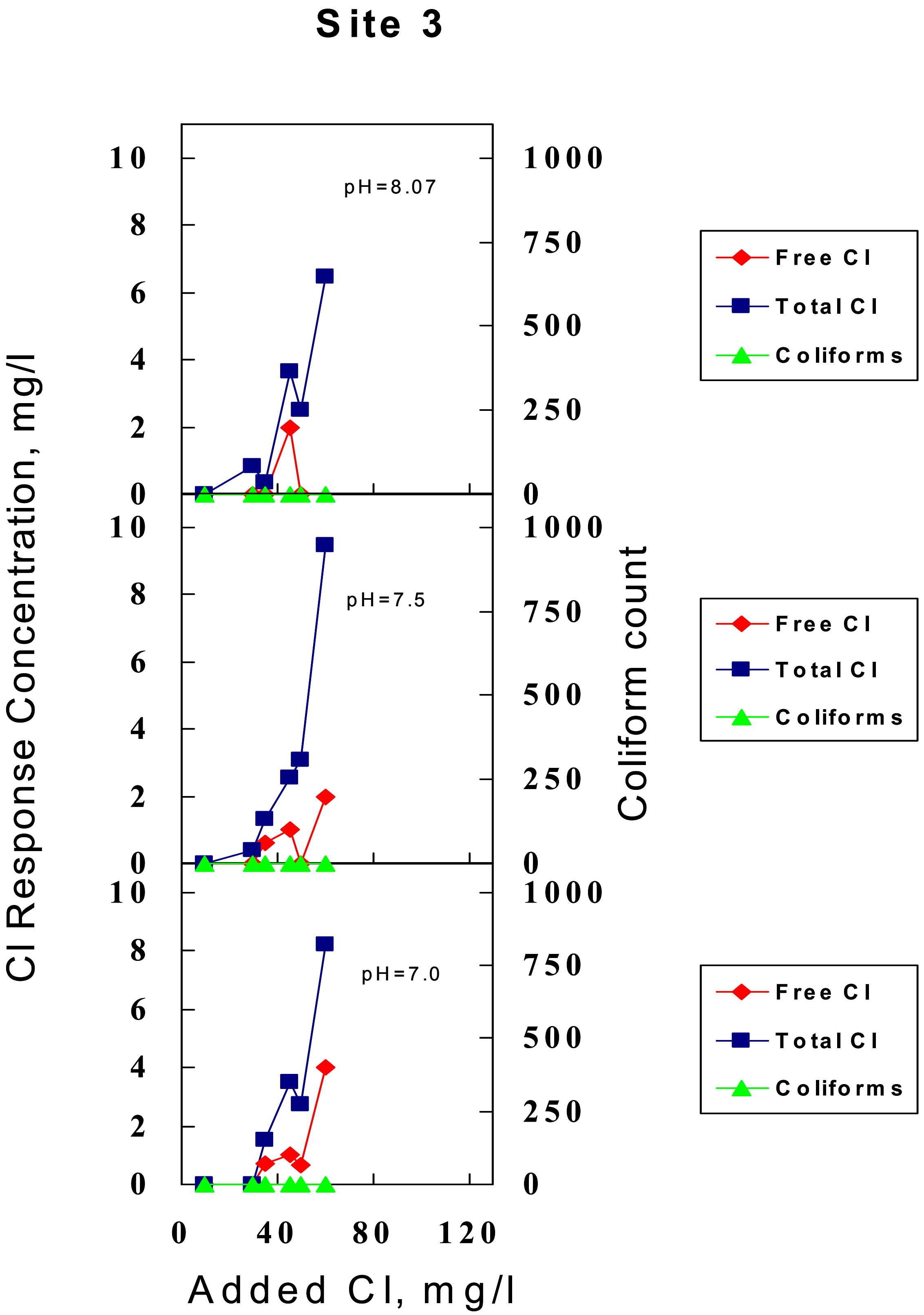

Figure 3. Chlorine dose/response for effluent from Site 3.

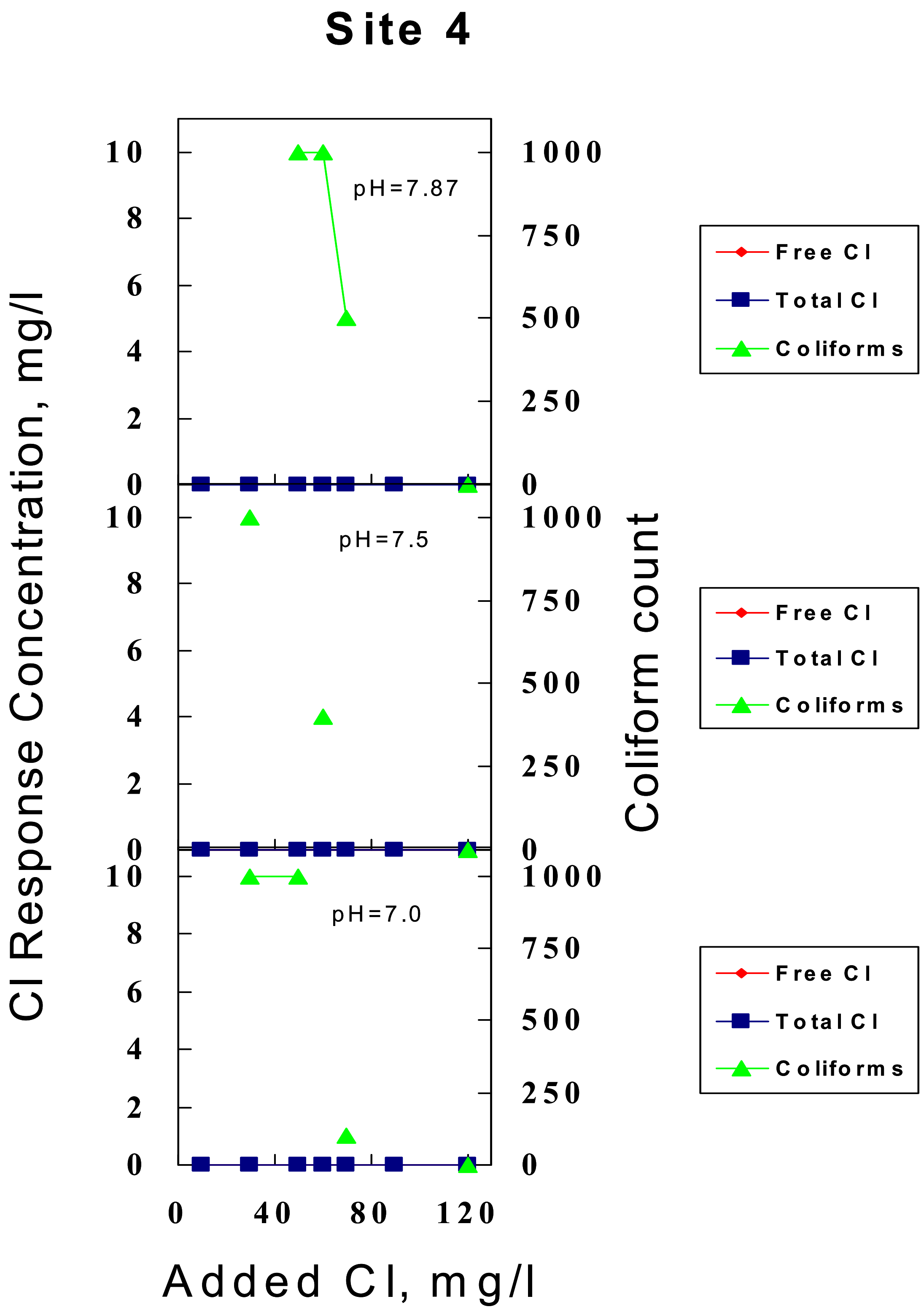

Figure 4. Chlorine dose/response for effluent from Site 4.

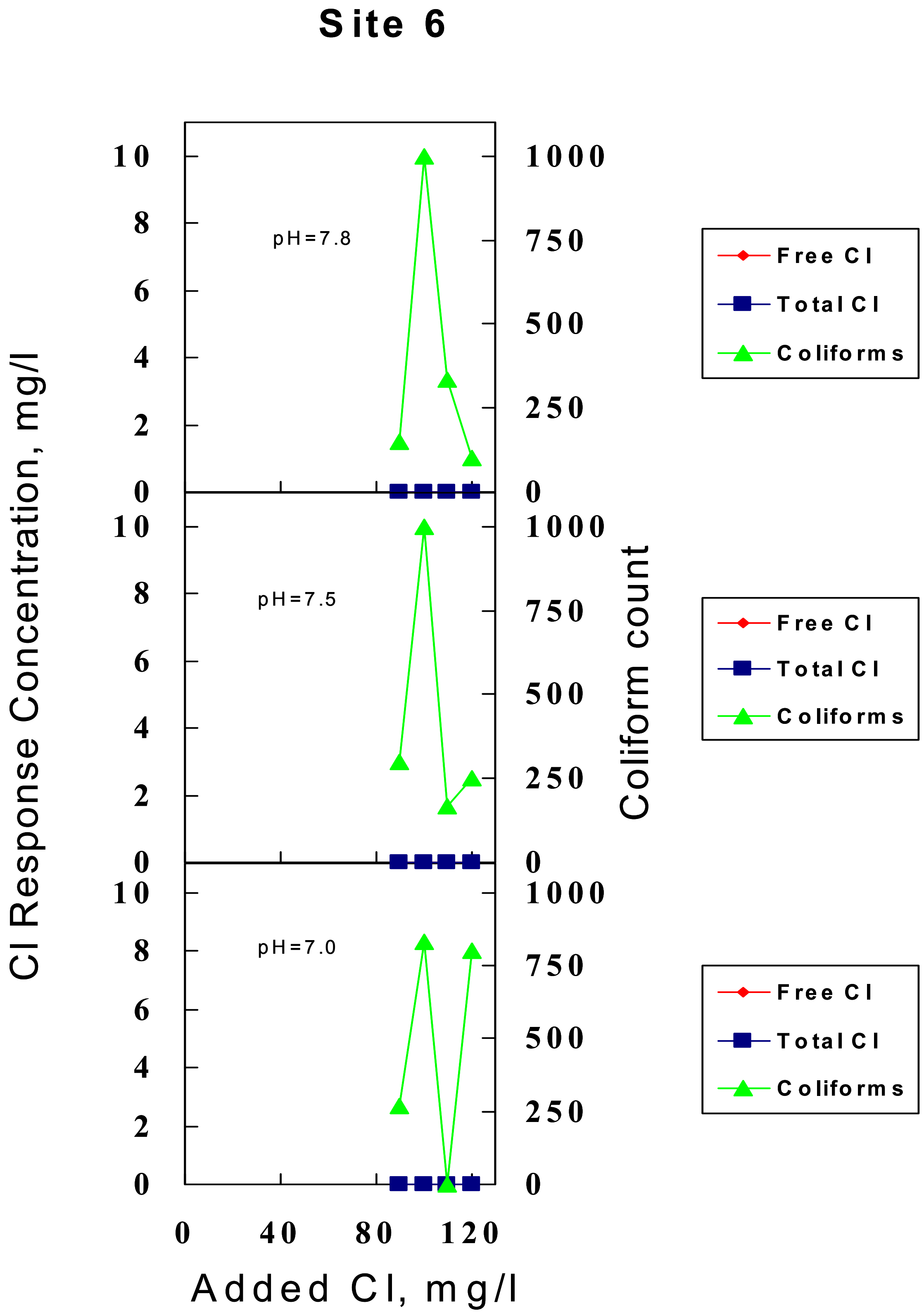

Figure 5. Chlorine dose/response for effluent from Site 6.

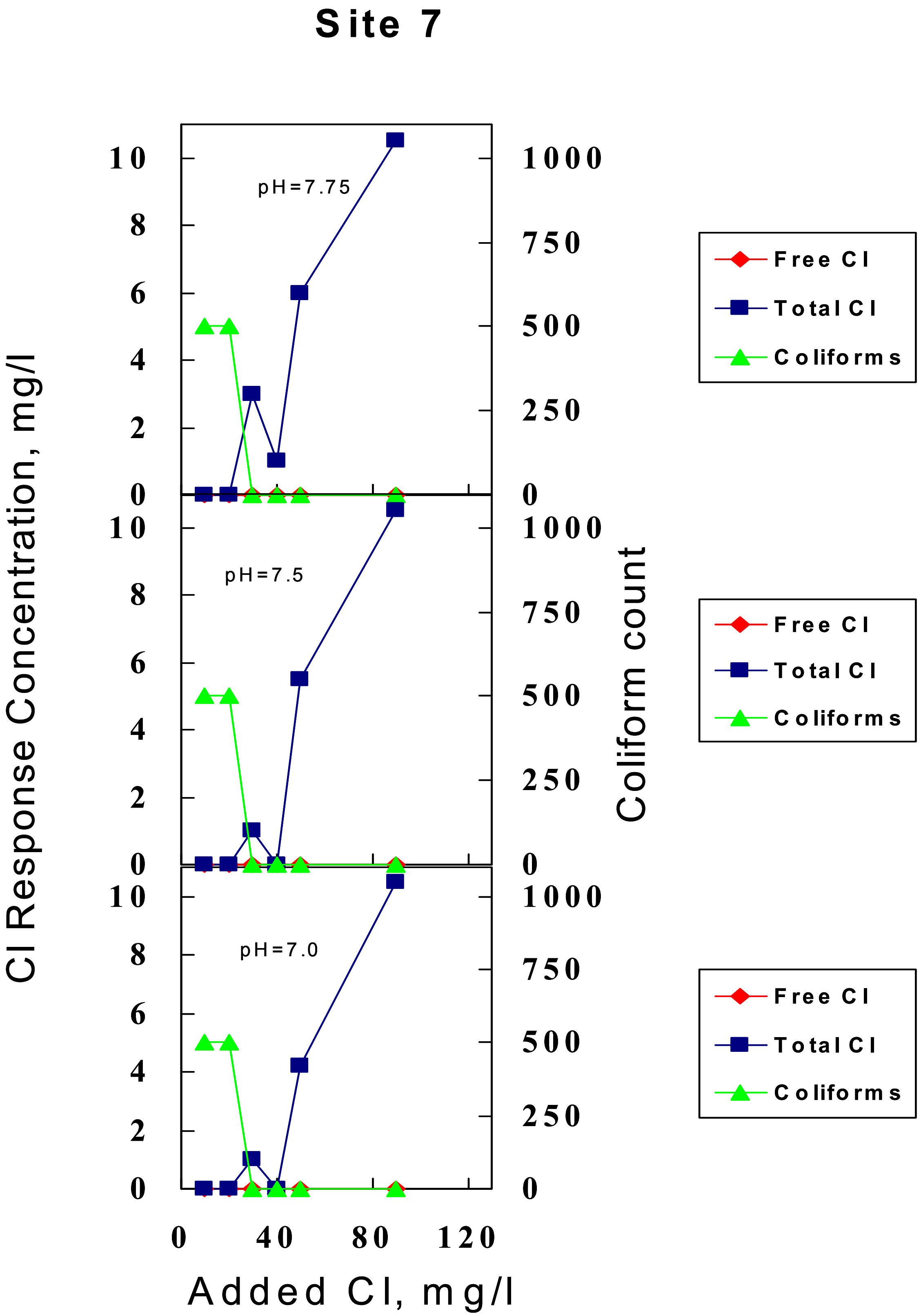

Figure 6. Chlorine dose/response for effluent from Site 7.

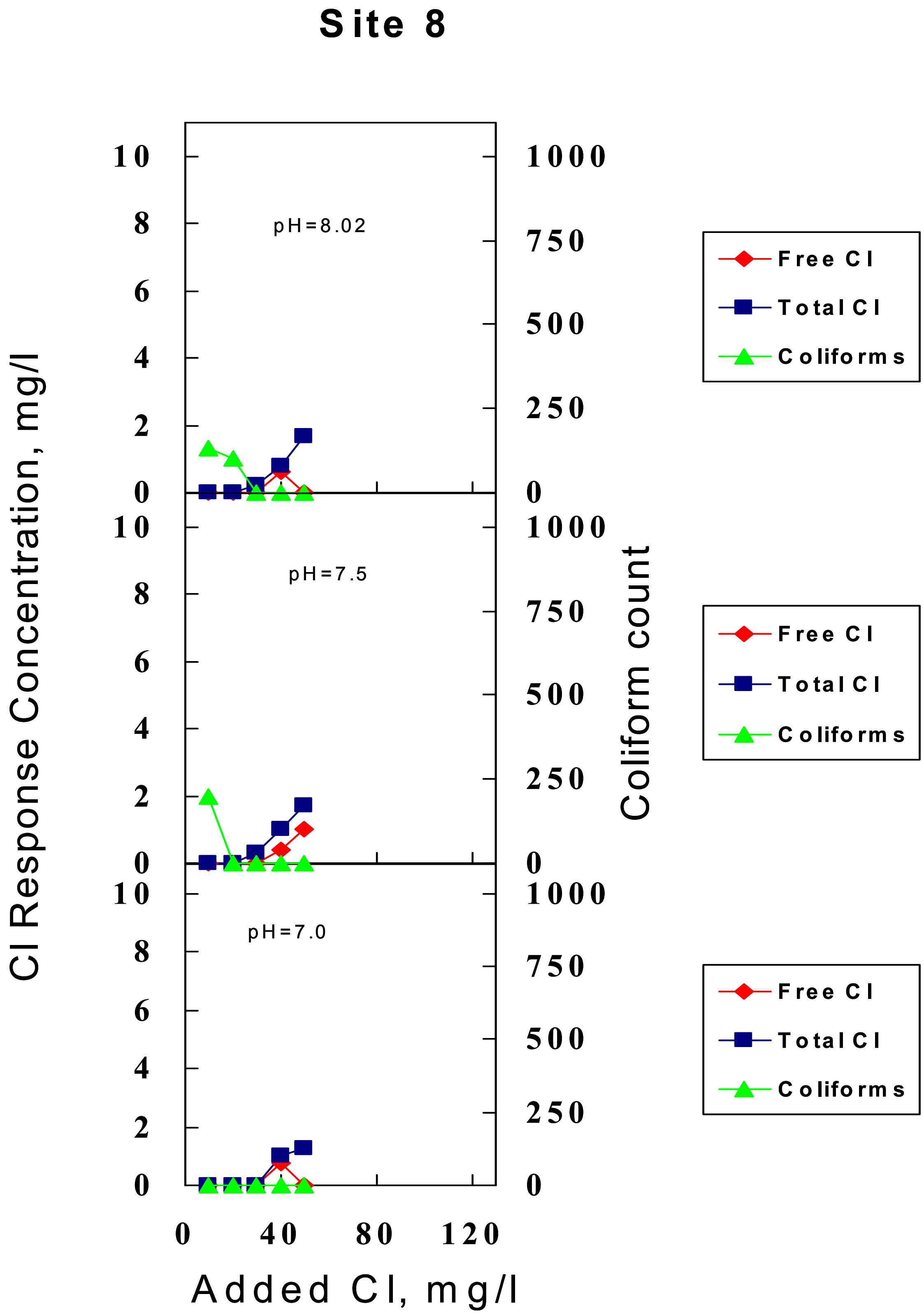

Figure 7. Chlorine dose/response for effluent from Site 8.

Pervaporation; Precision Irrigation of Strawberries Using Moderate EC Water Sources

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Introduction

There are many areas of the globe where crop growth is limited by access to suitable water- it's there, but is of too high a salinity for use on most crops. The extreme, of course, is land next to the ocean. In this presentation we would like to share information about a technology known as "pervaporation" that can be used to precisely deliver water to crops using lower quality water. You may be hard pressed to find a definition of pervaporation; it's not in any standard dictionary, and most textbooks mention it only in passing while discussing membranes separation processes including it's better known cousin reverse osmosis. For instance, a quick search of a web browser came up with 180,000 hits on reverse osmosis, but only 9,000 on pervaporation, a 20:1 ratio. Industry is a little more aware; the ratio of mention in US patent abstracts is only 6:1.

Definition of Pervaporation

Pervaporation is the separation of mixtures by differing rates of diffusion and solubility in a non-porous membrane, followed by an evaporative phase change. The permeant appears to evaporate through the membrane. The separation occurs because different materials permeate through such membranes, also termed as dense or monolithic, at different rates. This observation dates back to at least 1831, but it was not until the 1960's that scientists started developing commercial applications. Some of these include;

- treatment of wastewater contaminated with organics
- recovery of valuable organics from process side streams
- dehydration of ethanol and isopropanol
- purification and harvesting of organics from fermentation broths

Typically these technologies employ a membrane in sheet or tubular form; the product that permeates through the membrane is removed by vacuum or condensation.

Pervaporation Basics

The flow rate of a permeant across a dense is described by the following equation;

$J = DS (C_1 - C_2)/ l$

Terms are defined as follows;

J = **Flow rate**
D = **Diffusion coefficient**
S = **Solubility constant**
l = **thickness**
C_1 = **Concentration of permeant in feed**
C_2 = **Concentration of permeant in product**

The fundamental consequences for pervaporation in the context of a membrane used in irrigation are;

- **Flow increases as $(C_1 - C_2)$ increases**

This means that the flow varies depending on the difference in relative humidity between the fluid in the membrane system and the exterior soil water content. Exact determination requires understanding of things like the rate at which the water vapor condenses, how it moves in the soil, etc. Dry soil and low moisture content will pull water vapor across the membrane; if the soil is at capacity, it will not. It has the potential to provide water to the crop as it needs it

- **Flow increases as membrane thickness decreases**

This provides a means to fine tune the delivery capability of the membrane to meet the needs of a particular crop

- **Flow increases with increasing temperature**

The diffusion coefficient correlates with temperature through the Arrhenius equation. Just like chemical reactions go faster at higher temperature, as the temperature increases, the membrane is capable of providing a greater flux of water

- **Permselectivity (α) is independent of membrane thickness**

$$\alpha = C_{product} / C_{feed}$$

$$\text{Separation (\%)} = (1 - \alpha)\, 100$$

Features a Pervaporation Irrigation System Can Provide

The immediate benefit from a pervaporation based irrigation system is salt rejection. Because the membrane is non-porous, little or no salt will pass through it. In the same vein, the membrane will be a barrier to pathogens and non-soluble materials.

A pervaporation irrigation system will deliver water only when the surrounding soil is not at capacity; this creates a situation in which delivery occurs only on demand, when the crop requires it. This opens up opportunities for significant water conservation through precise irrigation.

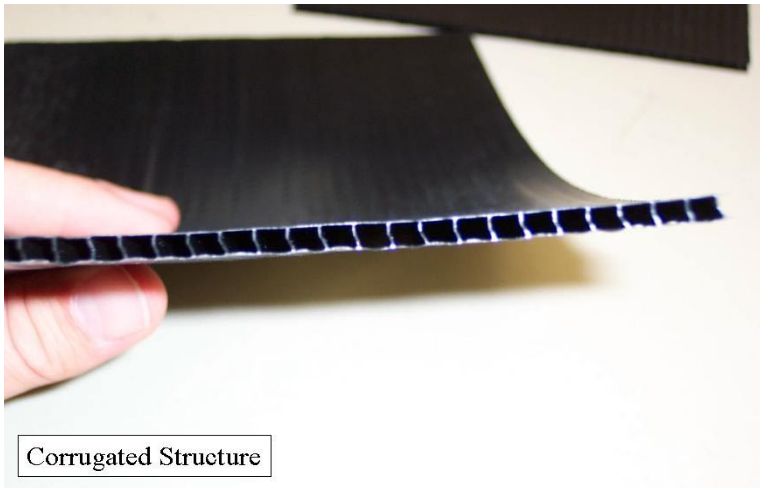
On the operations side, on demand delivery should reduce the control systems needed to initiate irrigation events; the system can always be “on”. In addition, no backpressure is required to force the flow, so energy requirements for pumping can be reduced. It is possible that even filtration requirements can be reduced, as water deliver is not dependent on small holes which can be clogged.

Design of a Pervaporation Based Irrigation System

The key physical attributes of the membrane would the capability to transmit enough water to meet the needs of crop and to provide excellent barrier to any dissolved salts. Once this basic science in place, it must also mechanical integrity and strength to be efficiently installed without damage and to have mechanical integrity for its expected lifetime. All this and it must deliver value to the grower; the payback for installation must meet his or her financial return criteria based on improved return or reduced costs.

Description of a Pervaporation Based Irrigation System

A system under current evaluation is based on specific grades of a polymer known to the plastics industry as a ***polyetherester***. Its key attributes are strength and extremely high water permeability. These polymers can be converted into strong and durable membrane based structures using conventional thermoplastic extrusion technology. The specific structure under evaluation is termed "corrugated sheet";



Corrugated Structure

Installation is carried out using conventional SDI machinery with a modified drop tube;

Field Installation

Description of a Pervaporation Based Irrigation System

Rows of membranes are connected to a header system using conventional piping;

Installed System

From a distance, you can’t tell what irrigation system is in use;

Oxnard Strawberry Trial – ’02-’03

Properties of a Pervaporation Based Irrigation System

Dimensions	
Width	85 mm (6.75 inches)
Height	4 mm (0.16 inch)
Channel width	4 mm (0.16 inch)
Top/ bottom membrane gauge	0.2 mm (0.007 inch)
Roll length	up to 180 m (600 feet)
Color	Black
Water delivery	24 –32 USG/ 100 linear ft/ 24 hrs
Separation of Dissolved Salts	≥ 95%

Typical Trial Conditions

Seven trials of 4-8 strawberry beds were carried out over October 2002 to mid 2003 between Oxnard and Watsonville in coastal California. One additional trial was conducted in Mexico. Typical conditions were as follows;

Soil Type	predominantly sandy loam
Bed Specifics	
Center line	64 inch
Top	40 inch
Plants	4/ bed
Row length	200-250 feet
Mulch film	dark opaque
# Pervaporation lines/ bed	2
Configuration of Pervaporation lines	surface or buried (5” depth)
Water EC	1-2.5
Control	Drip tape

Results

Field results were analyzed in the following terms. The small number of trials and the amount of natural precipitation led to wide variation in results between trials.

Total marketable berry weight		
	Buried	up to 88% of control
	Surface	up to 100% of control
Plant Vigor		No significant difference
Plant diameter		No significant difference
Soil salinity over trial		Control generally higher
Total water usage		
	Buried	typically 45%
	Surface	typically 60%
Soil Moisture		Control always higher

Conclusions

Pervaporation is a new technology that has the potential for irrigation of high value row crops, with the benefits of;

- Salt exclusion from moderate EC water sources
- Reduction in overall water needs
- Water delivery on demand

Irrigating Efficiently to Feed the World in 2050

Thomas D. Spears
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valmont
WATER MANAGEMENT GROUP

Introduction

The problem of water scarcity facing the world today and in the next few decades is quite serious. As I have explored in "Water Scarcity and Modern Irrigation" (Longo, Spears – 2003) utilizing highly efficient irrigation technology is a plausible solution to this problem, especially as modern irrigation uses less water and produces more food than traditional irrigated agriculture. In order to substantiate this proposal that efficiently irrigated agriculture offers the solution to the pending water scarcity crisis, I aim in this paper to lay out the quantitative data and qualitative assumptions from which my analysis derives. The calculation of future food demand and the dry land and irrigated land necessary to satisfy that demand is necessarily filled with debatable assumptions and estimates. The exact projection of food requirements and irrigated land requirements are less important than the confirmation that water availability for irrigated agriculture will present a major challenge, although a technically solvable problem, for the future. This paper attempts to project future irrigated agriculture demand and its associated costs, and concludes with a number of public policy recommendations for future action.

Food Demand

Food demand is driven by two primary factors: population growth and economic growth. While it is easy to see the relationship between population and food consumption, the influence of economic growth is less obvious. Essentially, wealthier people consume a greater quantity of calories on average than poorer people. This can be seen today in the difference in average kilocalories consumed by residents of the United States (roughly 3772 KCal/day) as compared to the world average consumption (roughly 2805 Kcal/day).[1] In addition, the calories consumed by wealthier individuals usually include significantly more meat than the diets of the poor. This is important to understand because calories consumed as meat are often produced using feed grains and take significantly more calories to generate than the direct consumption of the grains themselves. As a rule of thumb, one calorie of chicken requires two calories of feed grain to produce, one calorie of pork requires three calories of grain, and one calorie of beef requires five calories.

With these factors in mind, we can begin to make estimates of how much food demand will grow by 2050, as compared to our reference year (2000).

World Population

There are many estimates of future world population, which employ various assumptions about birth rates, death rates, economic growth rates, disease and medical advances. Most forecast world population around 9-10 billion by 2050. For the purpose of this analysis, the author selected a model developed by the International Institute for Applied Systems Analysis (IIASA) developed in 1996.[2] Population in 2000 is roughly 6.1 billion people. The model predicts population as low as 7.0 billion and as high as 13.0 billion in

2050 based on the assumptions utilized in the modeling process. The scenario with moderate assumptions for both mortality and birth rate produces a result of 9.9 billion population by 2050, which is used in the subsequent calculation. By comparison, the U.S. government census bureau projects approximately 9.1 billion in population in the same time frame.[3]

Gross World Product (GWP)

Projections of GWP are more difficult to come by and more volatile than population projections. The energy industry, which must make long term economic estimates for the purpose of long term capacity planning, is the best source of GWP that the author has found. According to the Energy Information Administration's International Energy Outlook for 2002, 1999 Gross World Product was \$30.6 trillion dollars (in 1997 dollars) and will grow to \$59.7 trillion (in 1997 dollars) by 2020.[4] This is a 3.2% annual average growth rate. The author assumed, conservatively, that this rate of growth would decline in 2020-2050 to roughly 2.4%, resulting in a GWP in 2050 of \$122.5 trillion dollars (in 1997 dollars). By my analysis, then, GWP per capita will grow from \$4,984 in 1999 to \$12,408 in 2050.

Calorie Consumption

In 2000, at \$4,984 per capita GWP, the average world citizen consumed 2,805 Kcalories/day. The average United Sates citizen with a per capita GDP of \$33,109 consumes 3,772 Kcalories/day. Interpolating between these numbers using the \$12,408 per capita GWP expected in 2050 would imply per capita consumption of roughly 3,070 Kcalories/day per capita. To this number, the author has added an additional 6% resulting from the substitution of meats for grain. This implies an average per capita farm output of 3,262 KCal/day required to support human consumption. We are now in a position to estimate the farm output required to feed the world population as a percentage of 2000 farm output. The calculation is as follows:

$$\text{Output Growth} = 100\% * \frac{(9.9 \text{ Billion} * 3{,}262)}{(6.1 \text{ Billion} * 2{,}805)} = 187\%$$

Land Availability

Irrigated and non-irrigated land totaled 1,497 million hectares in 2000, according to UNFAO.[5] Despite this large quantity of cultivated land, there remain significant reserve lands in the world, which could be converted to agricultural use. FAO estimates that cultivation could be successfully carried out on 2,600 million hectares.[6] While increases in cultivated land are likely to be seen in the next 50 years, the author believes widespread growth of non-irrigated land is unlikely for several reasons.

- Over the thousands of years of human civilization, most of the best and most productive non-irrigated land has already been put into service.

- The environmental costs of further land development, particularly non-irrigated land development are huge. We do not believe that future governments will be more accepting of rainforest destruction or the elimination of critical natural habitat in Africa in the future than they have been in recent history.
- Urbanization of the world population will continue to take some of the world's most productive land and convert it to uses with higher economic utility. A good example of this phenomena is China, which according to a 1999 IIASA study has over 20 million hectares of potential farmland in reserve. Under current practices roughly 1.0 million hectares of this land are put into production annually, but an offsetting 1.2 million hectares are lost each year to urbanization and other causes.[7]
- Total cultivated land was stable from 1990 (1,503 million ha) to 2000 (1,497 million ha). Non-irrigated land actually declined by almost 35 million hectares in the same time period.[8]

Unlike high quality dry farmland, the supply of land which could be cultivated using irrigation is relatively plentiful.

Availability of Non-Irrigated Land

The assumption for this study is that acceptable dry farming area will remain roughly constant over the next 50 years at roughly 1,225 million hectares.

Availability of Irrigated Land

The author allowed irrigated land to be an independent variable in the calculations.

Crop Yields

Starting in the late 1960's, agriculture experienced significant growth in average yields, which is sometimes referred to as the "green revolution". The "green revolution" was a concerted effort by Western agricultural experts to bring the benefits of modern farming to the developing world. Among the tools used to accomplish this objective were new seed varieties, improved cultivation techniques, the increased use of chemicals and fertilizers, and the increased use of irrigation.

The "green revolution" produced rapid increases in yield through the late 1960's and all of the 1970's, after which time yields have continued to grow, but at a declining rate each decade. If fact, throughout the 1980's and 1990's, growth in irrigated land was an increasingly important driver of crop yield growth, which overall was slowing. In the post- "green revolution" world, what kind of yield growth can be expected and in particular, how much growth in yields can we expect with dry land farming? In order to better understand this question it is instructive to examine the typical yield growth during the last decade in the United States.
Examining yield growth for corn and soybeans in the United States from 1991 to 2002 (using USDA yield data) can give us some insight into the future yield growth in the

balance of the world across all crops. For the years in question, conducting a linear regression on the yields for both crops shows that corn yield has grown 1.5% per year and soybean yield has grown 0.9% per year.[9]

In our analysis we used 0.8% per year average yield increase across all crops excluding the yield improvement caused by increased irrigation as our projection for the next 50 years. This quantity was selected for several reasons.

- Yield growth rates have progressively fallen in the U.S. since the 1960's. It is likely that we will see further reduction in yield growth in future years.
- The author wanted to exclude from the estimate the impact of additional irrigated land and its effect on yield growth, as this is the exact quantity to be calculated in the analysis. Irrigated land can produce much greater yield than dry land. An often quoted statistic is that the 20% of global irrigated land produces 40% of all crop output. In order for this to be true, irrigated land would have to be 2.7 times more productive than dry land. While our experience indicates that this number is too large, it gives an indication of how critical a role irrigation plays in improved yield. Valmont's experience indicates irrigated land yields closer to 2.2 times that of non-irrigated land.[10]
- Based on a study in the growth of irrigated land in the U.S., the author estimates that roughly 1/3 of yield growth is a result of increased irrigated land.

Our analysis ignores the potential for another "green revolution" generated by genetically modified organisms (GMO's) that could dramatically improve yield. To date the author is unaware of any dramatic improvements in yield shown by GMO's currently on the market or soon to be released.

Calculation of irrigated land required for food production.

In 2000, according to the United Nations FAO, there were roughly 1,225 million hectares of dry land cultivated and 272 million hectares of irrigated land.[11]

Total crop output is the product of non-irrigated area multiplied by non-irrigated yield plus the product of irrigated area multiplied by irrigated yield. With annual yield growth of 0.8% for non-irrigated land, and the estimate that irrigated yield is 2.2 times non-irrigated yield in 2000, we can solve these equations for irrigated area in 2050 as follows: Total output = (Dry Area * Dry Yield) + (Irrigated Area * Irrigated Yield)

Year	Dry Land Area (M HA)	Yield (Mil KCal/HA)	Dry Land Output (Tril KCal)	Irr. Land Area (M HA)	Yield (Mil KCal/HA)	Irrigated Land Output (Tril KCal)	Total Output (Tril KCal)	Avg. Yield (Mil KCal/HA)
2000	1,225	3.45	4,223	272	7.58	2,063	6,286	4.20
2010	1,225	3.74	4,580	323	7.88	2,544	7,125	4.60
2025	1,225	4.22	5,173	410	8.36	3,424	8,597	5.26
2050	1,225	5.17	6,337	582	9.31	5,420	11,757	6.51
CAGR '00-'50	0.0%	0.8%	0.8%	1.5%	0.4%	2.0%	1.3%	0.9%

Is there enough water to satisfy irrigated land needs?

Availability of Water

In 2000 humans withdrew roughly 3,900 billion cubic meters of water and consumed 2,329 billion cubic meters.[12] In a perfect world the excess withdrawals of water can become the source for consumption for other users. We see this happening today particularly where municipal and industrial waste water is partially treated and then used as irrigation water for agriculture. Although there is a limited amount of this type of water reuse today, we expect to see significantly more of it in the future. With this in mind, we can look at historic withdrawals of water as the ultimate supply available to humans, while water consumption represents the current demand if all non-consumptive withdrawals are re-used. If we fully re-used all excess withdrawals today, there would be a 1,571 billion cubic meter excess supply of water.

New Sources

Development of new sources of supply has slowed considerably. If we linearly regress historic growth in withdrawals, over the last 50 years (1950 – 2000), we find that roughly 51 billion cubic meters of supply were added annually.[13] From 1990-2000, only 30 billion cubic meters were added annually. The author estimated that the rate of growth of the last decade would continue to decline by 50 billion cubic meters per decade over the next 50 years. This assumption accounts for the increasingly higher costs of source development and the increasing unwillingness of humanity to disturb natural systems in the search for new water sources. Utilizing this assumption results in an estimated supply of water in 2050 of 4,650 billion cubic meters.

Demand Growth

- Municipal – If we assume that municipal demand is a function of population and wealth, which can best be represented by the product of population and per capita gross world product, we can estimate that global municipal demand will grow from 71 billion cubic meters[14] of water per year to 284 billion cubic meters by 2050. (Demand in 2050 = Demand in 2000 * (population * per capita GWP in 2000) / (population * per capita GWP in 2050).
- Industrial – Here the author makes the assumption that water per unit of economic output will remain flat in the future. This is almost certainly incorrect, as history in the United States has shown that industry responds to the cost of water and reduces the amount consumed as costs increase. On the whole, we can expect that the industrial share of water usage will grow somewhat slower than predicted due to cost pressures. Under the assumed circumstances industrial consumption goes from 93 billion cubic meters[15] in 2000 to 372 billion cubic meters in 2050. (Demand in 2050 = Demand in 2000 * (GWP in 2050) / (GWP in 2000)
- Agriculture – With the increased pressure on irrigated land to produce a greater portion of world agriculture, and with no change in irrigation practices, agricultural water consumption would grow from 2,165 billion cubic meters today[16] to 4,634 billion cubic meters by 2050. (Demand in 2050 = Demand in 2000 * (Irrigated land area in 2050) / (Irrigated land area in 2000).

Supply and Demand

If water supply grows to 4,650 billion cubic meters by 2050 (an average of 15 billion cubic meters/year), and the sum of municipal, industrial and agricultural demand is 5,290 billion cubic meters, we clearly have a significant (640 billion cubic meters annually) water gap by 2050. It is important to remember that this water gap includes a very liberal assumption in the growth of water reuse, with reuse satisfying 1,571 billion cubic meters of demand annually in 2050.

What solutions are available?

It is the author's belief that conservation, particularly in agriculture, represents the best available solution to the coming water shortage. However, there have been numerous other alternatives for supply or demand management also presented by academics, government and industry. It is worth mentioning a few of these other alternatives before further discussion of the agriculture conservation alternative.

- Water pricing at the "true" cost of water – Would help encourage conservation of water, particularly in industry. If imposed on municipal and agricultural users, it would inordinately impact the poor by driving up the costs of food and personal water usage.
- Desalination – Very energy intensive and very expensive. Of limited utility except for rich countries/regions, unless there is a major technical break-through.
- Water Transfers -- Expensive and very difficult to implement on a large scale due to environmental opposition.
- Salt Water Plants -- Allows irrigation with sea water. Might have some potential in dry coastal regions. Will require acceptance of dietary change.
- Water Re-Use – A very viable and practical method to increase the effective water supply. For this study we assumed that 100% of all non-consumed water is re-used.

Conservation of agricultural irrigation water.

Modern agricultural irrigation systems are significantly more water efficient than traditional irrigation methods. The vast majority of irrigated agriculture utilizes gravity irrigation which is roughly 40% - 50% efficient.[17] Modern pressurized systems such as subsurface drip and LEPA (Low Energy Precision Application) mechanical move can achieve much greater water application efficiencies. Subsurface drip irrigation systems are typically characterized as 90-95% application efficient.[18] Mechanical move systems can also achieve application efficiencies of 90% or higher.[19] These modern irrigation systems produce higher yields than gravity irrigation due to their better uniformity of water application and their timely availability. The amount of "crop per drop" improvement with modern irrigation is generally somewhere between 100% and 200% greater compared to traditional gravity flow. While some of the water saved in individual fields would have eventually made it back into the water basin (see the discussion of the basin argument in "Water Scarcity and Modern Irrigation"), and could potentially have been used again, it is Valmont's experience that a significant portion of the water conserved in individual fields represents net water consumption reductions for the purpose of satisfying human needs.

Based on Valmont's experiences the author believes that a 100% increase in crop yield per unit of water applied to the field is a conservative assumption when employing modern pressurized agricultural irrigation equipment (a 40% increase in output and a 30% reduction in water consumption).

With this estimate of the impact of modern pressurized agricultural irrigation equipment, we can calculate the potential water savings in 2050 by employing these technologies. The relevant equations used are given below:

Irrigated output = (efficient irrigated area * gravity yield *1.4) + (gravity irrigated area * gravity yield)

Water consumption = (efficient irrigated Area * 0.7 * gravity water consumption rate) + (gravity irrigated area * gravity water consumption rate)

Year	Scenario	Irrigated Food Output (in Tril KCal)	Efficient Irr. Area (Mil HA)	Gravity Irr. Area (Mil HA)	Total Irr. Area (Mil HA)	Estimated Water Consumption (Billion M^3)
2000	Current	2,063	26	246	272	2,165
2050	Business As Usual	5,420	56	526	582	4,634
2050	Low Investment	5,420	100	464	564	4,371
2050	Moderate Investment	5,420	200	324	524	3,778
2050	Med-High Investment	5,420	300	188	484	3,186
2050	High Investment	5,420	400	44	444	2,593

The moderate investment scenario saves more than enough water in total to close the calculated supply/demand gap. The actual required area of irrigation development with modern irrigation equipment will obviously depend on a complex interaction of major demographic factors, new technology development, and the validity of a number of assumptions. Political will power and the desire to preserve the natural environment are also factors that will significantly impact how the future emerges with respect to fresh water usage.

What might it cost?

Generally, pressurized irrigation systems require investment in the range of $800/ha for center pivot/linear (mechanical move) systems, and about $1,700/ha for subsurface drip.[20] If we assume that the bulk of new investment will be in mechanical systems (around 90% of production land in the U.S. that utilizes efficient pressurized irrigation today use sprinkler or mechanical move irrigation systems) a weighted average figure of $1,200 ha is not unreasonable to use. Average life of the systems must also be taken into account. Mechanical systems last on average 25 years.[21] Average life of subsurface drip irrigation systems are less certain as the technique is less mature. For the purpose of this analysis, an average life of 15 years was used. We utilized a weighted average life of 23 years for this analysis for the combination of mechanical and subsurface drip systems. Rough investment costs can be found in the table below.

Initial investment = $1,200 per hectare * Pressurized area

Replacement investment = 2000 Initial investment *50 years/23 years average life + ½ * 2050 initial investment * 50/23

Note that the figure of ½ is used in the above equation assuming that approximately half of the newly developed pressurized systems will be installed early enough to need replacing during the 2000 to 2050 time period.

Year	Scenario	Area Pressurized (Million HA)	Total Initial Investment ($ Billion)	Replacement Investment ($ Billion)	Investment above Business As Usual ($ Billion)	Annual Investment Above Business As Usual ($ Billion)
2000	Current	26	$22.6	N/A	N/A	N/A
2050	Business As Usual	56	$48.3	$102.0	0	0
2050	Low Investment	100	$86.9	$144.0	$80.5	$1.6
2050	Moderate Investment	200	$173.7	$238.0	$262.0	$5.2
2050	Med – High Investment	300	$260.6	$333.0	$443.0	$8.9
2050	High Investment	400	$347.4	$427.0	$625.0	$12.5

The "business as usual" case represents a reasonable estimate of the investment that will occur in pressurized systems if development trends from 2000 are extended to the year 2050, particularly the mix between efficient irrigation and gravity irrigation. It is interesting to note that without major public policy intervention in the next 50 years, private industry is likely to invest around $150 billion in modern irrigation equipment. This is because modern irrigation equipment is a productivity tool for farmers that earn a positive economic return. This makes accomplishing the goal of achieving an additional $260 billion (the total investment required to go from the "business as usual" case to the "moderate investment" case) in investment much easier as it is not necessary for public sources to provide full funding for these on-farm systems. Agriculture in much of the world, however, will require incentives to make these relatively large investments, as most of the world's farmers do not have sufficient capital to afford modern efficient irrigation investments.

It is the author's opinion that government and public entities need only partially fund investments in pressurized agricultural irrigation to achieve the results needed to adequately conserve water.

Public Policy

In light of this analysis, what should public policy be with respect to agricultural irrigation? While the author does not have a complete vision for all aspects and implications for the future of irrigated agriculture, a few thoughts can be offered.

1. Nations should be discouraged from holding food security as the ultimate goal of their agricultural sector. As irrigation water availability is likely to be the limiting factor in food production by 2050, we will need to irrigate where the available, sustainable water supplies reside. In the competitive advantages of the world's nations, food production for some relatively dry regions is simply impractical. No nation should ever have to worry about being cut off from world trade in food, and so the global community should make a commitment to continue selling food to every country, even pariahs.

2. Nations have a responsibility to ensure that water resources are developed and used in sustainable ways that are also consistent with basic human, industrial, agricultural and environmental needs. The needs of the poorest of earth's citizens for water access, sanitation and affordable food need to be given special consideration. Otherwise, competing interests are likely to outbid the poor in pursuit of scarce water.
3. Sources of additional water supply will need to be developed aggressively, but the needs of the natural environment cannot be ignored.
4. Water reuse should be vigorously pursued with the goal of making all non-consumed water withdrawals available for consumption.
5. Water pricing should be used to encourage conservation among industrial water users and some municipal users.
6. Nations must take responsibility for the social impacts of improved agricultural productivity (urbanization of the population, education and development of alternative employment opportunities). Agriculture is similar to other industries in that increased human productivity is necessary for economic gain for the farmer. This means that as productivity grows, we will see continual reduction in the human labor required to carry out agriculture, consolidation of farms, and greater resulting economic performance. It also means that rural populations will shrink as much farm labor becomes unnecessary. We see these impacts as predictable, economically inevitable and necessary to achieve more efficient and economically sustainable agricultural production. The author knows of no examples were traditional subsistence farming and strong capital accumulation and productivity growth coexist.
7. New agricultural development should be planned and implemented with modern pressurized irrigation systems in mind.
8. Governments should provide incentives for investment in modern pressurized irrigation equipment. Today effective incentives range from investment subsidization to low cost loans to loan guarantees.
9. Yield enhancing technologies must continue to be pursued vigorously as faster yield growth will reduce pressure on fresh water sources for irrigation.

Fresh water limitations represent a major challenge for food production in the twenty-first century. With competition from other sectors, agriculture stands to be the net loser in any battle for access to water. Such a situation will have its greatest impact on the lowest rungs of the economic ladder, where the need for water and food is intense, but the means to compete for this resource are limited. We possess the tools today to greatly reduce the water intensity of irrigated agriculture -- efficient irrigation and water reuse. Proper planning and public policy can avert what could be an agricultural water crisis in the years to come.

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Future Equipment and Research Needs Gleaned from Farmer Reactions to an Irrigation Water Conservation Education Program in Southwest Nebraska

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Introduction

Research on limited irrigation in Nebraska started in the 1970's at the former University of Nebraska's Sandhills Lab, where Gilley et al.(1980) used a line-source sprinkler irrigation system to study the effect of water-stressing corn at the vegetative, pollination and grain filling stages. They found no significant yield reduction when the crop was moderately stressed only during the vegetative stage. Significant yield reductions, however, were found when stress occurred during the reproductive stages (pollination and grain filling). Starting in the late 1980's, this idea was confirmed by further research conducted at North Platte, both using a solid-set sprinkler irrigation system and under surface irrigation.

Based on this research background, in 1996 the University of Nebraska started the Republican River Basin Irrigation Management Project, funded by the US Bureau of Reclamation (Schneekloth and Norton, 2000). The purpose of the project has been to demonstrate on farmers' fields the lessons learned at the plot-sized scale regarding the implications of alternative irrigation management strategies on water use and profitability. The ultimate purpose was to positively influence farmers to adopt the water saving strategies. The project has been conducted in southwest Nebraska, an area that has experienced substantial ground water declines and frequent seasons with less than adequate surface water supplies. This paper describes the methodology used in this project, lessons learned during the period of 1996-2003, and our thoughts about what is needed for farmers in southwest Nebraska to be able to adopt water saving strategies.

Methodology

The Republican River Basin Irrigation Management Project has been conducted in irrigated corn fields and has had two phases. The first phase was on larger one-half pivot sized fields and the second being on smaller plots in the edge of farmer fields. Both have had the farmer plant and care for the corn crop, with the timing and quantity of water application being the only variable.

Phase One (1996-2000)

The first phase of the project was started in 1996 with three on-farm sites. Two additional sites were added in 1997, a sixth site was added in 1999.

Cooperators and Site Selection: The cooperators were picked by the local Extension Educators in southwest Nebraska. They were picked because of their willingness to work with the project, interest in water issues, and excellent crop production skills. The fields that were selected ranged in soil type from sandy with a water holding capacity of about one in/ft of soil to silt loam, holding more than two in/ft (Table 1). The irrigation methods included four center pivots and two furrow systems. The tillage and cropping practices were what the farmers normally did on their farms. The North Platte site, which was surface irrigated and replicated, was on the University of Nebraska West Central Research and Extension Center farm.

Irrigation Management Strategies: The following four irrigation management strategies were demonstrated at each of the sites:

a. **FARM**-the irrigation scheduling was done the same as the farmer's current water management strategy.
b. **BMP**-the traditional Best Management Practice (BMP) irrigation management strategy focused on keeping soil-water at a high enough level to prevent moisture stress from being a limiting factor for yield. The goal of the strategy was to maintain the plant available soil-water (in the active root zone) between field capacity and 50% depletion from planting through maturity. Usually the soil was kept one-half to one inch below field capacity to allow for rain storage. After the hard dough stage, the soil was allowed to dry down to 60% depletion.
c. **LATE**- this deficit irrigation management strategy focused on saving water during the less sensitive vegetative growth stages and fully watering during the critical reproductive growth stages. Irrigation was delayed until about two weeks before tassel emergence of the corn, unless soil-water became 70% depleted (in the active root zone). Once the crop reached the reproductive growth stage, the plant available soil-water was maintained in a range between field capacity and 50% depletion. Usually the soil was kept one-half to one inch below field capacity to allow for rain storage. After the hard dough stage, the soil was allowed to dry down to 60% depletion.
d. **ALLOC**-this deficit irrigation management strategy focused on simulating an allocation system by correctly timing the application of a restricted quantity of water. Irrigation was restricted to 6 inches, except for the sandy site at Dickens, which was restricted to 10 inches during the growing season. The management strategy was to delay the application of water until about two weeks before tassel emergence, unless soil-water became 70% depleted. The available water (6 or 10 inches) was then applied between the period just before the reproductive growth stage and grain fill (approximately five weeks).

Plot Layout and Management*:* The demonstration plot layout was simple in that each treatment was only included once and the producer was allowed to pick his plot first (in each case he picked the better soils). The FARM and the BMP strategies were paired together and the LATE and ALLOC Deficit Irrigation treatments were also paired. The center pivot fields included one-half of the circle and were divided into four pie-shaped plots. Water application differences were achieved by using automated control panels that were available from the pivot manufacturer. The furrow irrigated field simply had field length strips. The irrigation scheduling was done by the project manager. Soil moisture data was gathered every two weeks by the neutron attenuation method and ET data from the High Plains Regional Climate Center was used to predict irrigation needs in-between.

Educational Activities: Fields days were held at some of the sites over the years. A phone survey was conducted with the producers that farmed the demonstration fields upon completion of the first phase.

Yields and Water Usage: The yields and water usage from the first six years and averaged over the six sites are shown in Table 1. It shows that the BMP strategy obtained 101% of the yield, as compared with the FARM strategy, using only 87% of the water. Using the LATE strategies, 97% the FARM yields was obtained, using only 69% of the irrigation water. The ALLOC strategy resulted in 89% of the FARM yield, using only 50% of the irrigation.

Phase Two (2002-present)

Armed with the earlier research and the results of phase one on-farm demonstration sites, phase two was started in 2002. During this phase, the irrigation strategies were demonstrated on farmer's fields, using a small plot line-source layout, instead of a half pivot. The focus of this phase has been on facilitation of demonstrations with public field days, as well as including lecture style winter programs, and news releases. The changes in

Table 1. Six Year Average of Corn Yields and Water Use by Management Strategy and Site.

		Management Strategy			
	Soil WHC[1] (in/ft)	FARM	BMP	LATE	ALLOC
Site		Average Yields (bu/acre)			
Arapahoe	2.1"	188	189	198	190
Elsie	1.5"	196	196	185	162
Dickens[2]	1.0"	202	201	187	175
Benkelman	1.8"	209	210	193	172
North Platte[3]	2.0"	-	203	202	188
McCook	2.0"	153	147	133	133
All Sites[4]		191	193	185	171
Percent of FARM Yield		100	101	97	89
		FARM	BMP	LATE	ALLOC
Site		Applied Water (acre-inches/acre)			
Arapahoe	2.1"	8.1	7.4	5.3	4.3
Elsie	1.5"	10.9	10.5	8.1	6.1
Dickens[2]	1.0"	15.3	14.1	12.0	9.7
Benkelman	1.8"	12.8	12.5	9.7	6.2
North Platte[3]	2.0"	-	10.2	7.8	4.9
McCook	2.0"	16.0	9.7	8.0	5.8
All Sites[4]		12	10.7	8.4	6.2
Percent of FARM Applied Water		100	87	69	50

[1] Soil Water Holding Capacity.

[2] Data for Dickens not included in 97 due to irrigation error & soybeans in 2000.

[3] FARM management strategy not used in North Platte.

[4] Yield and applied water are weighted by the number of years of data at each site.

methodology were to facilitate public viewing of the demonstration from the road and to make better field day sites. The smaller line-source layout makes a better field day site because the irrigation strategies are all within a few hundred feet and the line source irrigation system shows fully watered to dryland in a range of only 50ft.

Another change that was made was to name the irrigation strategies that were being demonstrated. The names needed to be something that was more descriptive and presented a positive image. The names that were chosen included; Fully Watered for the BMP, Water Miser BMP for the LATE, and Deficit Irrigation for the ALLOC. The definitions were changed slightly also, and are as follows:

a. **Fully Watered**-the traditional Best Management Practice (BMP) irrigation management strategy focused on keeping soil-water at a high enough level to prevent moisture stress from being a limiting factor for yield. The goal of the strategy was to maintain the plant available soil-water (in the active root zone) between field capacity and 50% depletion from planting through maturity. Usually the soil was kept one-half to one inch below field capacity to allow for rain storage. After the hard dough stage, the soil was allowed to dry down to 60% depletion.
b. **Water Miser BMP** - the Water Miser BMP irrigation management strategy focused on saving water during the less sensitive vegetative growth stages and fully watering during the critical reproductive growth stages. Irrigation was delayed until about two weeks before tassel emergence of the corn, unless soil-water became 70% depleted (in the active root zone). Once the crop reached the reproductive growth stage, the plant available soil-water was maintained in a range between field capacity and 40% depletion. Usually the soil was kept one-half to one inch below field capacity to allow for rain storage. After the hard dough stage, the soil was allowed to dry down to 60% depletion.
c. **Deficit Irrigation**-The deficit irrigation management strategy focuses on correctly timing the application of a restricted quantity of water, both within the growing season as well as over a several year period. The intent is to stabilize yields between years by applying irrigations based on soil-water depletion. Less water will be applied during wetter years, while more will be applied through the drier years, with an average over the years equaling the available quantity of water. The management strategy is to delay the application of water until about 2-weeks before tassel emergence for corn, unless soil-water becomes 70% depleted. Once the crop reaches the reproductive growth stage the plant available soil-water (in the active root zone) is maintained in a range between 30 to 60% depletion. It is allowed to dry down to 70% depleted after the hard dough stage. The idea is that these depletion numbers should be changed based on the amount of water the producer has to work with. More research is needed to determine guidelines for differing water use levels.

***Cooperators and Site Selection**:* The cooperators were picked with the help of the local Extension Educators and irrigation districts managers in southwest Nebraska. They were picked because of their willingness to work with the project, interest in water issues, excellent crop production skills, and location of their fields. To facilitate public viewing, the sites were located on the edge of production fields along public roadways. Big signs explaining the demonstrations were placed at each site (Fig. 1).The demonstrations were conducted at three sites 2002 and at two sites in 2003.

Figure 1. Big sign indicating the location and details about one of the demonstration sites.

***Plot Layout and Management**:* The irrigation demonstration sites used three line-source sprinkler systems (Fig.2). Each line-source was irrigated following the BMP, LATE or ALLOC strategies. The FARM strategy was not demonstrated during this phase.

Figure 2. Line-source sprinkler system used during phase two of the project.

The soil types were all silt loam and ranged in water holding capacity from about 1.9-2.5 in/ft. The tillage and cropping practices were what the farmers normally did on their farms. Timing and amount of water applied were the only management variables. The irrigation scheduling was done by the project manager. Soil moisture data was gathered every two weeks by the neutron attenuation method and ET data from the High Plains Regional Climate Center was used to predict irrigation needs in-between, using an irrigation scheduling spreadsheet.

***Educational Activities**:* Fields days were held at each of the sites each year with about 180 people attending during the first two years. Evaluation of the program consisted of after-meeting surveys and numerous one-on-one conversations.

Results and Discussion

Farmer Reactions

The farmers and crop consultants that were involved with the project and those attending field days were excited about the water saving strategies and indicated on surveys that they understood the concepts and planned to make changes in their operations. The end-of-meeting surveys from the 2003 field days showed that more than 90% of the participants planned to improve their management based on the knowledge and/or skills learned. They also indicated that they felt the value of the knowledge they had gained from this project was worth $15.35 per acre. The average number of cropland acres that they manage/influence annually was 1888 acres. The vast majority of the participants were farmers.

The Republican River Basin Irrigation Management Project in many ways has been a success. Producers are saying they are using less water after participating in the program and they are planning to do more in the future. However, information gathered from followup surveys and conversations with farmers and crop consultants have shown that the producers have only partially adopted the strategies. Part of the reason have been that farmers do not feel comfortable moisture stressing the crop as much as they could with their current moisture monitoring system. Therefore, they apply a little extra water to make sure they have enough. Additional limitations are that they simply do not have the time, know how, and the money to make better strategies work using current methods and equipment. These strategies can be made to work in research and even farm fields with enough labor and experience, but there is still the question of how to make them work on the average farm with the labor and expertise constraints the farmers and/or crop consultants have to deal with? In order to make the irrigation strategies work, it is necessary for the farmer to be able to follow the soil water status, either by monitoring soil moisture or by using crop water use information derived from weather data. In the current state of things, both methods present challenges for the farmers. Current systems are not as user-friendly as they need to be. And in fact, one could say that several good components are available to use in irrigation scheduling, but not a good, complete system or package is available for farmers to use.

Future Needs

Soil Moisture Monitoring Systems*:* Although soil moisture monitoring devices, like tensiometers, neutron scattering, and resistance blocks have been around for a long time, very few farmers in Nebraska actually use them. In the last few years, a new generation of moisture sensors using capacitance and time domain reflectometry technology have been developed. Many of these new sensors offer improvements over the old sensors, mainly in the form of datalogging and telemetry capabilities. Some of the same problems that have restricted the widespread adoption of the old sensors, however, still remain. One of the main restrictions is that the installation, calibration, and maintenance of current equipment require a lot of time and hard work during a very busy time of year. Simply put, most farmers and crop consultants will continue to use the hand-feel method until a system is developed that is reasonably priced and requires little, if any, additional time during the growing season. A second problem is that crop consultants do most of the irrigation scheduling in southwest Nebraska and are paid a per-acre fee by the producer. If better equipment is to be used, who will pay for it, the producer or the crop consultant?

Soil moisture monitoring systems need to be reasonably accurate, and the readout needs to be as straightforward as a fuel gage. Fuel gage readings are easy to understand and make informed management decision with their information, especially the ones in cars that tell how many more miles the car can go before refueling. Soil moisture monitoring systems of the future need to tell us where the soil moisture levels have been, where they are today, and how much water needs to be added in the near future.

The systems need to take and record the soil moisture profile at least once per day, four times per day would be better, to a sufficient depth for the crop being monitored (at least four feet for corn and soybeans). The data should be displayed by depth and the average for the root zone. The display module needs to be at the field edge or driveway and be connected to the sensors by wire or telemetry. Many producers and crop consultants would want this data uploaded into their computer in the pickup when they visit the field or better yet into the office. An industry standard file format needs to be developed to allow this data to be used in irrigation scheduling software. When this system has been developed, it could be easily interfaced with irrigation system control panels to partially or fully automate the water application.

Equipment installations need to be simple, quick, and easy. The most common complaint we hear about current and past soil moisture monitoring equipment is the installation. The problem is not just the work and precision required to install the equipment, but the time of year that it is being installed. In the early part of the growing season, farmers and crop consultants already have more to do then they can get done. Equipment that will be purchased by corn and soybean producers in the future will be permanently installed in the field during the off-season with only minor setups required each year. The components need to be placed below the soil surface during field operations (tillage, planting, cultivation, harvest, etc.) and relocated using GPS, a metal detector, field flags, measurements from a known location, etc. It will be important for the logger to continue to log data while all components are below ground. Equipment that can be installed very quickly in the crop row right after planting may meet these requirements as well. It should be kept in mind, that motor vehicles can only be driven in the field from harvest in the fall through the early plant growth stages the next spring. During the rest of the growing season only people can walk out to the equipment to install, do maintenance, or get things out of the way for harvest and components must be carried by hand that needs to be in or out of the field. Also, livestock grazing of crop residue is a common practice and permanently installed equipment need to be compatible.

The calibration of the equipment for a specific field and crop may be the biggest problem to overcome and is largely out of the control of the company that manufactures the devices. But that does not change the fact that successful calibration will be the key to making the products work in the field. Although most soil moisture sensors come with a factory calibration, our experience with several sensors indicate that developing site-specific calibration is critical to getting accurate soil moisture data. The factory calibration may be close to giving us the amount of water in the soil, but is that good enough? In addition to the soil moisture data, it would be a lot more useful for the farmers if the sensors would go the extra step to determine the available water holding capacity of the soil, field capacity, and permanent wilting point or some other moisture level that can be relate to irrigation scheduling.

Current calibration procedures have been developed by researchers for research projects where accuracy is very important (Evett and Steiner, 1995). The problem with moving these procedures to production agriculture is that they take too much time and effort. New procedures are needed that the average person can do with a minimal amount of effort and still have the accuracy needed for irrigation scheduling. If the equipment was installed during October or November, the procedure could require that data be logged for several months to do the calibration. During the off-season without crops removing soil water, the soil could be saturated and allowed to drain to field capacity. A simple easy-to-use procedure should be developed for each soil moisture monitoring system sold. Products with the best calibration procedures will be the easiest to market. Monitoring soil moisture in one spot in the field is difficult enough, but the problem of determining how that relates to the rest of the field must also be overcome. The most common method used today is the hand feel method comparing the field to the spot being monitored. A remote sensing system could accomplish this task plus could possibly eliminate the need for in-the-soil sensors and several of the problems described above. Research needs to continue into methods of using remote sensing to monitor soil moisture.

The cost a producer would be willing to pay for a soil moisture monitoring system is quite variable. If he has fairly low pumping costs and plenty of water, it may only be a few hundred dollars. However, if he is limited in how much water he can pump, it could be worth 15-16 bushels of corn for each inch of water saved or more efficiently used. This could amount to a few thousand dollars in a 100-130 acre field, which is a common size in. The impression we get from talking to producers in southwest Nebraska is that most would not be very interested once the costs get above the one thousand-dollar mark per field.

Evapotranspiration Estimates from Weather Data*:* Evapotranspiration estimates from weather stations have some distinct advantages. First, the data is very easy to get in Nebraska from newspapers, radio, telephone hotlines, and the internet. Second, there is no need to buy, install, calibrate and maintain equipment in the field. Thirdly, someone else manages the data.

So, with all this going for it, why would a producer not just use ET data and skip the infield stuff? Well, like most systems it has some short comings. First, if the producer does not adjust the data to the specific field and crop, the data is not very good. In Nebraska, this is not very hard if the data is retrieved from the High Plains Regional Climate Center web site (http://www.hprcc.unl.edu). From this site the field details can be specified once and an email will be sent to the producers' computer each day through the summer with the adjusted ET data. Secondly, the data is an estimation from a weather station that could be several miles away from the field and is usually located in a dryland pasture. Sometimes this can cause the estimated numbers to be quite high. Thirdly, the information tells you nothing about the quantity of water stored in the soil, or the amount of water added from rain or irrigation.

The data should play a very important role in any irrigation scheduling system, but needs to be corrected to the actual field's soil water level every week or two. Also, research needs to continue to increase the accuracy of the data.

Historical averages that are adjusted to the specific field location and crop are available from the web site. This data is very useful during the irrigation season in predicting the amount of water that will need to be applied in the next week or so.

Historical extremes adjusted to a specific field could provide a valuable management tool and should be developed in the future.

Data Management: The two different methods described above, evapotranspiration estimates from weather stations and soil moisture monitoring systems, both generate a phenomenal amount of data. This information is not very useful without a computerized method of retrieval, storage, viewing and analyzation. Currently, we are not aware of a software package that is designed for production agriculture in Nebraska that can help a producer or crop consultant retrieve, store, view, analyze and then help formulate an irrigation scheduling recommendation. Although very complete crop models have been developed, which are capable of providing irrigation scheduling information, most of these models are so complex that have been relegated to research applications. Other very good software exists that can do part of these functions, but not all of them in the same package. Thus, this type of software definitely fits into the future need's category.

A user friendly computer software needs to be developed that would make irrigation scheduling easy for the farmer. This software should be able to automatically obtain and update the weather data directly from the source (climate center) via the internet. It should be able to follow the soil moisture status of the field, and allow adjustments as the growing season progress. It also should be able to forecast future irrigation needs based on historical data and weather forecasting, and predict the ability of the farmer to meet the irrigation demands, based on the irrigation system capacity and water availability.

Conclusions

We currently know irrigation strategies that can save water compared to the current systems being used in production agriculture in Nebraska. Farmers and crop consultants that have learn about the strategies think they would help them use less irrigation water. The challenge to those of us in extension, industry, research, and other government agencies is to develop equipment and procedures to enable better water management. If a system can be developed, the producers in an area like water-short southwest Nebraska will be ready to purchase and use them.

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Farm-Size Characteristics of Western Irrigated Agriculture: Contributing to Water Conservation and Small Farm Policy Goals *

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USDA's 1998 National Commission on Small Farms brought to the forefront of the farm policy debate the plight of the small farm and the need for farm policy to influence the structure of U.S. agriculture in the future (USDA, 2000). In addition, USDA also recognizes the policy importance of improving agricultural water conservation to meet farm economic objectives, as well as "increasing water demands" for municipal/urban, industrial, and recreational uses under "increasingly scarce water-supply conditions" (USDA, 2001). In addition to growing water demands, the rising importance of high quality water supplies for both human and ecosystem health, and adequate water supplies to meet endangered species requirements and Native American water-right claims, have helped to clarify onfarm agricultural water conservation within USDA's resource conservation policy goals. The new farm bill, **The Farm Security & Rural Investment Act of 2002,** provides $250 million in new funding for a ground and surface water conservation program emphasizing cost-sharing of more efficient farm irrigation systems. This paper hypothesizes that the structure of irrigated agriculture in the western U.S. will play a significant role in the success of USDA water conservation and farm-structure policy goals applied to irrigated agriculture.

In 1997, irrigated agriculture in the 17 western States accounted for 29 percent of all farms in the West, with about 43.0 million irrigated acres (NASS - 1997 Census of Agriculture). In 1995, irrigated agriculture also accounted for 75 percent of total freshwater withdrawals in the West [132.1 million acre-feet (maf) out of 177.2 maf for all sectors], and 90 percent of consumptive water-use in the West (78.1 maf out of 87.2 maf for all sectors) (Solley, Pierce, and Perlman, 1998). In the 17 western States, most irrigated farms (81 percent) are "small farms" (farms with < $250,000 in total farm sales). But irrigated farms with ≥ $250,000 in total farm sales account for 61 percent of irrigated crop acres and 66 percent of the total farm water applied. Irrigated farms with total farm sales ≥ $500,000 alone (only 9.5 percent of all irrigated farms in the West) account for 48 percent of total farm water applied in the West.

Given the skewed nature of these distributions, meeting both USDA water conservation and small-farm policy goals requires understanding the farm-size structural distributions for irrigated farms, acres irrigated, applied irrigation water, irrigation technologies, water-management practices, barriers to irrigation system improvements, and producer participation in public cost-share water-conservation programs. This paper examines the status of the structural distributions of irrigation characteristics across farm-size classes for the 17 western States. In addition, the paper evaluates the degree of existing water-conserving and higher-efficiency irrigation occurring throughout the West, by farm-size class. Particular attention is given to assessing the capacity for additional water conservation improvement across western irrigated agriculture by farm-size class, and the implications farm-structural differences will likely have for USDA resource conservation and small farm policy goals.

Research Approach and Data Sources

Structural characteristics of western irrigated agriculture were evaluated using data from USDA's 1998 Farm & Ranch Irrigation Survey (FRIS). FRIS data were grouped into four farm-size classes, defined using the "total farm sales" variable from the 1997 Census of Agriculture – carried over to FRIS (by observation). The four farm-size classes, defined to be consistent with the farm typology as designed by the Economic Research Service (ERS), USDA (Hoppe and MacDonald, 2001), are presented in Table 1. Sampled observations for FRIS were selected from irrigated farms and ranches identified in the 1997 Census of Agriculture (6,875 farm operations across the 17 western States). Table 2 identifies, by farm-size class, the actual number of FRIS irrigated farm observations (and their corresponding NASS expanded farm numbers) used for this analysis. For a detailed explanation of FRIS sample design characteristics, coverage, statistical methodology, estimation, response rates, and reliability measures, see the National Agricultural Statistics Service, USDA website for FRIS at www.nass.usda.gov/census/census97/fris/fris.htm.

For this analysis, two additional data reliability issues deserve attention. First, for such key variables as the number of irrigated farms, acres irrigated, and water applied (total and by water source), values for the "total" column in the appropriate summary tables are equivalent to values reported in the FRIS report (NASS, 1999). The significance here is that the data tables for this analysis present a farm-size "structural" view of irrigation characteristics reported in the NASS-USDA FRIS report. Second, for all data tables summarizing a weighted-average statistic, coefficient of variation (CV) statistics were computed by farm-size class and by State (and region). Coefficient of variation values were computed as [(standard error of the estimate divided by the estimate) x 100], and reported in the appropriate data tables using * for CV ≤ 25; ** for 25 < CV ≤ 50; *** for 50 < CV ≤ 100; and **** for CV > 100. For most summary tables, CV values across farm-size classes across the western States were generally less than 25 and most often less than 50, indicating relatively low variability of irrigation characteristics within most farm-size classes.

FRIS-summarized data used for this paper were developed using the west-wide summarized values derived from a set of 147 summary data tables developed as an ERS electronic Data Product (in process), which includes irrigated farm characteristics across farm-size class by State, and for the 17 western-State region. Because of space limitations for this paper, only values for the 17-State region are reported in the attached Tables 3 – 12.

Table 1. Farm-Size Class Definitions Used to Examine Structural Characteristics of Irrigated Agriculture

Farm-Size Classes (1 – 4)[1] (based on total farm sales)	**Corresponding ERS Farm Typology Definitions**[2]
\$0 ≤ 1 < \$100,000	Includes ERS's limited resource, retirement, residential/-Lifestyle, & lower-sales/farm occupation groups.
\$100,000 ≤ 2 < \$250,000	Higher sales, farming-occupation group.
\$250,000 ≤ 3 < \$500,000	Large family farm group.
4 ≥ \$500,000	Very large family farm group.

[1] Farm-size classes were defined using the value of the total farm sales variable carried over to the 1998 FRIS data from the 1997 Census of Agriculture (by observation).

[2] Non-family corporate farms could not be identified with FRIS data.

Table 2. FRIS Irrigated Farm Numbers by Farm-Size Class for the 17 Western States

FRIS Sample Results:	Farm-Size Class (1 – 4) 1	2	3	4	Total (All Farm-Size Classes)
Actual FRIS Farm Observations:	1,498	1,373	1,386	2,618	6,875
NASS Expanded (Represented) Farms:	95,933	22,910	14,251	13,996	147,090

Summarized Farm-Size Characteristics for Western Irrigated Agriculture

Aggregate Irrigated Farm Values by Farm-Size Class

Irrigated Farms. For the 17 western States, most irrigated farms in 1998 were "small farms." Out of 147,000 irrigated farms (FRIS total expanded farms), 65 percent were farms with less than $100,000 in total farm sales (Table 3). Nearly 81 percent of irrigated farms had farm sales of less than $250,000. Just less than 20 percent had farm sales greater than or equal to $250,000 and only 9.5 percent of irrigated farms had farm sales greater than or equal to $500,000. These structural attributes are characteristic of irrigated farms for most western States, with Utah having the largest percent of "small irrigated farms" at 94 percent.

Total Irrigated Farm Sales. For the West as a whole, of the $38.7 billion in 1997 total farm sales (FS) for FRIS irrigated farms, 85 percent were from irrigated farms with sales ≥ $250,000 (Table 3). Small irrigated farms (FS < $250,000) accounted for only 15 percent of irrigated farm sales. These structural attributes are also characteristic of irrigated farms for most western States. While exceptions do exist for some States, overall, the largest 9.5 percent of irrigated farms in the West (FS ≥ $500,000) accounted for 72 percent of 1997 farm sales from irrigated farms. In addition, irrigated farms in the West are generally larger (in crop sales) than non-irrigated farms, averaging $850 and $120 per harvested acre for irrigated and non-irrigated farms, respectively (NASS, 1997).

Total Farm Irrigated Acres. Westwide, farm irrigated acres are more heavily skewed toward larger irrigated farms. Of the 38.5 million FRIS irrigated acres for the West, 61 percent are associated with farms with ≥ $250,000 in farm sales, while at least 41 percent are associated with farms with ≥ $500,000 in farm sales (Table 3). Arizona, California, Kansas, and Washington have the most heavily skewed distributions of farm irrigated acres toward larger farms (ranging from 74 to 89 percent). The structural distributions of irrigated acres are skewed toward smaller irrigated farms (FS < $250,000) for several States, including Montana, Utah, and Wyoming (64, 72, and 60 percent, respectively).

Total Farm Water Applied. Farm water use in the West is even more heavily skewed toward larger irrigated farms. Farms with farm sales ≥ $250,000 account for 66 percent of the 76.2 million acre-feet (maf) of total farm water applied by FRIS irrigated farms (Table 3). [*An acre-foot of water equals the volume of water that covers an acre of land to a depth of one foot, or 325,851 gallons*.] The nearly 81 percent of all smaller irrigated farms (FS < $250,000) account for only 34 percent of total farm water applied. At the same time, the 9.5 percent of the largest irrigated farms (FS ≥ $500,000) account for 48.4 percent of total farm water applied.

This skewed distribution in farm water applied is most dramatic for Arizona, California, Kansas, and Washington where larger farms (FS ≥ $250,000) account for between 75-87 percent of total farm water applied. For these States, irrigated farms with ≥ $500,000 in farm sales (5.2 percent of all irrigated farms in the West) account for 31 percent of total farm water applied in the West (about 23.4 maf out of 76.2 maf).

Total Groundwater Applied. While groundwater accounted for only 39 percent of all farm water use westwide, nearly 73 percent of groundwater use was by larger irrigated farms (FS ≥ $250,000), with 50 percent of all groundwater being applied by the largest farms (FS ≥ $500,000) (Table 3). Smaller irrigated farms (81 percent of all irrigated farms) accounted for only 28 percent of farm groundwater applied. A point worth noting, however, is that groundwater-dependent States (those States dependent upon groundwater for at least 50 percent of their farm water use) -- including Kansas, Nebraska, Oklahoma, New Mexico, Texas, and North Dakota -- are not the States with the more dramatically-skewed groundwater use distributions. These skewed groundwater-use distributions occur for heavily surface-water dependent States -- Arizona, California, and Washington. About 85 percent of the groundwater use for each of these States was applied by larger irrigated farms (FS ≥ $250,000), which are likely heavily dependent on using groundwater as a supplemental water supply to support their more extensive-margin irrigated agriculture.

Total Onfarm Surface Water Applied. While total surface-water use accounted for 61 percent of total farm water-use westwide, only about 12 percent originated from onfarm surface water sources. Use of onfarm surface water is less skewed toward larger farms than either groundwater use or water use from off-farm surface supplies. For the West, larger irrigated farms (FS ≥ $250,000) accounted for 59 percent of onfarm surface water use, while farms with FS ≥ $500,000 alone accounted for 40 percent of onfarm surface water use (Table 3). California and Oklahoma have the most skewed distributions for onfarm surface water use. Larger irrigated farms (FS ≥ $250,000) accounted for 93 percent of onfarm surface water use in California and 81 percent in Oklahoma.

Total Off-Farm Surface Water Applied. Westwide, off-farm surface water use (publicly-supplied water) accounted for 49 percent of all farm water use. In addition, off-farm surface-water is more heavily skewed toward larger irrigated farms (FS ≥ $250,000) than it is for onfarm surface water, but not as skewed as the distribution for groundwater (Table 3). Larger irrigated farms accounted for 63 percent of off-farm surface-water use, while the largest farms (FS ≥ $500,000) accounted for 49 percent. Again, Arizona, California, Oklahoma, and Washington are the States where off-farm surface-water use is the most skewed toward larger farms (91, 74, 72, and 76 percent, respectively).

Weighted-Average Irrigated Farm-Size Statistics

Average Value of 1997 Farm Sales Per Irrigated Farm ($/Irrigated Farm). Westwide, the average value of total farm sales (for 1997) for FRIS farms was $263,211 per irrigated farm. However, the westwide average is really not all that “telling”. The real story exists in the average irrigated farm sales value across farm-size classes. About 65 percent of irrigated farms (with FS < $100,000) had an average total farm sales value of $22.6 thousand dollars, while 9.5 percent of irrigated farms (with FS ≥ $500,000) had an average total farm sales value of nearly $2.0 million dollars (Table 4). Also, considerable variability exists across States by farm-size class. For all farm-size classes together, the average per irrigated-farm sales value ranges from $54 thousand for Utah to $640 thousand for Kansas. For the smallest farm-size class (FS < $100,000), the average per irrigated-farm sales value ranges from $7.3 thousand for Arizona to $59.7 thousand for Kansas. For the largest irrigated farms (FS ≥ $500,000), the average per farm total sales value ranges from $846 thousand for Montana to $2.9 million for Oklahoma (interestingly, not California).

Average Total Farm Acres Per Irrigated Farm (Acres/Irrigated Farm). For all western States, the average total farm acres per FRIS farm is 1,010 acres, ranging from 355 acres for the smallest farm-size class to 3,650 acres for the largest farm-size class (Table 4). However, it is important to note that for the western States, numbers for average total farm acres include the influence of rangeland, that is, privately owned/leased pastureland and grazing lands (but exclude lands grazed under a government grazing permit). Across States, average irrigated farm size (in total farm acres) varies dramatically. Among the smallest farms (FS < \$100,000), average farm size ranges from 68 acres for Washington to 1,314 acres for North Dakota. For the largest irrigated farms (FS ≥ \$500,000), average total farm acres ranges from 1,351 acres for Washington to 21,685 acres for Wyoming.

Average Total Farm-Irrigated Acres Per Irrigated Farm (Acres/Irrigated Farm). For all western States, average farm irrigated acres is 262 acres per FRIS irrigated farm (Table 4). This size statistic, however, varies across farm-size classes, from 79 irrigated acres for the smallest irrigated farms (FS < \$100,000) to 1,132 irrigated acres for the largest farms (FS ≥ \$500,000). Because these statistics remove the "rangeland" influence, the farm-size class variability across States is somewhat more meaningful. For the smallest irrigated farms, average irrigated acres ranges from 23 acres for Arizona to 360 acres for Kansas, and for the largest irrigated farms, from 757 acres for Washington to 2,286 acres for Nevada.

Average Total Farm Water Applied Per Irrigated Farm (Acre Feet/Irrigated Farm). Westwide, average acre-feet of total water applied per irrigated farm is 518 acre feet (Table 4). Average farm water use ranges from 145 acre feet per farm for the smallest irrigated farms (FS < \$100,000) to 2,632 acre feet per farm for the largest irrigated farms (FS ≥ \$500,000). For all farm-size classes, New Mexico and Utah have the lowest per farm applied water rates, averaging 287 acre-feet per irrigated farm, while Arizona has the largest rate, averaging 1,562 acre-feet per irrigated farm. However, a point worth noting here, is that these averages reflect the greater degree of extensive-margin irrigation/water use that occurs with larger irrigated farms.

Average Irrigation Application Rates - Total & by Water Source (Acre Feet/Acre). Based on westwide statistics for average total water applied per farm irrigated acre, the largest irrigated farms (FS ≥ \$500,000) tend to be the more intensive-margin irrigation operations, that is, their average applied-water rates (acre-feet per acre) tend to be slightly greater (Table 4). Irrigated farms in Arizona, California, New Mexico, and Washington influence this result more so than irrigation in other western States. Westwide, the average total water-application rate is 2.0 acre-feet per acre, while for the smallest farm-size class total water application is also at 2.0 acre-feet per acre, and for the largest farm-size class it is at 2.2 acre-feet per acre. For all farm-size classes, the average total water-application rate varies significantly across States, from a low of .8 acre-feet per acre for Nebraska and North Dakota, to a high of 3.9 acre-feet per acre for Arizona – reflecting differences in crops grown, climatic factors, technologies, water costs, and other factors.

Also, for the West as a whole, intensive-margin water use tends to be greater for surface-water irrigation (particularly for water applied from off-farm sources). The average application rate for groundwater for the West is 1.5 acre-feet per acre, ranging from 1.3 acre-feet per acre for the smallest farms to 1.7 acre-feet per acre for the largest farms (Table 4). On the other hand, the average application rate for off-farm surface water for the West is 2.6 acre-feet per acre, ranging from 2.2 acre-feet per acre for the smallest farms to 2.9 acre-feet per acre for the largest farms. Application rates for onfarm surface water for the West generally fall between application rates for groundwater and for off-farm surface water. So, barring consideration of crops irrigated (and all other factors), intensive-margin water-use statistics based on FRIS data indicate that groundwater irrigation is likely more efficient than irrigation using surface water sources. This is understandable, given that groundwater is generally viewed as the higher-cost irrigation alternative.

Weighted Average Farm Irrigation Costs By Farm-Size Class

Average Purchased Water Costs (\$/Acre). Westwide, purchased water costs (for publicly-supplied water) average about \$41.29 per acre (Table 5). However, for the West this average ranges from \$26.65 per acre for the smallest irrigated farms (FS < \$100,000) to \$56.72 per acre for the largest farms (FS ≥ \$500,000). Significant variability exists across States, both in total and by farm-size class. In total (across all farm-size classes), average purchased water costs range from a low of $9.96 per acre for Wyoming to a high of $84.69 per acre for Arizona. For the smallest farm-size class, average purchased water costs range from $8.97 per acre for Nebraska to $65.06 per acre for Arizona. For the largest irrigated farms, average purchased water costs range from $4.45 per acre for South Dakota to $81.75 per acre for Arizona.

Average Irrigation Energy (Pumping) Costs – Total & by Energy Source ($ Per Acre). Irrigation water is delivered and/or applied using either a gravity-based system or a pressurized system (which uses a pump to generate the required pressure for water movement). Irrigation pumping costs vary by the energy source used to power the pump (electric, natural gas, diesel fuel, gasoline, or the use of LP gas, propane, or butane). For the West, irrigation pumping costs (over all energy sources) average about $37.70 per acre, but they tend to be somewhat higher for larger farms, ranging from $29.41 per acre for the smallest irrigated farms (FS < $100,000) to $41.36 per acre for the largest irrigated farms (FS ≥ $500,000) (Table 5). These costs also vary across States, ranging from a low of $14.68 per acre for Montana to a high of about $62.60 per acre for both California and Arizona.

Average irrigation pumping costs by power source are generally relatively uniform across farm-size classes for all power sources, except for electricity. Here a distinct difference exists. Electric powered pumps are generally the higher-cost power source for irrigation pumping, averaging $43.75 per acre (these costs average $34.05 per acre for natural gas, $21.52 per acre for diesel fuel, $18.25 per acre for gasoline, and $17.82 per acre for LP gas, propane, and butane). Pumping costs for electric powered pumps range from $32.76 per acre for the smallest farms (FS < $100,000) to $48.44 per acre for the largest farms (FS ≥ $500,000). Pumping costs per acre for all other power sources are generally relatively uniform across farm-size classes throughout the West, with some small differences by farm-size for gasoline powered pumps.

Average Irrigation Maintenance & Repair Costs ($ Per Acre). Westwide, irrigation maintenance and repair costs (which average $11.11 per acre) are relatively uniform across farm-size classes (Table 5). However, these costs do vary significantly across States. For the smallest farms (FS < $100,000), these costs range from $3.77 per acre for Montana to $25.19 per acre for Arizona. For the largest farms (FS ≥ $500,000), these costs range from $2.65 per acre for Montana to $20.94 per acre for Washington.

Irrigation Technologies by Farm-Size Class

Sprinkler and Gravity Irrigation (Farm #'s & Acres Irrigated). The 1998 FRIS identifies acres irrigated for four broad irrigation-system technology categories, namely gravity-based systems, sprinkler systems, drip/trickle systems, and sub-irrigation systems. FRIS also identifies the irrigated acres that have been laser-leveled. Gravity irrigation is further subdivided into four field water-application systems, namely water applied through furrow-gravity application, between borders or within basins, uncontrolled flooding, or "other" gravity systems. In addition, for each of these field-application systems, gravity technology is identified across five field water-conveyance (delivery) methods, namely lined or unlined open-surface ditch delivery, underground pipe delivery, or above-ground pipe (including gated-pipe) delivery. Sprinkler irrigation is further subdivided between low, medium, and high-pressure sprinkler irrigation for center-pivot systems, linear-move systems, and side-roll, wheel-move, or "other" mechanical-move systems. Low-pressure sprinkler systems operate with an average water pressure under 30-pounds per square inch (PSI), medium-pressure systems operate with a PSI ranging from 30 to 59, while high-pressure systems operate with a PSI of 60 or greater. In addition, sprinkler irrigation is identified for hand-move systems and for solid-set or permanent systems. Drip/trickle irrigation technology includes surface and subsurface drip, and low-flow micro-sprinkler systems. Sub-irrigation technology involves the use of a water delivery or drainage system designed to maintain the aquifer water table at a predetermined depth (within the crop root zone). Laser-leveled irrigation involves grading and earthmoving to eliminate variation in field gradient using a laser-guided system for the purpose of controlling water advance and improving water distribution uniformity. For a detailed explanation of irrigation technologies, see the ERS website at www.ers.usda.gov/briefing/wateruse/questions/qa5.htm.

Table 6 summarizes, for all 17 western States, the number of farms and acres irrigated by major irrigation technology category and by farm-size class. Results indicate that a different story exists between the number of farms using particular irrigation technologies and the irrigated acres associated with these technologies. With all four broad irrigation technology classes, small farms (FS < $250,000) dominate in the total number of farms for each technology class across the West. However, this should not come as a surprise, since most irrigated farms are small farms. Small irrigated farms represent about 71 percent of all irrigated farms using a sprinkler irrigation system, 81 percent of farms using a gravity system, 82 percent of farms using drip/trickle irrigation, and 94 percent of farms using sub-irrigation. However, with acres irrigated by broad technology type, the structural distributions are generally skewed more heavily toward larger farms (more so for pressure-based technologies than for gravity or sub-irrigation systems). For ***sprinkler irrigation***, 68 percent of all sprinkler-irrigated acres in the West are irrigated by larger farms (FS ≥ $250,000), with 44.2 percent irrigated by the largest farms (FS ≥ $500,000). For ***drip/trickle irrigation***, 79 percent of all drip/trickle irrigated acres are irrigated by larger farms, with 73 percent being irrigated by the largest farms (FS ≥ $500,000). However, it is important to recognize that 86 percent of drip/trickle irrigated acres are from California (1.0 million acres out of 1.2 million acres). Within California, 80 percent of drip/trickle irrigated acres are with larger irrigated farms.

For gravity and sub-irrigation systems, the structural distribution story is a little different (Table 6). Here, the westwide acres-irrigated distributions are somewhat less skewed toward larger farms (FS ≥ $250,000), particularly for flood irrigated acres. First, for ***furrow gravity systems*** westwide, the acres-irrigated distribution only moderately favors larger farms, at 63 percent. For eight States, acreage distributions for furrow-gravity systems favor smaller irrigated farms (FS < $250,000) (Colorado, Idaho, Montana, New Mexico, Oregon, South Dakota, Utah, and Wyoming). But, these States account for only 26 percent of furrow-gravity acres irrigated westwide. Second, for ***flood irrigation systems*** westwide, the acres-irrigated distribution slightly favors smaller farms, at 55 percent. However, this percent ranges from a low of 17 percent for South Dakota to a high of 87 percent for Arizona. Third, for ***sub-irrigation systems*** westwide, irrigated acres are only slightly skewed toward larger farms (FS ≥ $250,000), at 55 percent. Across States, this percent ranges from about 17 percent for Nevada to 90 percent for California. Three States -- California, Idaho, and Wyoming -- account for 52 percent of sub-irrigated acres.

For ***laser-leveled irrigated acres***, the westwide structural distribution again heavily favors larger irrigated farms (FS ≥ $250,000), which account for 71 percent of these acres (Table 6). The largest farm-size class alone (FS ≥ $500,000) accounts for 56 percent of laser-leveled irrigated acres westwide. Across States, the percent for larger farms (FS ≥ $250,000) ranges from 19 percent for South Dakota to a high of 94 percent for Arizona. Only five western States have distributions for laser-leveled irrigated acres favoring smaller irrigated farms, these include Colorado, Idaho, Montana, South Dakota, and Utah (but they account for only 7 percent of all laser-leveled irrigated acres across the West).

Water-Conserving/Higher-Efficiency Irrigation by Farm-Size Class

Farm-level irrigation technologies vary widely in their irrigation-application efficiency potential. Application efficiency here refers to the relative amount of water applied that gets taken-up through plant consumptive-use; that is, the ratio of plant consumptive-use to actual water applied. Uncontrolled flood irrigation is widely recognized as the least efficient irrigation system, generally below 50 percent, but potentially 35 percent or lower (Negri and Hanchar, 1989). In general, gravity-based irrigation-application efficiencies can range from 35 to 80/85 percent, with higher efficiencies realized for improved gravity systems. These systems may involve distributing water across a field using furrows, between borders, or within a basin, in combination with a lined or piped field water-delivery system, cablegation or surge-flow water application, or gravity water-management practices, such as use of tail-water reuse pits, furrow-diking, alternate-row irrigation, and limited-irrigation set times. Pressure or sprinkler-based system application efficiencies can range from 50 to 90/95 percent, with low-pressure systems, low-energy precision application (LEPA) and drip/trickle systems all potentially realizing efficiencies as high as 85-95 percent. The higher the irrigation-application efficiency, generally the more water conserving the irrigation technology.

To gain a better perspective on the extent of water-conserving and higher-efficiency irrigation occurring by farm-size class in the West, FRIS acres irrigated by irrigation technology subcategory were used to structure a relative measure of "water-conserving/higher-efficiency" irrigation, from an aggregate system perspective, separately for pressure-based sprinkler irrigation (Table 7 below) and for gravity irrigation (Table 8 below). For each of these broad system types, acres irrigated across irrigation technology subcategories were summarized for three different levels (or definitions) of "water-conserving/higher-efficiency" irrigation. The purpose of the three alternative definitions is to provide a likely estimate of a relative range (or extent) of aggregate sector "water-conserving/higher-efficiency" irrigation across the 17 western States.

Water-Conserving/Higher-Efficiency Pressure/Sprinkler Irrigation by Farm-Size Class

Table 7 below presents statistics, by farm-size class, for three alternative definitions of the most "water-conserving/higher-efficiency" pressure-based sprinkler irrigation in the West (across all 17 western States) based on irrigated acres by pressure/sprinkler irrigation system category for 1998 FRIS irrigated farms.

Conserving Pressure-Irrigation Definition (1) defines water-conserving/higher-efficiency pressure-sprinkler irrigation as consisting only of acres irrigated with drip/trickle irrigation systems, accounting for about 1.2 million FRIS irrigated acres westwide in 1998 (Table 7). Given this definition, smaller irrigated farms (FS < $250,000), which make up nearly 81 percent of all irrigated farms in the West, account for only 21 percent of the most water-conserving/higher-efficiency irrigation (drip/trickle irrigated acres) in the West. Slightly more than 73 percent of FRIS drip/trickle irrigated acres in the West (or 873 thousand acres) are irrigated by the largest irrigated farms (FS ≥ $500,000). However, drip/trickle irrigated acres for the largest irrigated farms account for only 9.7 percent of all pressure-sprinkler irrigated acres for this farm-size class. In addition, given definition (1), water-conserving/higher-efficiency pressure irrigation would account for only about 6.1 percent of all FRIS pressure-based sprinkler irrigation in the West.

Conserving Pressure-Irrigation Definition (2) defines water-conserving/higher-efficiency pressure-sprinkler irrigation as including acres irrigated with low-pressure sprinkler systems (those operating with PSI < 30) and with drip/trickle irrigation systems. Expanding the scope of the "conserving" definition to include low-pressure sprinkler systems increases "conserving" irrigated acres westwide to about 9.1 million irrigated acres, accounting for 46.2 percent of all FRIS pressure-sprinkler irrigated acres in the West (Table 7). Again, about 72 percent of these acres westwide (or 4.3 million acres) are irrigated by the larger irrigated farms (FS ≥ $250,000). Given definition 2, the "water-conserving/higher-efficiency" irrigation rating for pressure-sprinkler irrigation for smaller irrigated farms (FS < $250,000) averages about 41.1 percent, while for larger irrigated farms (FS ≥ $250,000) the rating averages about 48.5 percent. Westwide, this "conserving" definition accounts for only about 24 percent of all farm-irrigated acres.

Conserving Pressure-Irrigation Definition (3) expands the concept of water-conserving/higher-efficiency pressure-sprinkler irrigation even further, to include all low- and medium-pressure sprinkler irrigated acres (for systems operating with PSI < 60) and drip/trickle irrigated acres. While it is likely a relatively "loose" definition, this definition does provide a reasonable estimate (based on FRIS data) of an "upper-bound" for the most water-conserving/higher-efficiency pressure-sprinkler irrigation occurring in the West. This definition accounts for 15.3 million FRIS irrigated acres, or about 78 percent of all pressure-sprinkler irrigated acres westwide, and about 39.8 percent of all farm-irrigated acres westwide (Table 7). Most of these acres (10.6 million acres, or 69.3 percent) are irrigated by larger irrigated farms (FS ≥ \$250,000). However, even given this skewed distribution, the "water-conserving/higher-efficiency " rating for pressure-sprinkler irrigation for smaller irrigated farms (FS < \$250,000) averages 76.4 percent, while for larger irrigated farms (FS ≥ \$250,000) the rating averages about 78.7 percent.

Westwide then, based on 1998 FRIS data and given the alternative "conserving" definitions, an estimate of an approximate relative range for "water-conserving/higher-efficiency" pressure-sprinkler irrigation in the West is likely between 46 percent (conserving definition 2) and 78 percent (conserving definition 3). Using the irrigation efficiency rating for definition 2 as a lower bound is probably quite reasonable. However, the efficiency rating for definition 3 as the upper bound could potentially be too broad. Even so, FRIS irrigation technology data indicates that room likely still exists for considerable "conservation improvement" in irrigation water-use efficiency across pressure-sprinkler irrigated agriculture in the West. Across farm-size classes, the relative "improvement potential" is slightly greater for smaller irrigated farms (FS < \$250,000) than for larger farms (FS ≥ \$250,000) [as much as 66 and 52 percent, respectively, when based on conserving definition (2)]. However, larger farms irrigate many more acres, so the extensive-margin "conservation effect" will likely be much greater for these farms.

Water-Conserving/Higher-Efficiency Gravity Irrigation by Farm-Size Class

Table 8 below presents statistics, by farm-size class, for three alternative definitions of the most "water-conserving/higher-efficiency" gravity-based irrigation in the West (across all 17 western States) based on irrigated acres by gravity irrigation system category for 1998 FRIS irrigated farms.

Conserving Gravity-Irrigation Definition (1) defines more water-conserving/higher-efficiency gravity irrigation as including furrow gravity-irrigated acres involving the use of an above or below ground pipe or a lined open-ditch field water-delivery system. In other words, furrow gravity irrigation, for this definition, is defined as "more conserving/efficient" because the irrigation system makes use of more efficient water delivery to the field. Based on this definition, 40.5 percent of all FRIS gravity-irrigated acres across the West are defined as conserving/efficient, or 7.8 million acres out of 19.2 million gravity-irrigated acres (Table 8). Nearly 64 percent of these more-conserving furrow irrigated acres are with larger irrigated farms (FS ≥ \$250,000). In addition, for larger irrigated farms, conserving/efficient furrow-irrigated acres account for an average of 47.4 percent of all gravity-irrigated acres, while accounting for only 22.2 percent of all gravity-irrigated acres for the smallest irrigated farms (FS < \$100,000). Clearly then, given this definition for conserving gravity irrigation, larger gravity-irrigated farms overall are likely relatively more irrigation efficient than the smallest gravity irrigated farms.

Conserving Gravity-Irrigation Definition (2) expands the gravity definition (1) to also include gravity-irrigated acres for flood irrigation that occurs between borders or within basins (but only for farms using laser-leveled acres and using a pipe or a lined open-ditch field water-delivery system). Nearly 93 percent of these <u>additional</u> gravity-irrigated acres are in larger farms (FS ≥ \$250,000) (Table 8). Westwide, this definition of conserving/efficient gravity irrigation still accounts for only 44.1 percent of all gravity irrigated acres (8.5 million acres out of 19.2 million acres). In addition, the overall water-conserving/higher-efficiency irrigation rating for gravity irrigation increases to 53.3 percent for larger irrigated farms, while remaining under 23 percent for the smallest irrigated farms. Clearly, the addition of laser-leveled flood-irrigated acres had a greater impact on larger irrigated farms than on smaller farms. The high capital costs of this technology option most likely significantly influenced this outcome.

Conserving Gravity-Irrigation Definition (3) further expands the gravity definition (1) to also include all flood irrigated acres supplied with water by an above or below ground pipe or a lined open-ditch field water-delivery system. Definition (2) is more restrictive because it excludes flood-irrigated acres that are not laser-leveled, but are irrigated using a pipe or lined open-ditch field water-delivery system. Westwide, the expanded definition (3) includes an additional 3.2 million acres as "conserving/efficient" gravity irrigation, increasing the share of water-conserving/higher-efficiency gravity irrigation in the West to 57.3 percent (nearly 11.0 million irrigated acres out of 19.2 million acres) (Table 8). Across farm-size classes, this conserving/efficiency rating for gravity irrigation remains much higher for the largest irrigated farms (at 63.9 percent) than for the smallest irrigated farms (at 42.7 percent).

Westwide then, based on 1998 FRIS data and given the alternative definitions for conserving/efficient gravity-irrigation, an estimate of an approximate relative acreage-share for "water-conserving/higher-efficiency" gravity irrigation in the West will likely range between either 40 to 44 percent, or 40 to 57 percent. The conserving gravity definition (1) likely provides a reasonable lower-bound estimate. However, the question arises as to whether an approximate upper-bound estimate of water-conserving/higher-efficiency gravity irrigation is a definition (2) or a definition (3), or somewhere in-between (2) and (3). But, whether definition (2) or (3) is used as the upper-bound, a range of 40 to 44 percent or 40 to 57 percent still strongly suggests that there exists considerable room for conservation improvement in irrigation water-use efficiency across gravity-irrigated agriculture in the West. Across farm-size classes, the relative improvement potential for gravity irrigation is much greater for the smallest irrigated farms than it is for larger farms (57.3 percent versus 36.1 percent, respectively). The difference here between water-conserving/higher-efficiency gravity irrigation, and similar statistics for pressure-sprinkler irrigation is that gravity irrigation is more uniformly distributed across farm-size classes. Therefore, because smaller farms irrigate a significant share of gravity-irrigated acres in the West, the potential exists for a water-conservation program that emphasizes improved gravity irrigation to have a more uniform "conservation effect" across farm-size classes.

Irrigation Water-Management Practices by Farm-Size Class

Two farm-level water-management items in FRIS help to shed additional insight on the potential for "conservation-improvement" across farm-size classes for western irrigated agriculture. The first relates to the degree producers participate in gravity water-management practices. The second item, a more general item across all irrigation, addresses producer irrigation water-management intensity, that is, the level at which producers use water management at the intensive-margin, or alternatively, the degree of sophistication used in determining when to apply irrigation water for a given crop. Applying water when the crop requires it and applying only what the plant requires for crop consumptive use (excluding any salt leaching requirement) will significantly improve irrigation efficiency. The structural-character for each of these water-management items is summarized below (in-turn).

Producer Participation in Gravity Water-Management Practices. For the 1998 FRIS, producers reported their participation in up to six gravity water-management practices (on an acreage basis). Gravity-irrigated acres were reported for the use of tailwater-reuse pits, surge-flow or cablegation irrigation, limited-irrigation techniques (that is, using limited irrigation set times and/or number of irrigations), alternative-row irrigation practices, water-soluble polyacrylamide, and special furrow water-management practices (including wide-spaced bed furrowing, compact furrowing, or furrow diking). Polyacrylamide (or PAM) is a water-soluble soil amendment, that when added to irrigation water has the effect of stabilizing soil and water-borne sediment. PAM reduces irrigation-induced soil erosion, enhances water infiltration, improves the uptake of nutrients and pesticides, reduces the need for furrow-reshaping operations, and reduces the need for sediment-control requirements below the field (Aillery and Gollehon, 1997).

Westwide, only about 44 percent of gravity-irrigated farms use one or more of the gravity water-management practices (Table 9). A greater percent of larger irrigated farms use gravity water-management practices (ranging between 62 – 64 percent) than do smaller farms (ranging between 37 – 53 percent). In addition, relative to total gravity-irrigated acres, gravity irrigators have a relatively low participation rate with any particular gravity water-management practice (ranging from a low of 2 percent for use of polyacrylamide to a high of 15 percent for use of alternate-row irrigation practices). This low participation is consistent across farm-size classes, although the distributions for each gravity water-management practice show that larger irrigated farms participate to at least a moderately higher degree than do smaller farms. Across the West, only 13 percent of gravity-irrigated acres make use of tailwater-reuse systems, about 4 percent of gravity-irrigated acres make use of surge-flow or cablegation systems, 15 percent use limited-irrigation practices, 15 percent use alternate-row irrigation, 2 percent use PAM, and only 9 percent make use of special-furrow water-management practices. Similar to earlier results for "more water-conserving/higher-efficiency" gravity systems, these results also suggest that there likely exists significant potential for "conservation improvement" with respect to gravity-irrigated agriculture in the West.

Producer Decisions on Irrigation Water-Management Intensity. The available means by which producers make their decisions on when to apply irrigation water generally involve an increasing level of producer management intensity. [Here, management intensity refers to a required increase in the level of management skill and time, as well as an increased level of understanding of more complex relationships integrating soil/hydrologic and atmospheric sciences to determine plant water needs at specific periods of time.] The means producers use to decide on when to apply irrigation water can be grouped into two categories. The first category, referred to as "conventional" means, include applying irrigation water upon delivery of the water to the farm-gate, observing the condition of the crop, feeling the soil, use of a crop calendar schedule, and/or use of media reports on crop-water needs. The second category, referred to as "intensive water-management practices", include use of soil-moisture sensing devices (such as moisture blocks or tensiometers), use of a commercial irrigation-scheduling service, and/or use of computer simulation models (which generally use fairly complex mathematical equation systems to monitor seasonal variations in both soil hydrologic and atmospheric weather conditions that influence crop evapotranspiration (ET) requirements). The increasing level of sophistication and complexity of the means used to decide irrigation applications reflect producer irrigation water-management skill and intensity. The higher the level of water-management intensity, generally the more water-conserving is irrigated agriculture.

FRIS information on irrigation water-management intensity is available only on a "farm-level participation basis," not on an acreage basis. Therefore, summaries of these results are based on the percentage of FRIS farms using alternative means of deciding when to apply irrigation water.

In general, conventional means of deciding when to apply irrigation water dominate producer decisions on irrigation water-management intensity across the West. Both "condition of the crop (by producer observation)" and "feel of the soil" are by far the dominant means irrigated farms use to decide on when to apply irrigation water. Nearly 71 percent of irrigated farms across the West simply observe the condition of the crop, and 40 percent judge irrigation water needs by feeling the soil (Table 10). The next level of reported water-management intensity involves the irrigation decision using crop calendar schedules (used by 19.8 percent of irrigated farms), or simply applying water whenever it is delivered to the farm "in-turn" by the local water-supply organization (used by 12.5 percent of irrigated farms). Use of media reports on crop water needs is the conventional means least used to decide on when to apply irrigation water (used by only 5.3 percent of irrigated farms in the West).

Across farm-size classes, for each of the conventional means of deciding when to apply irrigation water, all are decision means heavily favored by smaller irrigated farms. Westwide, of the irrigated farms using "condition of the crop (by producer observation)" as a means to decide on when to apply irrigation water, 77 percent are smaller farms (FS < $250,000), with the smallest farms (FS < $100,000) accounting for 59.4 percent (Table 10).

Likewise, smaller farms make up nearly 76 percent of the farms using "feel of the soil," 91 percent of farms applying water when it is delivered "in-turn," and 82 percent of farms using a crop calendar schedule. Therefore, even though the farm-size distribution for farms using "media reports on crop water needs" is fairly uniformly distributed, use of conventional, less-efficient means of onfarm water management remains characteristic of most smaller irrigated farms (FS < $250,000) in the West.

For the modern, more intensive water-management means of deciding when to apply irrigation water (including use of either soil-moisture sensing devices, commercial irrigation-scheduling services, and/or computer simulation models), only about 11.6 percent of irrigated farms in the West use one or more of these means. In addition, in aggregate, use of intensive water-management practices are relatively uniformly distributed between smaller and larger irrigated farms (49.6 and 50.4 percent, respectively). However, both the level of use and the farm-size distributions vary significantly across the alternative management-intensive means of deciding when to apply irrigation water.

Westwide, only 8.1 percent of irrigated farms reported that they used soil-moisture sensing-devices to make their decision on when to apply irrigation water (Table 10). In aggregate for the West, the farm-size distribution for this decision tool is relatively uniform between small and large irrigated farms (51 and 49 percent, respectively). For commercial irrigation-scheduling services, only about 4 percent of irrigated farms in the West use these services to assist in their decisions on when to apply irrigation water. Nearly 64 percent of these farms are larger irrigated farms (FS ≥ $250,000). On the other hand, computer simulation models (the most management-intensive means of deciding when to apply irrigation water) are used by only one percent of irrigated farms in the West. However, 60 percent of the farms using this decision means are surprisingly smaller farms [with 47 percent alone being the smallest irrigated farms (FS < $100,000)].

Clearly, across all the 1998 FRIS data on irrigation water-management intensity, the data indicate that use of the less management-intensive, less water-use efficient means of deciding when to apply irrigation water dominates western irrigated agriculture. This farm-level inefficiency in irrigation water-management is particularly acute for smaller irrigated farms. Most irrigated farms use very conventional means of deciding when to apply irrigation water. Less than 12 percent of western irrigated farms make use of the more water-management intensive/water-conserving means to apply irrigation water. Even for the largest irrigated farms (FS ≥ $500,000), less than 35 percent of these farms make use of the more water-management intensive means of deciding when to apply irrigation water. Overall then, these results support and confirm the conclusions drawn earlier, that there likely exists significant potential for water conservation improvement within irrigated agriculture across much of the West.

Barriers to Irrigation System Improvements by Farm-Size Class

From a private economic perspective, irrigators will generally adopt newer irrigation technologies in order to conserve water, reduce irrigation pumping (energy) costs, and/or to increase crop yields when benefits exceed costs. However, research that examines the transitions of irrigation technology over time in the West indicates that the transitions to more water conserving, and generally more water-management intensive and often yield-enhancing irrigation systems are likely relatively slow (Schaible, et al., 1991; Schaible and Aillery, 2003). The relatively slow pace of change in the adoption of more efficient irrigation technology systems reflects the impact of barriers to farm-level irrigation system improvements. FRIS reports data on up to eight specific barriers to producers implementing irrigation system improvements that might reduce energy and/or conserve water. For FRIS, producers were asked to identify all listed barriers that apply to their farm operation. Listed barriers included: i) the producer did not investigate improvements; ii) risk of reduced yield or poorer quality crop yields from not meeting water needs; iii) physical field/crop conditions limit system improvements; iv) improvements will reduce costs (but not enough to cover installation costs); v) cannot finance improvements (even if they reduce costs); vi) landlord(s) will not share in the cost of improvements; vii) uncertainty about future availability of water; and viii) the producer will not be farming this place long enough to justify investments in water-conserving improvements.

From a westwide perspective, results show that any particular barrier to system improvements is generally more of a problem for smaller irrigated farms (FS < \$250,000) than for larger irrigated farms (FS ≥ \$250,000) (Table 11). For example, a small-farm skewness ranges from 60.0 percent (for farm-size classes 1 and 2) for the barrier "landlord will not share in the cost of improvements," to 88.3 percent for the barrier "have not investigated improvements." Results also show that for both small farm-size classes, three barriers to system improvements standout as the most important. These barriers include "have not investigated improvements" (22.8 percent of FRIS irrigators westwide); "improvement installation costs are greater than benefits" i.e., perceived benefits don't cover installation costs (23.8 percent of FRIS irrigators westwide); and "lack of financing ability" (23.4 percent of FRIS irrigators westwide). However, for both large farm-size classes, the dominant producer perceived barriers to irrigation system improvements are "improvement installation costs are greater than benefits" and "lack of financing ability." In other words, "perceived economic benefits" or "financing" problems are the likely more important producer barriers to farm-level irrigation system improvements across all irrigated farms, while for smaller irrigated farms, "not investigating" the merits of such system improvements represents an additional barrier. These results suggest a strong likelihood for a beneficial water-conservation payoff from increased extension/educational efforts on the economic merits of water-conserving/more efficient irrigation systems and to alternative private and public financing options, particularly for smaller irrigated farms. Such efforts could also help to focus implementation of water conservation programs in meeting desired regional resource and small-farm policy objectives.

Producer Participation in Irrigation-Related Public Cost-Share Programs by Farm-Size Class

The 1998 FRIS collected data on farm-level participation in public cost-share programs designed to encourage irrigation or drainage system improvements. More specifically, FRIS farm operators reported whether in the previous five years (1994-98) they received irrigation-related cost-share payments for irrigation improvements from one or more of the following funding sources: i) USDA conservation cost-share programs [including the Environmental Quality Incentive Program (EQIP) or other earlier USDA cost-share programs]; ii) non-USDA Federal cost-share programs [including those from the Environmental Protection Agency (EPA), the Bureau of Reclamation (BoR), or other programs]; iii) State programs, local water management or supply district programs; and iv) other cost-share programs.

FRIS information on farm participation in public cost-share programs is available only on a "farm-level participation basis," not on an acreage basis. Therefore, summaries for these results are based on a percentage of FRIS farms participating in a public cost-share program.

Westwide, FRIS results indicate that only about 13 percent of FRIS irrigated farms participated in any public cost-share program for irrigation or drainage improvements between 1994-98 (Table 12). Most of these farm participants were smaller irrigated farms (FS < \$250,000), accounting for 74 percent of all FRIS cost-share program participants (across all programs). However, a larger percent (21 percent) of irrigated farms within the largest farm-size class (FS ≥ \$500,000) participated in public cost-share programs than participated (11 percent) from the smallest farm-size class (FS < \$100,000). This likely implies that a larger share of larger irrigated farm operators recognize and/or are capable of taking advantage of irrigation-related public cost-share programs, more so than are smaller irrigated farms.

Westwide, Federal programs have accounted for a greater level of cost-share program participation (11.1 percent of FRIS farms) than have State and local water-management/water-supply districts (7.1 percent of FRIS farms). In addition, among Federal program participants, a greater share (10.5 percent) of FRIS farms participated in cost-sharing programs through USDA (for example, use of EQIP), than participated (at 6.7 percent) through non-USDA Federal programs (for example, through EPA and the BoR). Of USDA program participants, 77 percent were smaller farms (FS < \$250,000). Of non-USDA Federal program participants, 86 percent were smaller farms. Of FRIS irrigated farms using State and/or local cost-share programs, 81 percent were smaller farms.

Summary and Policy Implications

This paper summarizes the farm-structural characteristics of irrigated agriculture in the 17 western States using data from USDA's 1998 Farm and Ranch Irrigation Survey. Farm-structural characteristics were summarized across four farm-size classes representing 147,090 irrigated farms in the West. The four farm-size classes were defined to be consistent with ERS's farm-typology definitions.

Most irrigated farms are small farms. Westwide, about 81 percent are small farms (FS < \$250,000), but State distributions can range as high as 94 percent (Utah). Almost 65 percent of irrigated farms are within the smallest farm-size class (FS < \$100,000), with average total farm sales of \$22.6 thousand dollars. Only 9.5 percent of irrigated farms in the West had total farm sales for 1997 greater than or equal to \$500,000, with average total farm sales of \$2.0 million per irrigated farm. However, small-irrigated farms accounted for only 15 percent of total farm sales from all irrigated farms, while about 85 percent of irrigated farm sales were from larger irrigated farms (FS ≥ \$250,000), and 72 percent were from the largest 9.5 percent of irrigated farms (FS ≥ \$500,000).

Irrigated acres and farm water use are also heavily skewed toward larger irrigated farms. About 61 percent of irrigated acres are with larger farms, with 41 percent alone with the largest 9.5 percent of irrigated farms. Average irrigated acreage per farm in the West is 262 acres. This ranges from 79 irrigated acres for the smallest farm-size class (FS < \$100,000) to 1,132 irrigated acres for the largest farm-size class (FS ≥ \$500,000). Farm water use is even more heavily skewed. About 66 percent of all farm water use is applied by larger irrigated farms (FS ≥ \$250,000), with the largest 9.5 percent of irrigated farms (FS ≥ \$500,000) accounting for 48 percent of total farm water applied. Small farms (81 percent) account for only 34 percent of total farm water use. The average total farm water applied per farm in the West is 518 acre-feet. This ranges from 145 to 2,632 acre-feet per farm between the smallest and largest irrigated farms. On average, it takes the equivalent of 18.2 smallest irrigated farms to apply the same amount of water as one largest irrigated farm.

For irrigation technologies throughout most of the West, pressure-based sprinkler irrigation systems are more heavily skewed toward larger irrigated farms, which account for 68 percent of sprinkler-irrigated acres and 79 percent of acres irrigated with drip/trickle systems. For gravity irrigation systems across the West, furrow-based gravity systems are also skewed toward larger irrigated farms, which account for nearly 63 percent of gravity, furrow-irrigated acres. However, flood irrigation systems are slightly skewed toward smaller irrigated farms, which account for nearly 55 percent of flood-irrigated acres. Also, larger irrigated farms account for nearly 71 percent of laser-leveled irrigated acres throughout the West.

For much of irrigation occurring in the West, results demonstrate that there exists considerable potential for conservation improvement in irrigation water-use efficiency. For pressure-based sprinkler irrigation, the relative acreage-share in "water-conserving/higher-efficiency" systems likely ranges from a low of 46 percent to a high of 78 percent. For gravity irrigation, similar relative shares likely range from a low of 40 percent to a high of 57 percent. For pressure/sprinkler irrigation, the relative conservation improvement potential is slightly greater for smaller irrigated farms than for larger farms (66 and 52 percent, respectively). However, larger irrigated farms irrigate many more acres, so conservation policy could be designed to encourage a greater extensive-margin conservation effect for these farms. For gravity irrigation, the relative conservation improvement potential is also much greater for smaller irrigated farms than for larger farms (57 and 36 percent, respectively). However, because gravity irrigated acres are more uniformly distributed across farm-size classes, a water-conservation program emphasizing improved gravity irrigation is likely to have a more uniform conservation effect across farm-size classes.

The level of farm water-use conservation in the West is also restricted by the relatively low rate of adoption of gravity water-management and/or irrigation application-management practices. Westwide, only about 44 percent of gravity-irrigated farms use one or more of available gravity water-management practices. Gravity irrigators have a relatively low participation rate for most gravity water-management practices (ranging from a low of 2 percent for use of polyacrylamide to a high of 15 percent for use of alternate-row irrigation). In general, across western States, a greater percent of larger irrigated farms use improved gravity water-management practices (ranging between 62 – 64 percent) than do smaller irrigated farms (ranging from 37 – 53 percent).

Use of irrigation application-management practices involves the means by which irrigators make their decisions on when to apply irrigation water. Across the West, conventional means of deciding when to apply irrigation water dominate producer irrigation application-management practices. Over 70 percent of irrigated farms simply observe the condition of the crop and 40 percent judge irrigation water needs by feeling the soil for its moisture content. Only 8 percent of irrigated farms make use of soil-moisture sensing devices, 4 percent use commercial irrigation-scheduling services, and 1 percent use computer-based crop-water simulation models. Smaller irrigated farms are the dominant users of conventional means of deciding when to apply irrigation water, ranging from 76 – 91 percent of irrigated farms across conventional application-management practices. For the more management-intensive means of deciding when to apply irrigation water, these practices are more uniformly distributed between smaller and larger irrigated farms.

Survey results demonstrate that use of less management-intensive, less water-use efficient means of deciding when to apply irrigation water dominates western irrigated agriculture. This farm-level inefficiency in irrigation water-management is particularly acute for smaller irrigated farms. Overall, these results suggest that considerable potential exists for additional water-conservation improvement across western irrigated agriculture.

Westwide, “perceived economic benefits” and “availability of financing” are the key producer barriers to irrigation system improvements common to all farm-size classes. However, smaller irrigated farms are confronted with an additional barrier to system improvements, that is, these farms generally have “not investigated” the merits of system improvements. The results imply that increased extension-educational efforts could help demonstrate the economic/conservation and nutrient/pest-management merits of efficient irrigation systems. In addition, innovative private/public financing options could help encourage broader adoption of more water-conserving irrigation systems, particularly among larger irrigated farms.

Results also indicate that across the West, only about 13 percent of FRIS irrigated farms participated in any public cost-share program for irrigation or drainage improvements between 1994-98. However, nearly 75 percent of all FRIS cost-share program participants have been smaller irrigated farms (FS < $250,000). USDA cost-share programs account for the largest share of all FRIS program participants (nearly 80 percent), with 77 percent of its participants being smaller farms. These results suggest that public cost-share programs for irrigation and drainage improvements very likely contribute to the support of small farms.

Finally, summarized FRIS results across farm-size classes suggest: 1) that considerable potential exists for conservation improvement in irrigation water-use efficiency throughout the West; and 2) that farm size matters in the effectiveness of agricultural water conservation programs to serve both conservation/environmental and small-farm policy goals. The emphasis of past conservation cost-share programs (1994-98) on strong small-farm participation is likely consistent with efforts to support small farms. However, increased targeting of conservation programs for greater large farm participation will enhance the likelihood of conserved-water supplies to contribute to future environmental policy goals (including water needs for human health, ecosystem habitat, and bio-diversity requirements) and to meet Native American trust responsibilities. In other words, given that larger irrigated farms are a source for 66 percent of farm water use, conservation cost-share programs that more heavily target larger irrigated farms will have the capability of conserving more water. In addition, conventional conservation cost-share programs could potentially be integrated more closely with innovative institutional arrangements (including use of water banks, water markets, and conserved-water right programs) to enhance the opportunity for greater conservation across larger irrigated farms.

* The views expressed in this paper are the sole responsibility of the author and do not necessarily reflect those of the Economic Research Service or the U.S. Department of Agriculture.

Table 3. Aggregate Irrigated Farm Values by Farm-Size Class (Westwide – 17 Western States)

Farm Characteristic:	Farm Size Class (1 to 4)[1] 1		2		3		4		All Farm-Size Classes	
		Row %		Row %		Row %		Row %		Row %
Total # of Irrigated Farms:	95,933	65.2	22,910	15.6	14,251	9.7	13,996	9.5	147,090	100.0
1997 Value of Farms Sales: ($ millions)	2,167.3	5.6	3,788.4	9.8	4,995.5	12.9	27,764.6	71.7	38,715.8	100.0
Total Farm Irrigated Acres: (1,000 ac.)	7,537.2	19.6	7,326.4	19.0	7,793.1	20.2	15,837.1	41.1	38,493.8	100.0
Total Farm Water Applied: (1,000 ac. ft.)[2]	13,924.7	18.3	11,887.7	15.6	13,536.3	17.8	36,834.9	48.4	76,183.6	100.0
-- Total GW:[3]	3,182.3	10.6	5,077.8	16.9	6,719.3	22.3	15,091.0	50.2	30,070.3	100.0
-- Total OnFSW:	2,185.2	24.7	1,438.9	16.3	1,710.9	19.4	3,500.5	39.6	8,835.6	100.0
-- Total OfFSW:	8,557.2	23.0	5,371.0	14.4	5,106.1	13.7	18,243.3	48.9	37,277.7	100.0

[1] Farm size classes were defined using the value of farm sales variable carried over to the 1998 FRIS data from the 1997 Census of Agriculture (by farm). Farm size classes (1 – 4) are: $0 ≤ 1 < $100,000; $100,000 ≤ 2 < $250,000; $250,000 ≤ 3 < $500,000; and class 4 ≥ $500,000. These size-class groups correspond to the ERS typology groups with class 1 including limited resource, retirement, residential/lifestyle, and lower-sales/farm occupation groups; class 2 including the higher sales, farming occupation group; class 3 including large family farms; and class 4 including very large family farms. (Non-family corporate farms could not be identified with FRIS data.)

[2] One acre-foot of water = 325,851 gallons.

[3] GW = Groundwater; OnFSW = Onfarm Surface Water; OfFSW = Off-Farm Surface Water.

Source: 1998 Farm & Ranch Irrigation Survey, National Agricultural Statistics Service, USDA. (Data was summarized by the Economic Research Service, USDA.)

Table 4. Irrigated-Farm Characteristics, Weighted-Average Values By Farm-Size Class (Westwide – 17 Western States)

Farm Characteristic:	Farm Size Class (1 to 4) [1]				All Farm-Size Classes
	1	2	3	4	
Total # of Irrigated Farms:	95,933	22,910	14,251	13,996	147,090
-- (% of All Irrigated Farms)	65.2	15.6	9.7	9.5	100.0
Ave. Farm-Size Characteristics					
1997 Value of Farm Sales: ($ Per Irrigated Farm)	$ 22,591	$ 165,362	$ 350,534	$ 1,983,753	$ 263,211
Ave. Total Farm Acres Per Irrigated Farm: (Ac.)	355	1,343	2,291	3,650	1,010
Ave. Total Irrigated Acres Per Irrigated Farm: (Ac.)	79 [4]	320	547	1,132	262
Farm Water-Use Characteristics					
Ave. Total Farm Water Applied (Ac.Ft./Irr.Fm.)[2]	145	519	950	2,632	518
Ave. Total Water Applied Per Irrigated Acre (Ac.Ft./Ac.)	2.0	1.7	2.1	2.2	2.0
By Water Source [3]					
Ave. GW Applied Per Acre (Ac.Ft./Ac.)	1.3	1.3	1.3	1.7	1.5
Ave. OnFSW Applied Per Acre (Ac.Ft./Ac.)	1.6	1.5	1.9	2.1	1.8
Ave. OfFSW Applied Per Acre (Ac.Ft./Ac.)	2.2	2.2	2.6	2.9	2.6

[1] See footnote 1 in Table 3 for a description of farm-size classes.

[2] One Acre-Foot of Water = 325,851 Gallons.

[3] GW = Groundwater; OnFSW = Onfarm Surface Water; and OfFSW = Off-Farm Surface Water.

[4] Coefficient of variation (CV) statistics were ≤ 25 for all values. CV statistics were computed as follows: [standard error of the estimate / estimate] x 100.

Source: 1998 Farm & Ranch Irrigation Survey, National Agricultural Statistics Service, USDA. (Data was summarized by the Economic Research Service, USDA.)

Table 5. Farm Irrigation Costs, Weighted-Average Values By Farm-Size Class (Westwide – 17 Western States)

Farm Characteristic:	Farm Size Class (1 to 4) [1] 1	2	3	4	All Farm-Size Classes
Total # of Irrigated Farms:	95,933	22,910	14,251	13,996	147,090
-- (% of All Irrigated Farms)	65.2	15.6	9.7	9.5	100.0
Ave. Purchased Water Cost for Off-farm Surface Water: ($/Acre)	26.65	25.35	42.36	56.72	41.29
Ave. Energy (Pumping) Costs (All Energy Sources): ($/Acre)	29.41	29.33	42.52	41.36	37.70
-- For Pumps Powered With:					
Electricity	32.76	30.29	52.47	48.44	43.75
Natural Gas	26.27	34.98	35.51	34.38	34.05
LP Gas, Propane, Butane	17.67	18.02	15.45	21.21	17.82
Diesel Fuel	20.66	20.41	25.46	20.19	21.52
Gasoline	23.38	9.12**	15.19**	13.09**	18.25
Ave. Irrigation Maintenance & Repair Costs: ($/Acre)	10.56	8.76	12.24	11.72	11.11

[1] See footnote 1 in Table 3 for a description of farm-size classes.

Source: 1998 Farm & Ranch Irrigation Survey, National Agricultural Statistics Service, USDA. (Data was summarized by the Economic Research Service, USDA.)

Coefficient of variation (CV) statistics were computed for all values, for **, 25 < CV ≤ 50, for all other values, the CV statistics were ≤ 25. CV statistics were computed as follows: [standard error of the estimate / estimate] x 100.

Table 6. Sprinkler & Gravity Irrigation: Farms & Acres Irrigated By Farm-Size Class (Westwide - 17 Western States)

	Farm Size Class (1 to 4) [1]								All Farm-Size Classes	
Irrigated Farms:	1		2		3		4			
	Farms	%	Farms	%	Farms	%	Farms	%	Farms	%
Total # of Irrigated Farms:	95,933	65.2	22,910	15.6	14,251	9.7	13,996	9.5	147,090	100.0
# of Farms Using a Sprinkler Irrigation System:	29,543	47.9	14,288	23.1	9,287	15.0	8,605	13.9	61,723	100.0
# of Farms Using a Gravity Irr. System:	58,246	65.5	13,917	15.7	8,037	9.1	8,573	9.7	88,773	100.0
# of Farms Using a Drip/Trickle System:	14,665	79.1	515	2.8	1,233	6.6	2,138	11.5	18,551	100.0
# of Farms Using a Sub-Irrigation System:	3,270	83.1	431	11.0	128	3.3	107	2.7	3,963	100.0

Irrigated Acres:	1		2		3		4		All Classes	
	Acres (1,000)	%	Acres (1,000)	%	Acres (1,000)	%	Acres (1,000)	%	Acres (1,000)	%
Total Farm Irrigated Acres:	7,537.2	19.6	7,326.4	19.0	7,793.1	20.2	15,837.1	41.1	38,493.8	100.0
Pressure Irrigated Acres										
All Sprinkler Systems:	2,368.8	12.8	3,537.8	19.2	4,407.4	23.9	8,157.2	44.2	18,471.2	100.0
All Drip/Trickle Systems:	189.3	15.8	61.2	5.1	71.2	6.0	873.0	73.1	1,194.8	100.0
Gravity Irrigated Acres										
All Gravity Systems:	4,984.5	26.0	3,743.8	19.5	3,314.8	17.3	7,121.7	37.2	19,164.7	100.0
- Gravity Furrow Systems:	1,759.7	17.2	2,066.1	20.2	2,086.9	20.4	4,305.6	42.1	10,218.3	100.0
- Flood Irrigation Systems:	3,224.8	36.0	1,677.7	18.8	1,227.9	13.7	2,816.5	31.5	8,946.8	100.0
SubIrrigation Systems:	61.3	27.8	39.1	17.7	46.2	21.0	73.7	33.5	220.3	100.0
All Laser-Leveled Acres:	897.1	17.1	634.1	12.1	765.2	14.6	2,938.3	56.1	5,234.7	100.0

Source: 1998 Farm & Ranch Irrigation Survey, National Agricultural Statistics Service, USDA. (Data was summarized by the Economic Research Service, USDA.) [1] See footnote 1 in Table 3 for a description of farm-size classes.

Table 7. Water-Conserving/Higher Efficiency Pressure/Sprinkler Irrigation By Farm-Size Class (Westwide – 17 Western States)

Alternative Technology Definitions:	Farm Size Class (1 to 4) [1]								All Farm-Size Classes	
	1		2		3		4			
	Acres (1,000)	%[2]	Acres (1,000)	%[2]	Acres (1,000)	%[2]	Acres (1,000)	%[2]	Acres (1,000)	%
For All Sprinkler & Drip/ Trickle Irrigation Systems:	2,558.1	13.0	3,599.0	18.3	4,478.6	22.8	9,030.2	45.9	19,666.0	100.0
Water-Conserving/-Higher Efficiency <u>Pressure Irrigation</u>										
Definition (1) -- **For All Drip/Trickle Irrigation Systems:**	189.3	15.8	61.2	5.1	71.2	6.0	873.0	73.1	1,194.8	100.0
- [% of All Pressure Irrigated Acres (for Farm-Size Class)**]** [3]**:**	(0.7)		(1.7)		(1.6)		(9.7)		(6.1)	
Definition (2) -- **For All Low-Pressure Sprinkler (PSI < 30) & Drip Trickle Irrigation Systems:**	883.2	9.7	1,648.9	18.2	2,249.6	24.8	4,302.7	47.4	9,084.5	100.0
- [% of All Pressure Irrigated Acres (for Farm-Size Class)**]** [3]**:**	(34.5)		(45.8)		(50.2)		(47.6)		(46.2)	
- [% of All Pressure Irrigated Acres (**Westwide**)**]:**	(4.5)		(8.4)		(11.4)		(21.9)		(46.2)	
- [% of All Farm Irrigated Acres (**Westwide**)**]:**	(2.3)		(4.3)		(5.8)		(11.2)		(23.6)	
Definition (3) -- **All Low/Medium Pressure Sprinkler (PSI < 60) & Drip/Trickle Irrigation Systems:**	1,768.7	11.5	2,937.2	19.2	3,626.6	23.7	7,000.5	45.6	15,333.0	100.0
- [% of All Pressure Irrigated Acres (for Farm-Size Class)**]** [3] **:**	(69.1)		(81.6)		(81.0)		(77.5)		(78.0)	
- [% of All Pressure Irrigated Acres (**Westwide**)**]:**	(9.0)		(14.9)		(18.4)		(35.6)		(78.0)	
- [% of All Farm Irrigated Acres (**Westwide**)**]:**	(4.6)		(7.6)		(9.4)		(18.2)		(39.8)	

[1] See footnote 1 in Table 3 for a description of farm-size classes.

[2] For each farm-size class column, the second column number (percent) reflects the percent of the row total or the farm-size class percent of the total of all farm-size classes for that row technology definition. For example, for row definition (1) and farm-size class 1, the value 15.8 indicates that 15.8 percent of all drip/trickle irrigated acres westwide are irrigated by the smallest-sized irrigated farms.

[3] The corresponding row values in ( ) reflect a column percent; for example, for pressure technology definition 1 and farm-size class 1, the value (0.7) indicates that drip/trickle irrigation accounts for .7 of one percent of all sprinkler and drip/trickle irrigated acres for farm-size class 1.

Source: 1998 Farm & Ranch Irrigation Survey, National Agricultural Statistics Service, USDA. (Data was summarized by the Economic Research Service, USDA, October 2002.)

Table 8. Water-Conserving/Higher Efficiency Gravity Irrigation By Farm-Size Class (Westwide -- 17 Western States)

Alternative Technology Definitions:	Farm Size Class (1 to 4)[1]								All Farm-Size Classes	
	1		2		3		4			
	Acres (1,000)	Row %[2]	Acres (1,000)	Row %[2]	Acres (1,000)	Row %[2]	Acres (1,000)	Row %[2]	Acres (1,000)	%
For All Gravity (GR) Irrigation Systems:	4,984.5	26.0	3,743.8	19.5	3,314.8	17.3	7,121.7	37.2	19,164.7	100.0
More Water-Conserving/ Higher Efficiency <u>Gravity Irrigated Acres</u>										
***Definition (1)* – Furrow Gravity Irrigation** [for farms using an above or below ground pipe or lined open-ditch water delivery system]**:**	1,107.6	14.3	1,707.4	22.0	1,735.9	22.4	3,206.9	41.3	7,757.8	100.0
- (% of Total GR Acres)[3]**:**	(22.2)		(45.6)		(52.4)		(45.0)		(40.5)	
***Definition (2)* – Flood Irrigation Between Borders or Within Basins** [for farms with laser leveled acres & using pipe or lined open-ditch water delivery systems]**:**	32.6	4.6	21.7	3.1	61.6	8.8	586.6	83.5	702.6	100.0
Sum of (1) & (2) Above:	1,140.2	13.5	1,729.1	20.4	1,797.5	21.2	3,793.5	44.8	8,460.4	100.0
- (% of Total GR Acres)[3]:	(22.9)		(46.2)		(54.2)		(53.3)		(44.1)	
***Definition (3)* – Flood Irrigation** [all flood for farms using above or below ground pipe Or lined open-ditch field water delivery systems]**:**	1,019.1	31.6	530.1	16.4	336.2	10.4	1,345.1	41.6	3,230.6	100.0
Sum of (1) & (3) Above:	2,126.7	19.4	2,237.5	20.4	2,072.1	18.9	4,552.0	41.4	10,988.4	100.0
- (% of Total GR Acres)[3]:	(42.7)		(59.8)		(62.5)		(63.9)		(57.3)	

[1] See footnote 1 in Table 3 for a description of farm-size classes.

[2] For each farm-size class column, the second column number (percent) reflects the percent of the row total or the farm-size class percent of the total of all farm-size classes for that row technology definition. For example, for row definition (1) and farm-size class 1, the value 14.3 indicates that 14.3 percent of all furrow-gravity irrigated acres west-wide (for farms using an above or below ground pipe or lined open-ditch water delivery system) are irrigated by the smallest-sized irrigated farms.

[3] The corresponding row values in ( ) reflect a column percent; for example, for gravity technology definition 1 and farm-size class 1, the value (22.2) indicates that furrow-gravity irrigation accounts for 22.2 percent of all furrow-gravity irrigated acres for farm-size class 1.

Source: 1998 Farm & Ranch Irrigation Survey, National Agricultural Statistics Service, USDA. (Data was summarized by the Economic Research Service, USDA, October 2002.)

Table 9. Producer Participation in Gravity Water Management Practices By Farm-Size Class (Westwide – 17 Western States)

Westwide (17 Western States):	Farm Size Class (1 to 4) [1]								All Farm-Size Classes	
	1		2		3		4			
# of Farms Using a Gravity (GR) Irrigation System:	**Farms**	**%**	**Farms**	**%**	**Farms**	**%**	**Farms**	**%**	**Farms**	**%**
	58,246	65.6	13,917	15.7	8,037	9.1	8,573	9.7	88,773	100.0
# of Farms Using GR and One or More GR Mgmt. Practice:	21,297	54.4	7,318	18.7	5,008	12.8	5,518	14.1	39,141	100.0
-- (% of All GR Farms):	(36.6)		(52.6)		(62.3)		(64.4)		(44.1)	
	Acres (1,000)	**%**	**Acres (1,000)**	**%**	**Acres (1,000)**	**%**	**Acres (1,000)**	**%**	**Acres (1,000)**	**%**
Total Gravity Irrigated Acres:	4,984.5	26.0	3,743.8	19.5	3,314.8	17.3	7,121.7	37.2	19,164.7	100.0
Irrigated Acres by GR <u>Water Mgmt. Practice</u>										
Tailwater ReUse Pits:	376.7	15.8	335.6	14.1	388.4	16.3	1,286.6	53.9	2,387.3	100.0
-- (% of All GR Irr. Acres):	(7.6)		(9.0)		(11.7)		(18.1)		(12.5)	
Surge-Flow/Cablegation:	66.0	8.8	252.8	33.6	206.4	27.4	228.2	30.3	753.3	100.0
-- (% of All GR Irr. Acres):	(1.3)		(6.8)		(6.2)		(3.2)		(3.9)	
Limited Irrigation Techniques:	662.7	23.4	607.0	21.4	419.3	14.8	1,145.6	40.4	2,834.6	100.0
-- (% of All GR Irr. Acres):	(13.3)		(16.2)		(12.6)		(16.1)		(14.8)	
Alternate-Row Irrigation Practices:	372.4	12.7	718.5	24.4	660.1	22.4	1,190.6	40.5	2,941.6	100.0
-- (% of All GR Irr. Acres):	(7.5)		(19.2)		(19.9)		(16.7)		(15.3)	
Water-Soluble Polyacrylamide (PAM)[2]:	42.7	13.4	51.3	16.1	80.1	25.1	144.8	45.4	318.9	100.0
-- (% of All GR Irr. Acres):	(0.9)		(1.4)		(2.4)		(2.0)		(1.7)	
Special-Furrow Water Management Practices:	154.6	9.0	251.8	14.7	468.7	27.3	839.5	49.0	1,714.6	100.0
-- (% of All GR Irr. Acres):	(3.1)		(6.7)		(14.1)		(11.8)		(8.9)	

[1] See footnote 1 in Table 3 for a description of farm-size classes.

[2] Polyacrylamide (or PAM) is a water-soluble soil amendment, that when added to irrigation water has the effect of stabilizing soil and water-borne sediment.

Source: 1998 Farm & Ranch Irrigation Survey, National Agricultural Statistics Service, USDA. (Data was summarized by the Economic Research Service, USDA.)

Table 10. Irrigation Water-Management Intensity: Alternative Means Used to Decide When to Apply Irrigation Water, By Farm-Size Class (Westwide – 17 Western States)

Westwide (17 Western States):	Farm Size Class (1 to 4) [1]								All Farm-Size Classes	
	1		2		3		4			
	Farms	%	Farms	%	Farms	%	Farms	%	Farms	%
Total # of Irrigated Farms:	95,933	65.2	22,910	15.6	14,251	9.7	13,996	9.5	147,090	100.0
Alternative Producer Means of Deciding When To Apply Irrigation Water:	Column %	Row %	Column %	Row %	Column %	Row %	Column %	Row %	Column %	Row %
(1) Condition of Crop (by Observation):	(63.9)	59.4	(80.6)	17.9	(82.1)	11.3	(84.1)	11.4	(70.2)	100.0
(2) Feel of the Soil:	(36.2)	59.4	(41.8)	16.4	(46.7)	11.4	(53.4)	12.8	(39.7)	100.0
(3) Soil-Moisture Sensing Devices:	(4.1)	33.2	(9.2)	17.8	(15.9)	19.1	(25.5)	30.0	(8.1)	100.0
(4) Commercial Irrigation Scheduling Services:	(0.9)	14.5	(5.5)	21.7	(12.4)	30.5	(13.8)	33.3	(3.9)	100.0
(5) Media Reports on Crop Water Needs:	(2.2)	27.3	(8.7)	25.6	(11.9)	21.7	(14.1)	25.3	(5.3)	100.0
(6) Water Delivered "In-Turn" by Irrigation Organization:	(15.1)	78.5	(10.0)	12.5	(6.1)	4.7	(5.6)	4.3	(12.5)	100.0
(7) Use Calendar Schedule:	(22.0)	72.7	(11.7)	9.2	(19.5)	9.6	(17.8)	8.6	(19.8)	100.0
(8) Use Computer Simulation Models:	(0.7)	46.8	(0.8)	13.3	(1.1)	11.5	(2.9)	28.4	(1.0)	100.0
Most Water-Management Intensive/Water-Conserving Means to Apply Water: [Includes farms using one or more of the above means for Items (3), (4), and/or (8)]	(5.3)	30.1	(14.5)	19.5	(26.0)	21.8	(34.8)	28.6	(11.6)	100.0

[1] See footnote 1 in Table 3 for a description of farm-size classes.

Source: 1998 Farm & Ranch Irrigation Survey, National Agricultural Statistics Service, USDA. (Data was summarized by the Economic Research Service, USDA.)

Table 11. Barriers to Farm-Level Irrigation System Improvements that would Reduce Energy Use and/or Conserve Water, By Farm-Size Class (Westwide – 17 Western States)

Westwide (17 Western States):	Farm Size Class (1 to 4)[1]								All Farm-Size Classes	
	1		2		3		4			
	Farms	%	Farms	%	Farms	%	Farms	%	Farms	%
Total # of Irrigated Farms:	95,933	65.2	22,910	15.6	14,251	9.7	13,996	9.5	147,090	100.0
Barriers to Irrigation System Improvements:	% of Column Total	Row %	% of Column Total	Row %	% of Column Total	Row %	% of Column Total	Row %	% of Column Total	Row %
(1) Have not investigated Improvements:	(25.9)	74.2	(20.6)	14.1	(12.8)	5.4	(15.2)	6.3	(22.8)	100.0
(2) Perceive increased risk Of reduced yield or poorer quality crop yield (from not meeting water needs):	(13.5)	69.2	(9.9)	12.2	(12.2)	9.3	(12.5)	9.3	(12.7)	100.0
(3) Physical field/crop Conditions limit system improvements:	(8.4)	48.0	(18.2)	24.9	(16.5)	14.1	(15.5)	13.0	(11.4)	100.0
(4) Improvement installation costs are greater than benefits: (benefits don't cover installation costs)	(22.8)	62.5	(24.0)	15.7	(24.1)	9.8	(30.3)	12.1	(23.8)	100.0
(5) Lack financing ability (even with reduced costs):	(23.0)	64.1	(26.4)	17.6	(23.6)	9.8	(21.2)	8.6	(23.4)	100.0
(6) Landlord will not share in cost of improvements:	(4.1)	36.5	(10.9)	23.5	(14.3)	19.2	(15.8)	20.7	(7.2)	100.0
(7) Uncertainty about future water availability:	(9.5)	60.0	(12.0)	18.2	(12.9)	12.1	(10.5)	9.7	(10.3)	100.0
(8) Will not be farming the farm in the near future:	(5.0)	58.0	(7.7)	21.1	(7.3)	12.5	(5.0)	8.4	(5.7)	100.0

[1] See footnote 1 in Table 3 for a description of farm-size classes.

Source: 1998 Farm & Ranch Irrigation Survey, National Agricultural Statistics Service, USDA. (Data was summarized by the Economic Research Service, USDA.)

Table 12. Participation in Public Cost-Share Programs for Irrigation or Drainage Improvements (1994-98), By Farm-Size Class (Westwide – 17 Western States)

Westwide (17 Western States):	Farm Size Class (1 to 4) [1]								All Farm-Size Classes	
	1		2		3		4			
	Farms	%	Farms	%	Farms	%	Farms	%	Farms	%
Total # of Irrigated Farms:	95,933	65.2	22,910	15.6	14,251	9.7	13,996	9.5	147,090	100.0
Funding Sources for Cost-Share Payments:	% of Column Total	Row %	% of Column Total	Row %	% of Column Total	Row %	% of Column Total	Row %	% of Column Total	Row %
(1) From Any Program Source (Federal, State, Or Other):	(10.9)	54.0	(16.6)	19.6	(15.9)	11.7	(20.5)	14.8	(13.2)	100.0
(2) From Any Federal Program Source (USDA & Non-USDA):	(9.7)	56.8	(14.4)	20.3	(11.9)	10.4	(14.5)	12.5	(11.1)	100.0
(3) From USDA Programs Only (EQIP or any Previous Programs):	(9.3)	57.3	(13.3)	19.7	(11.8)	10.8	(13.5)	12.2	(10.5)	100.0
(4) From Non-USDA Programs (EPA, BoR, & Others):	(7.0)	68.2	(7.7)	18.0	(4.5)	6.5	(5.1)	7.2	(6.7)	100.0
(5) From State Programs or Local Water Mgmt. or Supply Districts:	(7.0)	64.1	(7.7)	16.9	(6.6)	9.0	(7.4)	10.0	(7.1)	100.0

[1] See footnote 1 in Table 3 for a description of farm-size classes.

Source: 1998 Farm & Ranch Irrigation Survey, National Agricultural Statistics Service, USDA. (Data was summarized by the Economic Research Service, USDA.)

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A Simulation Model for Evapotranspiration of Applied Water

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Abstract

The California Department of Water Resources and the University of California recently developed a weather generator application program "SIMETAW" to simulate many years of daily weather data from climatic records and to estimate reference evapotranspiration (ET_o) and crop evapotranspiration with the simulated data. In addition, simulated daily rainfall, soil water holding characteristics, effective rooting depths, and ET_c are used to determine effective rainfall and to generate hypothetical irrigation schedules to estimate the seasonal and annual evapotranspiration of applied water (*ETaw*), where *ETaw* is an estimate of the crop evapotranspiration minus any water supplied by effective rainfall. The actual water requirement is estimated by dividing by the application efficiency. Weather generators allow one to investigate how climate change might affect the water demand in California. In this paper, we will discuss how the simulation model uses monthly input data to generate daily weather data over variable periods of record and how *ETaw* is determined.

Keywords: *Evapotranspiration, Crop Coefficients, Crop Water Requirements, Evapotranspiration of Applied Water, Climate Change.*

1- Introduction

The 'Simulation of Evapotranspiration of Applied Water' program (SIMETAW) was developed to help the State of California to plan for future water demand by agriculture and landscape irrigation. Using Borland Professional C++, the program was written by Sara Sarreshteh based on a design by R. Snyder, M. Orang, S. Geng, and S. Matyac. SIMETAW has a user-friendly design and, while mainly empirical, it accounts for many factors affecting crop coefficients that are generally ignored in other programs. Rainfall, soil water-holding characteristics, effective rooting depths, and ET_c are needed to determine effective rainfall. Combining crop evapotranspiration (ET_c) with effective rainfall estimates provides net water application requirements for various crops. When divided by the weighted mean application efficiency, the result is a site-specific total irrigation requirement to produce a crop. Weather generators allow us to investigate how changes in weather will affect the water demand in the state. This paper will discuss how the simulation model uses monthly input to generate daily weather data over variable periods of record and the advantages of the new model over traditional long-term ET_c estimates.

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2- Entering Crop and Soil Information

Crop and soil information are input into a data file and the data are stored under a filename using the ‘Detailed Analysis Unit’ or ‘DAU’, which is used by the State of California as a region for determining ETaw. The input data include the crop name, planting and ending date, initial growth irrigation frequency, pre-irrigation information, immaturity factors, presence of cover crops, soil water holding characteristics, maximum soil and rooting depths, etc. Data are saved as a row of data in the DAUnnn.csv file before going onto the next crop-soil combination entry. Each row of data in the file contains information on crop growth, crop coefficients, irrigation frequency, cover crops, crop maturity, etc.

3- Calculating the Yield Threshold Depletion

Crop rooting depth, soil depth, and water holding characteristics are used to determine the yield threshold depletion (YTD), which is used for determining an irrigation schedule. A user selects one of three general categories for the soil water holding characteristics. If a light soil is selected, the program uses 0.075 inches per inch for the available water holding capacity of the soil. A value of 0.125 inches per inch is used for the water holding capacity of a medium textured soil. For a heavy soil, a value of 0.175 inches per inch is used. The selected value is multiplied by the smaller of the rooting depth or the soil depth to determine the plant available water (PAW) within the soil reservoir at the maximum rooting depth for the crop. Although not strictly correct, the water holding content at field capacity for the soil reservoir is estimated as twice the available water holding content. This is only done to simplify graphing of the results. The YTD for the crop is calculated as the product of the allowable depletion (expressed as a fraction) and the PAW. In reality, the rooting depth and PAW increases as the roots extend, but, because of the additional complexity, this is ignored in the SIMETAW model.

4- Entering Climate Data

Either daily or monthly climate data are used to determine ETaw in SIMETAW. The daily data can come from CIMIS (California Irrigation Management Information System) or from a non-CIMIS data source as long as the data are in the correct format, which is described in the HELP files. After reading the data, ETaw can be calculated directly from the raw daily data. In addition, the monthly means can be calculated from the daily files and then daily data are generated using the simulation program. Since daily data were input directly, the calculation of monthly data for use in simulation of daily data is unnecessary. However, it was included to test if similar results are obtained using raw or simulated data.

The monthly data can be read from a file or calculated from daily CIMIS or non-CIMIS data files, or from some other source. The monthly data file must have the proper, comma-delimited format as described in the HELP files. SIMETAW will generate daily weather data for a specified period of record from the monthly data.

SIMETAW either generates a daily data file from monthly data or uses a raw data file consisting of daily solar radiation, maximum, minimum and dew point temperature, and wind speed for calculating daily ET_o. After calculating ET_o, if the data were generated, the program sorts the rainfall data within each month to force a negative correlation between rainfall amount and ET_o rate. Only the rainfall dates are sorted and there is no change in the dates for the weather and ET_o data. The results are output to a file with the extension ‘wrk’. For non-simulated (raw) data, the data are directly saved in the file with the ‘wrk’ extension without sorting the rainfall dates.

5- Weather Simulation

Weather simulation models are often used in conjunction with other models to evaluate possible crop responses to environmental conditions. One important response is crop evapotranspiration (ET_c). Crop evapotranspiration is commonly estimated by multiplying reference evapotranspiration by a crop coefficient. In SIMETAW, daily data are used to estimate reference evapotranspiration. Rainfall data are then used with estimates of ET_c to determine ETaw. One can either use raw or simulated daily data for the calculations.

5.1- Rainfall

Characteristics and patterns of rainfall are highly seasonal and localized, so a making a general, seasonal model that is applicable to all locations is difficult. Recognizing the fact that rainfall patterns are usually skewed to the right toward extreme heavy amount and that the rain status of previous day tends to affect present day's condition, a gamma distribution and Markov chain modeling approach was applied to described rainfall patterns for periods within which rainfall patterns are relatively uniform [1–4]. This approach consists of two models: two-state, first order Markov chain and a gamma distribution function. These models require long-term daily rainfall data to estimate model parameters. SIMETAW however, uses monthly averages of total rainfall amount and number of rain days to obtain all parameters for the Gamma and Markov Chain models.

5.2- Wind Speed

The simulation of wind speed is a simpler procedure, requiring only the gamma distribution function, as described for rainfall. While using a gamma distribution provides good estimates of extreme values of wind speed, there is a tendency to have some unrealistically high wind speed values generated for use in ET_o calculations. Because wind speed depends on atmospheric pressure gradients, no correlation between wind speed and the other weather parameters used to estimate ET_o exists. Therefore, the random matching of high wind speeds with conditions favorable to high evaporation rates leads to unrealistically high ET_o estimates on some days. To eliminate this problem, an upper limit for simulated wind speed was set at twice the mean wind speed. This is believed to be a reasonable upper limit for a weather generator used to estimate ET_o because extreme wind speed values are generally associated with severe storms and ET_o is generally not important during such conditions.

5.3- Temperature, Solar Radiation, and Humidity

Temperature, solar radiation, and humidity data usually follow a Fourier series distribution. Therefore, the model of these variables may be expressed as:

$$X_{ki} = \mu_{ki} (1 + \delta_{ki} C_{ki}) \qquad (1)$$

where k = 1, 2 and 3 (k=1 represents maximum temperature; k = 2 represents minimum temperature; and k =3 represents solar radiation). μ_{ki} is the estimated daily mean and C_{ki} is the estimated daily coefficient of variation of the i^{th} day, i = 1, 2, … , 365 and for the k^{th} variable.

SIMETAW simplifies the parameter estimation procedure of Richardson and Wright [4], requiring only monthly means as inputs. From a study of 34 locations within the United States, the coefficient of variability (CV) values appear to be inversely related to the means. The same approach is used to calculate the daily CV values. In addition, a series of functional relationships between the parameters of the mean curves and the parameters of the coefficient of variation curves, which made it possible to calculate C_{ki} coefficients from μ_{ki} curves without additional input data requirement, were developed.

6- Reference Evapotranspiration Calculation

Reference evapotranspiration (ET_o) is estimated from daily weather data using a modified version of the Penman-Monteith equation [5–7]. The equation is:

$$ET_o = \frac{0.408\ \Delta\ (R_n - G) + \gamma \frac{900}{T + 273} u_2\ (e_s - e_a)}{\Delta + \gamma\ (1 + 0.34\ u_2)} \tag{2}$$

where Δ is the slope of the saturation vapor pressure at mean air temperature curve (kPa $^{o}C^{-1}$), R_n and G are the net radiation and soil heat flux density in MJ $m^{-2}d^{-1}$, γ is the psychrometric constant (kPa $^{o}C^{-1}$), T is the daily mean temperature (^{o}C), u_2 is the mean wind speed in m s^{-1}, e_s is the saturation vapor pressure (kPa) calculated from the mean air temperature (^{o}C) for the day, and e_a is the actual vapor pressure (kPa) calculated from the mean dew point temperature (^{o}C) for the day. The coefficient 0.408 converts the $R_n - G$ term from MJ $m^{-2}d^{-1}$ to mm d^{-1} and the coefficient 900 combines together several constants and coverts units of the aerodynamic component to mm d^{-1}. The product 0.34 u_2, in the denominator, is an estimate of the ratio of the 0.12-m tall canopy surface resistance (r_c=70 s m^{-1}) to the aerodynamic resistance (r_a=205/u^2 s m^{-1}). It is assumed that the temperature, humidity and wind speed are measured between 1.5 m (5 ft) and 2.0 m (6.6 ft) above the grass-covered soil surface. For a complete explanation of the equation, see Allen and others [5]. If only temperature data are available, then the SIMETAW calculates daily ET_o using the Hargreaves-Samani equation. The equation may be written:

$$ET_o = 0.0023\ (T_c + 17.8)\ R_a\ (T_d)^{1/2} \tag{3}$$

Where T_c is the monthly mean temperature (degrees centigrade), R_a is the extraterrestrial solar radiation expressed in mm/month, and T_d is the difference between the mean minimum and mean maximum temperatures for the month (degrees centigrade).

If pan data are used in the program, then the program automatically estimates daily ET_o rates using a fetch value (i.e. upwind distance of grass around the pan). The approach in the SIMETAW provides a simple method to estimate ET_o from *Epan* data without the need for wind speed and relative humidity data.

6.1- Verification of the Simulated Reference Evapotranspiration

We used number of years of estimated daily ET_o data from CIMIS (California Irrigation Management Information System) at Davis, Oceanside, and Bishop to validate our model predictions of ET_o. The performance of our model ET_o predictions was evaluated at sites influenced by coastal and windy desert climates. Figures 1, 2, and 3 compare daily mean ET_o estimates of SIMETAW and CIMIS averaged over the period of records. As seen in figures, a close agreement between CIMIS-based estimates of ET_o and those of the SIMETAW model exists. Bishop is influenced by a windy desert environment on the eastern side of the Sierra

Nevada range. Oceanside is a coastal site in San Diego County. Davis is in the Central Valley influenced by the Delta weather pattern.

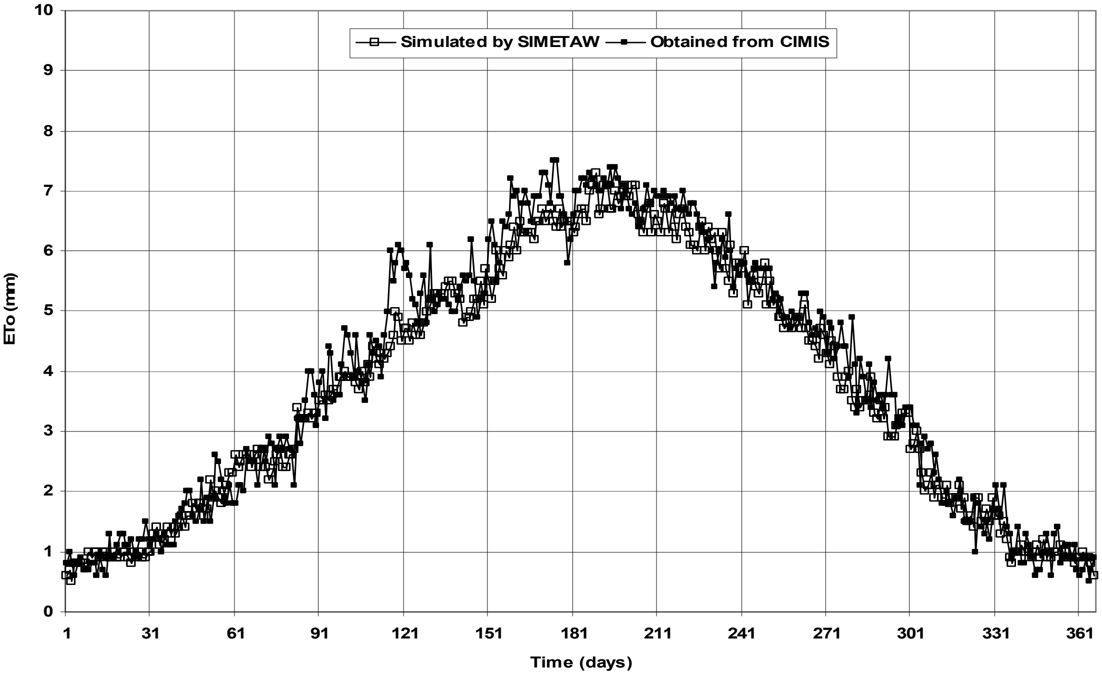

Figure 1. Comparison of daily ET_o estimates from SIMETAW and CIMIS at Davis, California

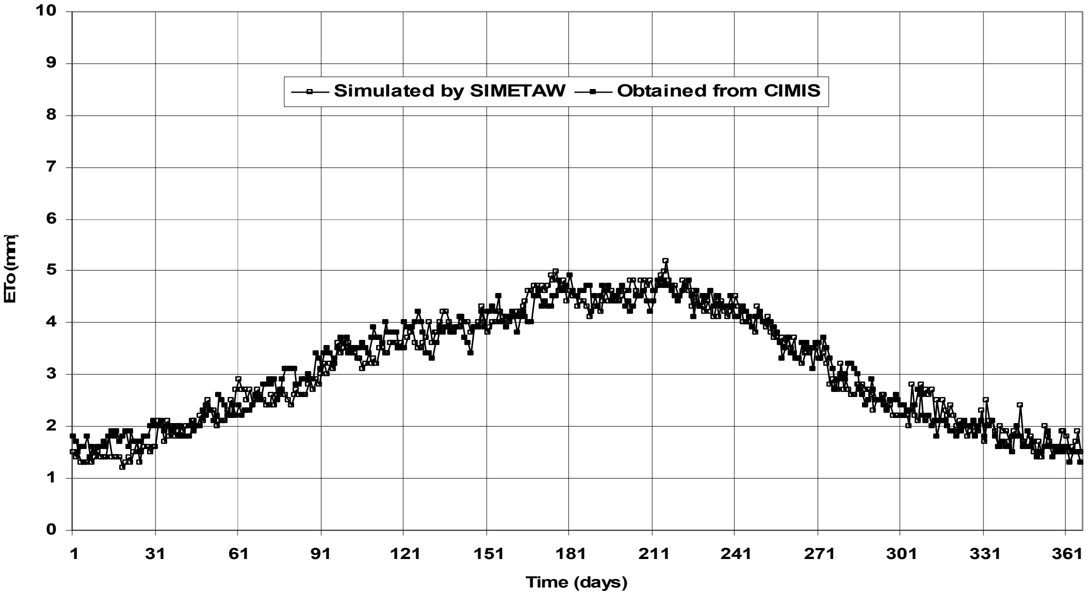

Figure 2. Comparison of daily ET_o estimates from SIMETAW and CIMIS at Oceanside, California

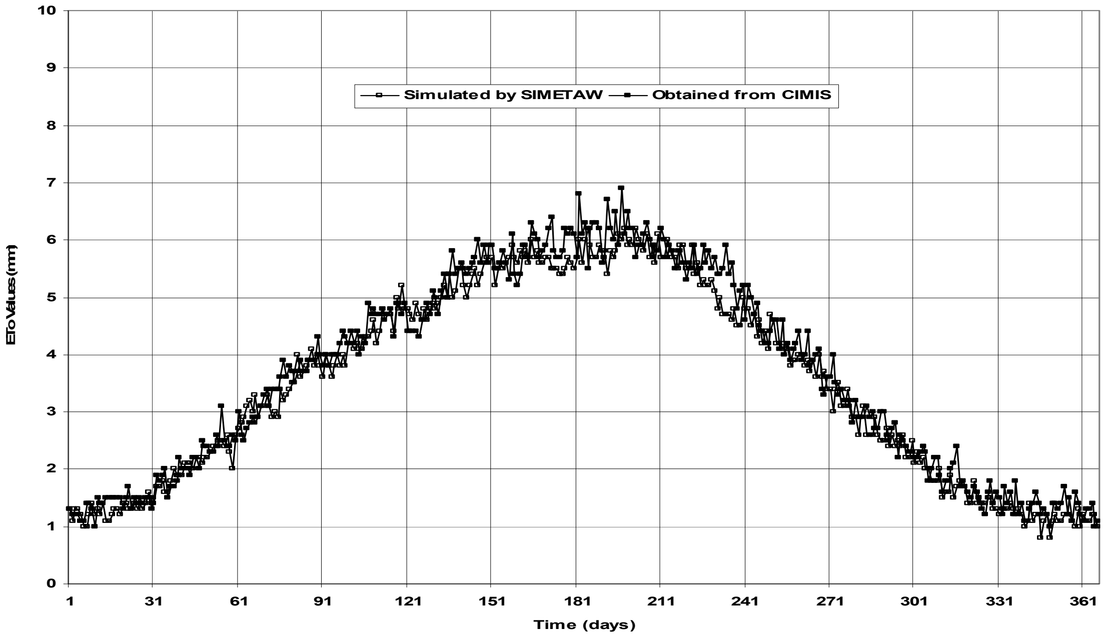

Figure 3. Comparison of daily ET_o estimates from SIMETAW and CIMIS at Bishop, California

7- Crop Coefficients

While reference crop evapotranspiration accounts for variations in weather and offers a measure of the 'evaporative demand' of the atmosphere, crop coefficients account for the difference between the crop evapotranspiration and ET_o. The main factors affecting the difference are (1) light absorption by the canopy, (2) canopy roughness, which affects turbulence, (3) crop physiology, (4) leaf age, and (5) surface wetness. Because evapotranspiration (*ET*) is the sum of evaporation (*E*) from soil and plant surfaces and transpiration (*T*), which is vaporization that occurs inside of the plant leaves, it is often best to consider the two components separately. When not limited by water availability, both transpiration and evaporation are limited by the availability of energy to vaporize water. During early growth of crops, when considerable soil is exposed to solar radiation, ET_c is dominated by soil evaporation and the rate depends on whether or not the soil surface is wet. If a nearly bare-soil surface is wet, the ET_c rate is slightly higher than ET_o, when evaporative demand is low, but it will fall to about 80% of ET_o under high evaporation conditions. However, as a soil surface dries off, the evaporation rate decreases considerably. As a canopy develops, solar radiation (or light) interception by the foliage increases and transpiration rather than soil evaporation dominates ET_c. Assuming there is no transpiration-reducing water stress, light interception by the crop canopy is the main factor determining the ET_c rate. Therefore, crop coefficients for field and row crops generally increase until the canopy ground cover reaches about 75%. For tree and vine crops the peak K_c is reached when the canopy has reached about 70% ground cover. The difference between the crop types results because the light interception is somewhat higher for the taller crops.

During the off-season and during initial crop growth, *E* is the main component of *ET*. Therefore, a good estimate of the K_c for bare soil is useful to estimate off-season soil evaporation and ET_c early in the season. A two-stage method for estimating soil evaporation presented by Stroonsnjider [8] and refined by Snyder and others [9] is used to estimate bare-soil crop coefficients. This method gives *Kc* values as a function of wetting frequency and *ETo* that are quite similar to the widely used bare soil coefficients that were published in

Doorenbos and Pruitt [10]. The soil evaporation model is used to estimate crop coefficients for bare soil using the daily mean ET_o rate and the expected number of days between significant precipitation (P_s) on each day of the year. Daily precipitation is considered significant when $P_s > 2 \times ET_o$.

7.1- Field and Row Crops

Crop coefficients are calculated using a modified Doorenbos and Pruitt [10] method. The season is separated into initial (date A-B), rapid (date B-C), midseason (date C-D), and late season (date D-E) growth periods (see Fig. 1).

Tabular default K_c values corresponding to important inflection points in Fig. 4 are stored in the SIMETAW program. The value *Kc1* corresponds to the date B *Kc* (*KcB*). For field and row crops, *Kc1* is used from date A to B. The value *Kc2* is assigned as the *Kc* value on date C (*KcC*) and D (*KcD*). Initially, the *KcC* and *KcD* values are set equal to *Kc2*, but for tree and vine crops, the values for *KcC* and *KcD* are adjustable for the percentage shading by the canopy to account for sparse or immature canopies. During the rapid growth period, when the field and row crop canopy increases from about 10% to 75% ground cover, the K_c value changes linearly from *KcB* to *KcC*. For deciduous tree and vine crops, the Kc increases from KcB to KcC as the canopy develops from leaf out on date B to about 70% shading on date C. During late season, the K_c changes linearly from *KcD* on date D to *KcE* at the end of the season. The values for *KcB* and *KcC* depend on the difference in (1) energy balance due to canopy density and reflective qualities, (2) crop morphology effects on turbulence, and (3) physiological differences between the crop and reference crop.

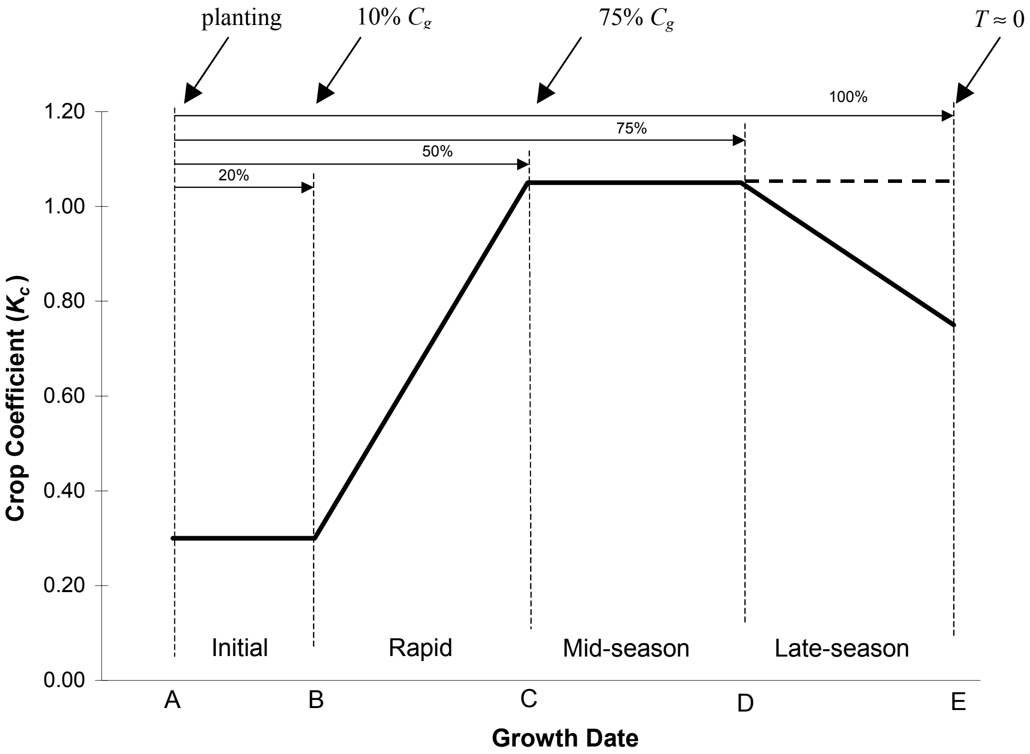

Figure 4. Hypothetical crop coefficient (K_c) curve for typical field and row crops showing the growth stages and percentages of the season from planting to critical growth dates.

7.2- Field Crops with Fixed Crop Coefficients

Fixed annual K_c values are possible for some crops with little loss in accuracy. These crops include pasture, warm-season and cool-season turfgrass, and alfalfa averaged over a season. In the SIMETAW program, these field crops are identified as type-2 crops.

7.3- Deciduous Tree and Vine Crops

Deciduous tree and vine crops, without a cover crop, have similar K_c curves but without the initial growth period (Fig. 5). The season begins with rapid growth at leafout when the K_c increases from *KcB* to *KcC*. The midseason period begins at approximately 70% ground cover. Then, unless the crop is immature, the K_c is fixed at *KcC* until the onset of senescence on date D (*Kc2=KcC=KcD*). During late season, when the crop plants are senescing, the K_c decreases from *KcD* to *KcE*. The end of the season occurs at about leaf drop or when the tree or vine transpiration is near zero.

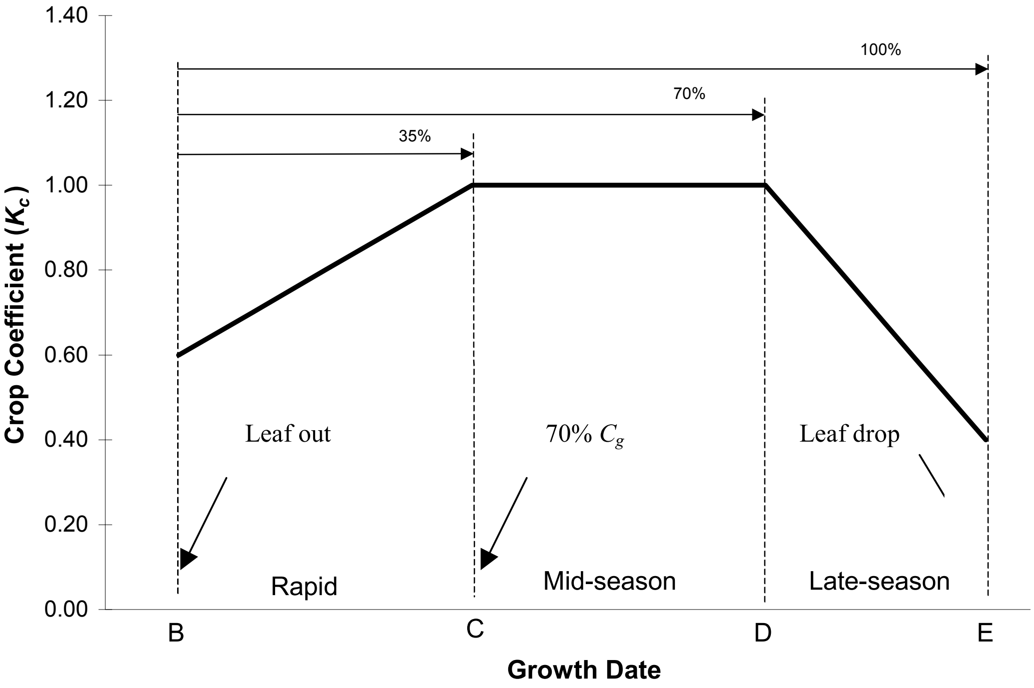

Figure 5. Hypothetical crop coefficient (K_c) curve for typical deciduous orchard and vine crops showing the growth stages and percentages of the season from leaf out to critical growth dates

The initial K_c value is refined by using the K_c for bare soil evaporation on that date based on ET_o and rainfall frequency. The assumption is that the ET_c for a deciduous orchard or vineyard at leaf out should be about equal to the bare soil evaporation. The *Kc2* and *Kc3* values again depend on (1) energy balance characteristics, (2) canopy morphology effects on turbulence, and (3) plant physiology differences between the crop and reference crop. The *Kc1* corresponds to *KcB* and *Kc3* corresponds to *KcE*. Again, the K_c is initially fixed at *Kc2* during midseason, so *Kc2=KcC=KcD*. However, the *KcC* and *KcD* can be adjusted for sparse or immature canopies. Adjustments can also be made for the presence of a cover crop.

With a cover crop, the K_c values for deciduous trees and vines are increased depending on the amount of cover. In SIMETAW, adding 0.35 to the in-season, no-cover K_c for a mature crop, but not to exceed 1.15, is used.

7.4- Subtropical Orchards

For mature subtropical orchards (e.g., citrus), using a fixed K_c during the season provides acceptable ET_c estimates. However, if higher, the bare soil K_c is used for the orchard K_c.

8- ET of Applied Water Calculations

The ET_o data come from the 'name.wrk' file, which is created from either input raw or simulated daily weather data. The K_c values are based on the ET_o data and crop, soil, and management specific parameters from a row in the 'DAUnnn.csv' file. During the off-season, crop coefficient values are estimated from bare soil evaporation as previously described. It is assumed that all water additions to the soil come from rainfall and losses are only due to deep percolation. Rainfall runoff as well as surface water running onto a cropped field is ignored. Because the water balance is calculated each day, this assumption is reasonable.

During the off-season, if the soil water depletion (SWD) is less than the YTD, ET_c is added to the previous day's SWD to estimate the depletion on the current day. However, the maximum depletion allowed is 50% of the PAW in the upper 30 cm of soil. If the SWD at the end of a growing season starts at some value greater than the maximum soil water depletion, then the SWD is allowed to decrease with rainfall additions but it is not allowed to increase with ET_c (Fig. 6). If half of the available water is gone from the upper 30 cm, it is assumed that the soil surface is too dry for evaporation. Once the off-season SWD is less than the maximum depletion, it is again not allowed to exceed the maximum off-season depletion.

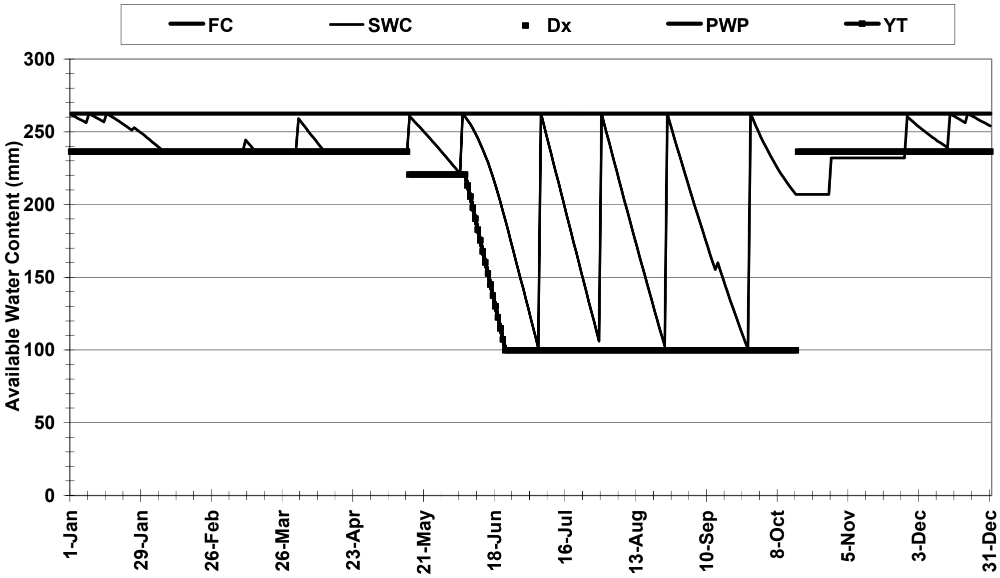

Figure 6. An annual water balance for cotton showing fluctuations in soil water content between field capacity and the maximum depletion during the off-season and between field capacity and the YTD during the season.

If a crop is pre-irrigated, then the SWD is set equal to zero on the day preceding the season. If it is not pre-irrigated, then the SWD on the day preceding the season is determined by water balance during the off-season before planting or leafout. It is assumed that the SWD equals zero on December 31 proceeding the first year of data. After that the SWD is calculated using water balance for the entire period of record.

During the growing season, the SWD depletion is updated by adding the ET_c (or by subtracting ET_c from the soil water content 'SWC') on each day (Fig. 3). If rainfall occurs, SWD is reduced by an amount equal to the rainfall. However, the SWD is not allowed to be less than zero. This automatically determines the effective rainfall as equal to the recorded rainfall if the amount is less than the SWD. If the recorded rainfall is more than the SWD, then the effective rainfall equals the SWD. Irrigation events are given on dates when the SWD would exceed the YTD. It is assumed that the SWD returns to zero on each irrigation date. The ETAW is calculated both on a seasonal and an annual basis as the cumulative ET_c minus the effective rainfall. The calculations are made for each year over the period of record as well as an overall average over years. The results are output to a summary table.

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Soil water regimen of sugarbeet in reduced irrigation

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Abstract

In the main agricultural regions of Serbia and Montenegro, where the sum and distribution of rainfall are highly variable within a single year and from one year to another, irrigation is a supplementary practice. The average annual rainfall is 600 mm, with variations from 400-800 mm. Variations are also large during the growing season, especially in July and August, from 0 to 150 mm. In 70-90% of the years the rainfall in July and August does not meet sugarbeet requirement for water and irrigation becomes necessary.

A study has been conducted on a loamy soil which had favorable water-physical and chemical properties. The content of total nitrogen in soil layer 0-30 cm was 0.185%, i.e., below the sugarbeet requirement.

Sprinkling irrigation was scheduled on the basis of soil moisture measurements made with a neutron probe. The irrigation variants included: A_5 - 60 mm at soil moisture of 60-65% FWC, and variants with reduced amounts of water: A_4 - 45 mm (75% of the full rate), A_3 - 30 mm (50%) and A_2 - 15 mm (25%). Variant A_1, the control, was not irrigated.

Sugarbeet root yields varied with the amount and distribution of rainfall and air temperatures during growing season.

In irrigation, the highest average yield was obtained in variant A_3 - 112.96 t/ha. This yield was higher than those in variants A_1 (90.58 t/ha), A_2 (108.47 t/ha), A_4 (108.74 t/ha) and A_5 (102.57 t/ha) by 25.0%, 4.1%, 3.9% and 10.2%, respectively. The relatively low effects of irrigation were due to the relatively favorable rainfalls in the experiment years, resulting in high yields without irrigation. The highest yield in the experiment (137.94 t/ha) was obtained in 1996, in the variant with irrigation rate of 50%. This yield was higher by 46% than the yield obtained in the non-irrigated variant.

Key words: soil moisture, irrigation rate, weather conditions, sugarbeet yield, sugar content

Introduction

In the agricultural parts of Serbia and Montenegro, the amount of rainfall during growing season is often insufficient and unfavorably distributed for high yields and intensive crop production. Droughts of various intensities occur almost every year, and they are a limiting factor for achieving high yields.

Insufficient rainfall is particularly detrimental for sugarbeet, which is grown in Serbia and Montenegro at 70-80,000 ha for the country's 11 sugarbeet refineries. The sugarbeet is capable of synthesizing and accumulating considerable amounts of sugar. Under favorable conditions of soil moisture and fertility, it develops large leaf mass and a large storage root with a high percentage of sugar. The sugarbeet has a high water requirement because of its high production of organic matter per unit area. At the same time, it is a thrifty consumer of water. The well-developed root system takes up water from the depth of two meters. The sugarbeet has a high coefficient of soil water utilization, higher than most field crops (Dragovic and Panic, 1981). Depending on the conditions of growing, cultural practices applied, properties of genotype and yield level, sugarbeet water requirement ranges in Serbia and Montenegro from 500 mm to 600 mm (550 mm on average). Sugarbeet needs irrigation in order to achieve high yields, since its water requirement cannot be met solely by the rainfall during growing season and winter soil moisture reserves. The most critical period for water supply includes July and August - this period accounts for 40% to 50% of the total sugarbeet requirement for water. As the amount of rainfall during growing season is 350 to 450 mm, there regularly occurs a deficit of 100-200 mm, which may reach 300 mm in some years.

Because sugarbeet acreages in different regions are limited to suit the processing capacity of the nearest refinery, it is desirable to minimize yield variation and maximize yield level. In semihumid and semiarid conditions, only irrigation may ensure such production. The increase of sugarbeet yield by irrigation will depend on the weather conditions and the amount and distribution of rainfall during growing season. According to Maksimovic and Dragovic (2000), the average yield in a series of long-term field trials on irrigated chernozem was 76.7 t/ha, while the average yield without irrigation reached 59.8 t/ha. According to Panic and Dragovic, (1991) irrigation affected sugarbeet yield by 32.3% (17.8 t/ha), ranging between 5% (3 t/ha) and 98% (51.0 t/ha) in various years of the study.

Material and Method

Experiments with different irrigation norms were conducted on the loamy chernozem soil of favorable water-physical and chemical properties in the period 1996-1999 at the experiment field of Institute of Field and Vegetable Crops in Novi Sad.

The experiments included the following variants of soil water regimen:
A_1 - Non-irrigated control - 0 mm (0%)
A_2 - Irrigation rate 15 mm (25%)
A_3 - Irrigation rate 30 mm (50%)
A_4 - Irrigation rate 45 mm (75%)
A_5 - Irrigation rate 60 mm (100%)

Irrigation dates were scheduled after soil moisture analysis by a Troxler neutron probe - Model 4300. The probe was previously calibrated by the gravimetric method. The calibration curve was plotted on the basis of a large number of analyses (Figure 1). The curve had the form of linear regression and a high correlation coefficient (r = 0.99). Similar curves were plotted in previous studies of Dragovic (1983), with coefficient correlation r = 0.735, and Djorovic and Maksimovic (1993).

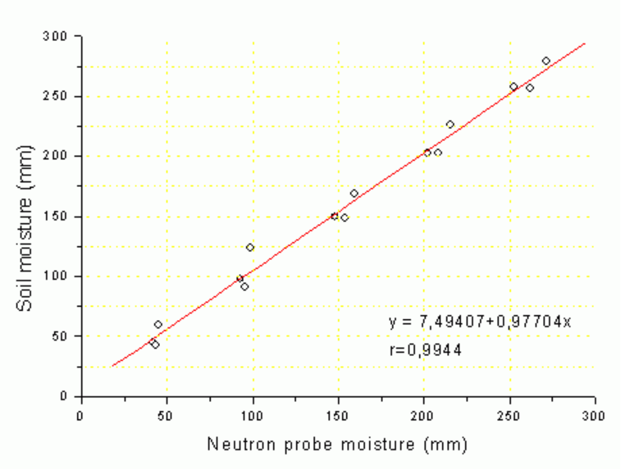

Figure 1 - Calibration curve for neutron probe measurements of soil moisture

The scheduling was done in the variant of 100% irrigation norm, at soil moisture of 60-65% of field water capacity (FWC). All variants were irrigated on the same dates. Sprinkling irrigation was used.

Calculation of nitrogen requirement to achieve the desired yield level took into account the content of NO_3-N in the soil, determined each spring at the beginning of sugarbeet growing season by the N-min method, and the rate of mineralization during growing season. The missing portion was added by nitrogen fertilization. Since the experiment was rotated each year, there were different contents of NO_3-N in the soil of the experiment plots and different amounts of nitrogen had to be added to achieve the target root yield of 120 t/ha. The following amounts of nitrogen were added: 175 kg/ha in 1996, 267 kg/ha in 1997, 170 kg/ha in 1998, 257 kg/ha in 1999.

The experiment included the sugarbeet variety NS-Dana developed at the Institute of Field and Vegetable Crops in Novi Sad. The sowing was performed in late March or early April, in the plant arrangement of 50 cm between rows and 20 cm in the row, with about 100,000 plants per hectare. Harvesting was performed in late October. Vegetation period was about 180 days.

Results

Weather conditions and water requirement of sugarbeet. Because of relatively favorable rainfall sums and distribution in all four years of the experiment, the effects of irrigation were not as high as they usually are in dry years. The high rainfalls and their favorable distribution were responsible for the negative effects of the high irrigation rates, regardless of the high sugarbeet requirement for water. This confirmed an earlier finding Vucic (1991), later corroborated by Dragovic (1994), that in conditions of high soil moisture sugarbeet plants tend to spend water unproductively, above the actual requirement.

The average rainfall sum for the four growing seasons (April-September) was 473 mm (from 416 to 521 mm), the average rainfall sum for July was 130 mm (from 85 to 192 mm) and for August 86 mm (from 28 to 124 mm). On the other hand, the long-term average rainfall for the growing season is 356 mm, the long-term average rainfall for July is 64 mm and for August 59 mm. Clearly, the four experiment years had the rainfalls above the average (Figure 2).

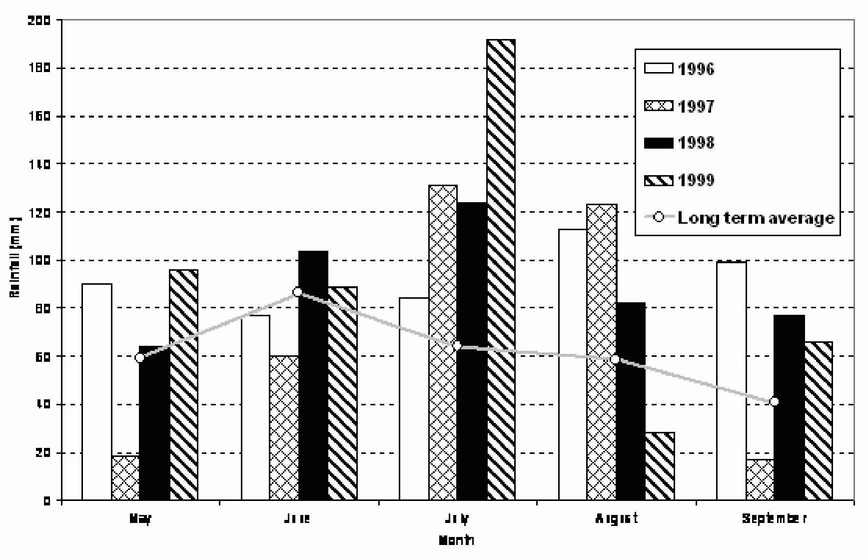

Figure 2 - Monthly and long-term average rainfall sums in the growing seasons

Table 1 shows the distribution of rainfall per month and per 10-day periods during the four growing seasons. Irrigations were performed in the periods with low rainfall (Table 2). In 1996, there were 11 mm of rain in the first 20 days of June and only 2 mm of rain in the first half of July, two irrigations were performed in these two months. In 1997, a period without rainfall occurred only in the second half of June and only one irrigation was needed. In 1998, low rainfalls occurred in the last 20 days of July and in the first half of August so that two irrigations had to be performed. In 1999, there were only 11 mm of rain in the last ten days of June and there were no rain at all at the beginning of July and one irrigation was needed. However, 74 mm of rain fell around the end of the first 10-day period of July and 106 mm in the third 10-period. After that, soil moisture to the depth of 60 cm remained well above 65% FWC and supplementary irrigation was not needed.

Table 1 –Total monthly and 10-day rainfall sums (mm) at Rimski Šančevi experiment field

Month	10-day period	Year				Long-term average (1964-1996)
		1996	1997	1998	1999	
Outside of the growing season		210	321	292	250	246
April	I	5	13	11	15	12
	II	15	4	23	7	19
	III	5	51	5	28	16
	Σ	25	68	39	50	47
May	I	16	10	36	26	18
	II	39	0	6	42	16
	III	35	7	20	28	25
	Σ	90	17	62	96	59
June	I	0	13	31	4	32
	II	11	47	47	74	30
	III	66	2	14	11	24
	Σ	77	62	92	89	86
July	I	2	50	53	74	24
	II	34	57	27	12	17
	III	49	21	34	106	23
	Σ	85	128	116	192	64
August	I	26	105	1	10	15
	II	58	3	12	15	17
	III	29	16	68	3	27
	Σ	113	124	81	28	59
September	I	51	1	24	33	14
	II	30	16	29	0	15
	III	18	0	23	33	11
	Σ	99	17	76	66	40
Growing season		489	416	466	521	356
Hydrologic year		699	737	758	771	602

Table 2 - Irrigation schedule and rates

Year	Date of irrigation	Variant			
		100%	75%	50%	25%
1996	15 June	60	45	30	15
	24 July	60	45	30	15
	Total	120	90	60	30
1997	05 July	60	45	30	15
1998	24 July	60	45	30	15
	13 August	60	45	30	15
	Total	120	90	60	30
1999	07 July	60	45	30	15

Root yield. Effects of irrigation on sugarbeet yield varied in dependence of weather conditions during growing season, soil moisture, cultural practices applied, etc.

The highest average yield in the experiment was obtained in variant A_3 (50% of the full rate) - 112.96 t/ha. This yield was significantly higher, by 22.38 t/ha or 25%, than the yield in the non-irrigated control. Further increases in irrigation rate caused gradual yield reductions. The yield obtained in variant A_4 (75% of the full rate) was 4% lower than that in variant A_3. The variant with the highest irrigation rate (A_5) yielded 10% less than variant A_3 (Table 3). This difference was highly significant. Marinkovic (1996) warned that application of large amounts of water might depress sugarbeet yield, especially in wet conditions.

Effect of irrigation differed in independence of rainfall and its distribution during growing season. The highest effect of irrigation on sugarbeet root yield was obtained in 1996 year with 50% irrigation rate (A_3), 137.94 t/ha. This yield was higher by 43.56 t/ha or 46% that the yield obtained in the non-irrigated variant. The difference was highly significant. The other irrigation variants (A_2, A_4 and A_5) had lower yields than variant A_3 by 1.7%, 1.3% and 14.2% respectively.

The lowest average yield as well as the lowest effect of irrigation were registered in 1999, when the total sum of rainfall during growing season (April-September) was 521 mm, 192 mm of that occurring in July alone. Furthermore, the sum of temperatures was 10 to 20% lower than in the other years. Compared against 1996, the 1999 average yield was lower by 42% and the effect of irrigation was lower by 2.5 times.

In May and June of 1997, the rainfall was below the sugarbeet requirement. The single irrigation that was performed still increased the root yield by 20%. The highest yields were achieved with irrigation rates of 75% and 100% (variants A_4 and A_5). These yields were similar and only marginally higher than that in variant A_3, without significant differences.

In 1998, the sum of rainfall met the sugarbeet requirement but the distribution of rainfall in July and August necessitated two irrigations to be performed. The average yield was 94.90 t/ha, which was lower by 32 and 16% than the average yields obtained in 1996 and 1997, respectively. The highest yield was obtained in variant A_3, 105.07 t/ha, the higher irrigation rates causing significant yield reductions. Variant A_3 outyielded the control variant A_1 by 23%.

Table 3 – Effect of soil water regimen on sugarbeet yields (t/ha)

Irrigation variant	1996	1997	1998	1999	Average
A_1 – Ø	94.38	96.67	85.22	86.06	90.58
A_2 – 25%	135.69	108.80	101.30	88.08	108.47
A_3 – 50%	137.94	114.59	105.07	94.25	112.96
A_4 – 75%	136.18	116.32	95.19	87.28	108.74
A_5 –100%	120.81	116.14	87.67	85.57	102.57
Average	125.00	110.50	94.90	88.27	104.66

LSD	0.05	7.75	4.59	4.06	5.24	5.41
	0.01	10.33	6.13	5.41	6.98	7.21

Numerous studies, conducted in Serbia and Montenegro and elsewhere in the world, have shown high effects of irrigation. Analyzing the effect in irrigation on sugarbeet yield on the basis of long-term data (1966-1995), Maksimovic and Dragovic (1996) found that the minimum and maximum yields were 39.9 and 74.1 t/ha, respectively, under rainfed conditions and 58.2 and 114.8 t/ha, respectively, under irrigated conditions. The average yield increase in irrigation was 29%, the actual increases varying in dependence of weather conditions from 4 to 98%. Other authors too have reported high effects of irrigation on sugarbeet yield. Jaggard and Glover (1996) reported an increase by 37%, Winter (1980) by 50%.

In extremely dry years, however, Dragovic (1994) has found increases of 64% in experiments and 76% in commercial production. On the other hand, the maintenance of high soil moisture throughout the growing season does not bring a proportional increase of sugarbeet yield, as reported in earlier studies (Panic et al., 1992; Maksimovic and Dragovic, 1994). Figure 3 shows that root yield increases to the irrigation rate of 50% of the full rate and after that it gradually goes down.

Yield variations among years are also due to sugarbeet diseases, which tend to intensify in rainy years, and low temperatures. Clover et al. (1998) stated that yields of sugarbeet vary from 85 t/ha (15 t of sugar) to 45-50 t/ha (7.5-8.0 t of sugar). A major reason for the difference is that the crops experience stress most commonly caused by disease or drought. In different growing regions in California, according to Hills et al. (1986), root yield averaged from 49 to 77 Mg·ha^{-1}, and sucrose contents from 14.1 to16.4%.

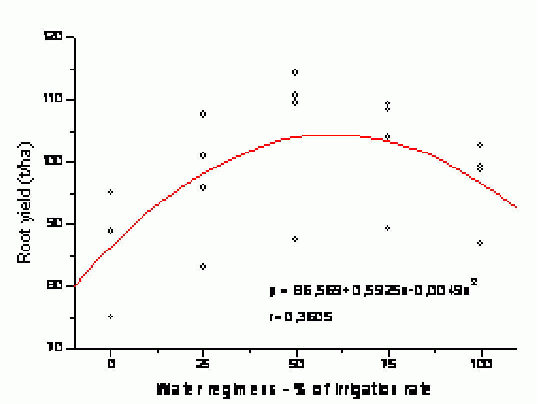

Figure 3 - Dependence of sugarbeet root yield on irrigation schedule and rate

Soil moisture determination. According to the research plan, soil moisture in the variant of 100% irrigation rate was maintained above the level of readily available water for plants (60-65% FWC). In the variants with reduced irrigation rates, soil moisture was supposed to be maintained below the level of available water (technical minimum). However, the favorable rainfalls in all experiment years made the values of soil moisture similar in all irrigation variants and in all years. Therefore, we shall present here only the 1998 results (Figure 4).

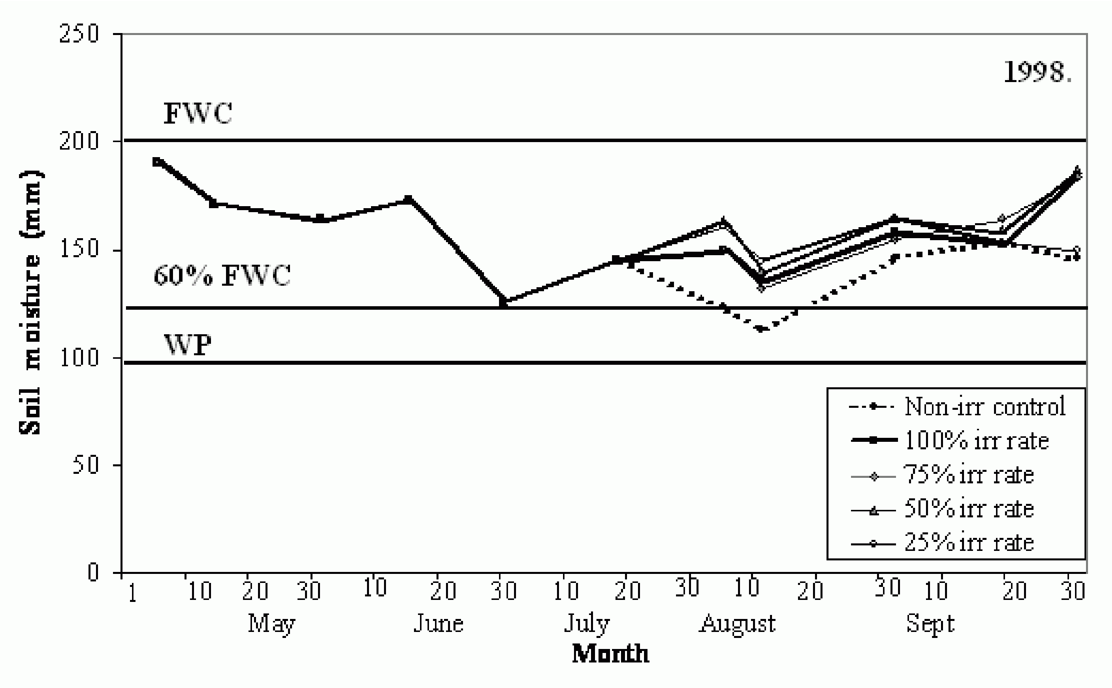

Figure 4 - Dynamics of soil moisture in the soil layer 0-60 cm in 1998

Sugar content. Sugar contents in sugarbeet roots differed per year and irrigation variant (Table 4). In 1999, the year with the highest rainfall sum and the lowest air temperature, sugar content was considerably lower than in the previous tree years, by 22.6; 24.4 and 4.9% respectively. Regarding the irrigation variants, the lowest sugar content was registered in the variant of 100% of irrigation rate. Sugar contents in the other irrigation variants were very similar.

Sugar content in the non-irrigated variant was higher than that in the variant of 100% of irrigation rate but it was similar to the contents in the other irrigation variants.

Table 4 - Sugar content in dependence of irrigation rate (%)

Irrigation variant	1996	1997	1998	1999	Average
A_1 – Ø	16.45	16.39	13.46	12.99	14.85
A_2 – 25%	15.00	14.94	14.08	12.60	14.15
A_3 – 50%	14.90	15.71	13.66	12.55	14.20
A_4 – 75%	16.02	16.01	12.26	12.57	14.21
A_5 –100%	14.77	15.33	12.66	12.31	13.77
Average	15.43	15.68	13.22	12.60	14.23

Conclusion

Under variable climatic conditions, with fluctuating rainfall, irrigation in experiments increased the yields of sugarbeet from 4 to 90%. In the years with relatively favorable sums and distributions of rainfall (1996-1999), the yields were 25% higher in the variant with the optimum soil water regimen than in the non-irrigated control.

The highest yield was obtained in variant A_3 (50%), 112.96 t/ha. The yield in the variant A_5 (100%) was lower by 10.39 t/ha or 10% than in A_3, and lower by 5.90 t/ha or 6% than in variant A_2 (25%). The root yield in the non-irrigated control, 90.58 t/ha, was below the yields obtained in the irrigated variants.

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WATER CONSERVATION FOR THE SMALL FARMER IN THE PHILIPPINES

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ABSTRACT:

Establishment of Small Community Center to demonstrate the practicality of a sustainable integrated farming system using intense cropping, precision irrigation and water recycling.

Use small site typical of the amount of land owned by Land Reform Beneficiaries to explore irrigation methods that will conserve water, decrease dependence on external energy sources, and decrease salinity in both soil and groundwater. This would allow farmers to evaluate the benefit of different farming and irrigation systems without risking their crop

Intense farming and precision irrigation combine to permit more effective utilization of land and water resources. We hope to expand opportunities for women to generate an income from home such that they do not have to work in the sugar cane fields.

BACKGROUND:

While the Comprehensive Agricultural Reform Program (CARP) implemented in the Philippines may strike many as an admirable program, it is failing to reach the objective of providing the small farmer with a sustainable livelihood.

As some of the larger land holdings have been broken into 1.5 to 2 hectare parcels, the economies of scale have been lost, and once productive lands for rice and sugar have been converted into marginally productive smallholdings.

While the farmers now own the land they till, many do not have the basic skills to operate the various aspects of their farm. Typical would be the sugar cane worker whose job was harvesting. During the growing season he would be out of work, and only able to do some casual labor as the job market would permit. He would not have the knowledge to produce sugar cane from start to market. His job specialty was harvesting.

In addition, he would not have access to production credit that would allow him to purchase the necessary inputs such as cane points, fertilizer, insecticide and herbicide. This scenario is repeated with the rice farmers who have been "beneficiaries" of the Agricultural Reform Program.

Some of the beneficiaries have resorted to seeking loans from loan sharks who charge usurious interest rates that would be intolerable in the developed world. (The system is called 5/6, whereby the borrower pays 6 pesos back for 5 borrowed – monthly rate of 17%). The debt burden almost insures the farmer's failure. Other farmers contract their land out for raising game fowl or other non-crop related enterprises.

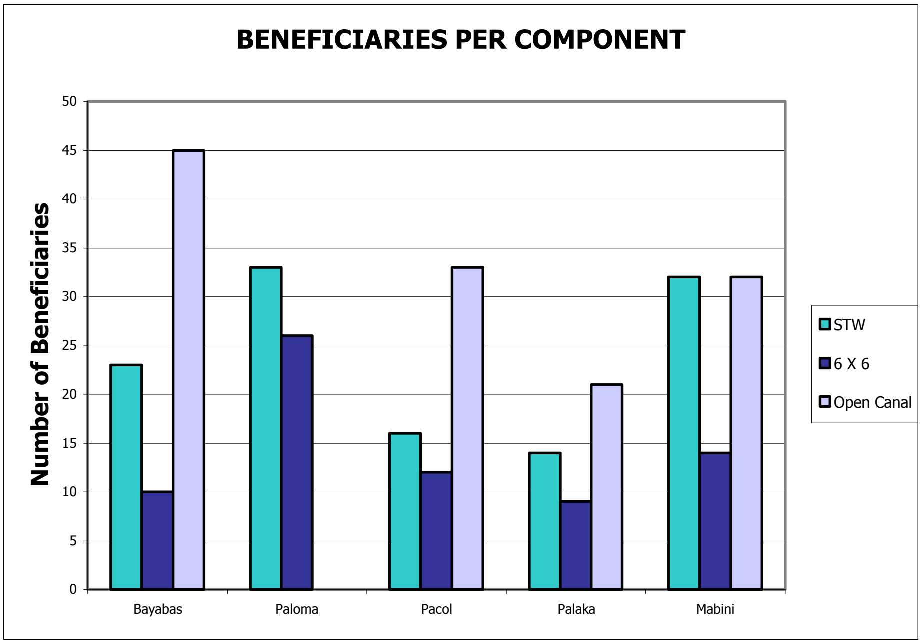
Typically the small farmer does not have the influence with the Irrigation System managers to ensure adequate water supply during the dry months (December-May). The National Irrigation Administration (NIA) has its own problems and as one proceeds down the irrigation canal the problems become more evident as the dry season progresses. During the dry season, loss due to drought is the highest contributor to crop loss. Other factors include pests and wind damage (Department of Agriculture 2002).

IRRIGATION AND SMALL FARM DEVELOPMENT PROJECT:

With major funding provided by the Rotary Foundation of Rotary International, we have worked with a group of small farmers in 5 villages located in the Municipality of Valladolid, Negros Occidental, Philippines. The typical farmer is planting lowland varieties of rice and generates two crop cycles during the wet season. Many plant vegetables during the dry season. The overall goal of the project was to assist in establishing irrigation sub-systems to supplement the government program and to provide pre and post harvest assistance in the form of working animals, power tillers and threshers. In addition, we provided credit for production or enterprise development.

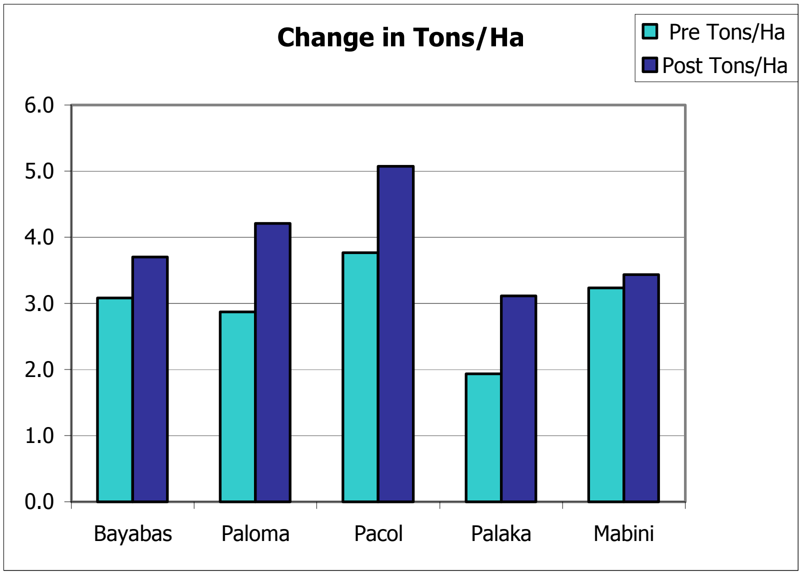
The irrigation component is comprised of 10 shallow tube wells with 4-inch pumps powered by 8 hp diesel engines and 5 small check dams to impound water that is pumped by 6-inch pumps powered by 14 hp diesel engines. In addition 9 km of open canals were rehabilitated or constructed.

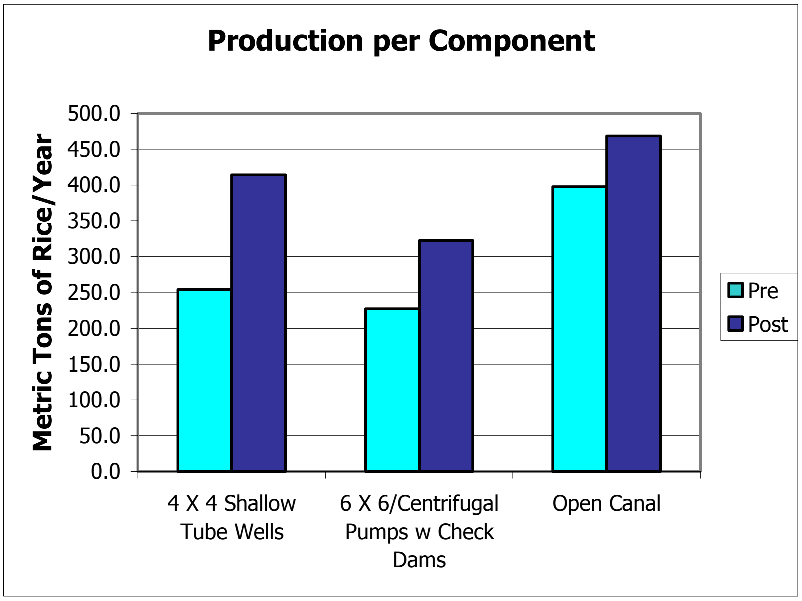
The overall increase in production among the 5 villages was 37%. This was the result of either increased land area farmed due to the irrigation or increased production per hectare as a result of water availability.



- Barangay Paloma did not construct new open canals, but did refurbish 1500 meters of distribution canal that served the 6” centrifugal pumpset

Three hundred eight irrigation beneficiaries were able to increase production by 37%. We do not have the data to establish a control group to determine the significance of the production increase. In the Western Visayas, however, the metric tons per hectare rose by .03 tons/ha to 2.71 t/ha, while our beneficiaries noted an average of 1.0 t/ha increase to 4.1 t/ha for the same period.





* The Shallow Tube Wells gave an overall 63% increase in production and 52% increase in yield/ha
The Centrifugal Pumps gave an overall 42% increase in production and 30% increase in yield/ha
The Open Canals gave an overall 18% increase in production and 12% increase in yield/ha

SMALL FARM RESOURCE DEVELOPMENT CENTER:

It was felt that perhaps a different approach to sustainable irrigation would be through a small experimental farm. With funds donated by friends and family, we leased some land near the municipality of Talisay, and have started a small demo farm to evaluate different methods of irrigation and cropping on our own land so we do not endanger the livelihood of the farmer.

We installed a hydraulic ram pump in a small nearby creek and now have the ability pump water twenty- two meters up into two holding tanks. One is a 17,000 liter ferrocement tank, and the other is an elevated plastic drum with a capacity of 1,000 liters. We plan to raise tilapia in the ferrocement tank and use the surplus water for irrigation. The plastic tank feeds drip tape for vegetables and other value added crops.

During the summer months when the small creek that feeds the ram pump is dry, we are able to use buckets suspended on bamboo “Ts” to feed the drip tape. We can supply 200 plants per bucket using 5/8” drip tape w/12” spacing.

SYSTEM OF RICE INTENSIFICATION (SRI):

We currently have about 1,000 sq. meters of rice planted using the System of Rice Intensification (SRI) model developed in Madagascar. SRI is composed of five recommended practices:

1. Early transplanting (8 days opposed to 20-25 day)
2. Plant single seedlings (opposed to 3-4 per hill)
3. Wide spacing (30 cm opposed to 15-20 cm)
4. Intermittent irrigation and good water control (opposed to constant flooding)
5. Frequent weeding (opposed to herbicides)

The SRI is gaining some popular support in the Philippines and there are currently trials underway with Broad Initiatives for Negros Development (BIND), the Consortium for Development for Mindanao Cooperatives (CDSMC) and the Philippine Rural Reconstruction Movement (PRRM) among others.

Preliminary results are encouraging, and in a comparative study between SRI and Non-SRI methods yields of 5.1 t/ha using SRI methods opposed to 3.1 t/ha using conventional techniques were obtained. Other Non-comparative studies between November 2000 and March 2001 have yielded averages of 6.9 t/ha (Gasparilla 2002).

Typical rice farmers are oftentimes reluctant to attempt novel methods of production for fear of losing a crop, or experiencing decreased production. Their existence lies in the fragile balance between natural and man made calamities.

One can understand their concern when they are told to plant 4 kg/ha of seeds in the seedbed instead of 40 kg. Additionally, transplanting takes place at a very early age, 7-8 days instead of the routine 20-25 days. The single seedlings look fragile, and at one seedling per hill instead of 3-4 seedlings, the farmer has more reason for concern.

Wide spacing between seedlings also contributes to the farmer's reluctance to adopt this method. Typically the seedlings are planted at 15-20 cm apart, whereas SRI spacing is wider at 25 to 50 cm apart. Gasparilla's study shows the 33 cm spacing to provide the best average production.

In Madagascar, where the system was initially developed, researchers are finding a large number of farmers abandon the system in spite of the yields obtained using SRI. The average number of farmers who tried the system and then abandoned it was 40%. It was also found that those continuing to use the system rarely planted more than half their land to the SRI. It was thought that the need to hire themselves out for income during the planting season caused many to drop the system (Moser and Barrett, 2002).

Many people are of the belief that rice requires continual flooding in order to develop. However, constant flooding decreases the amount of oxygen to the roots, and may hinder development of the plant. The SRI method involves intermittent flooding during the vegetative growth phase and 1 – 2 cm of water after panicle formation and during the ripening stage as opposed to the traditional 5 cm.

The Philippine Dept of Agriculture figures that it requires one cubic meter of water to produce .5 kg of rice. Using that figure, we can calculate the theoretical water usage for the rice grown in the 300 ha irrigation and small farm development project for the 2002-03 cropping season, we come up with 2.4 million cu. meters of water used. To put that figure into perspective, that would be around one square mile of water 3 feet deep. Some of the claims for SRI are that the system uses about 50% of the normal water requirements (Vallois 1997), so the water saving alone would be significant.

As with any new system, it takes time for people to adopt and change their habits. Skeptics are plentiful and it takes a determined farmer to go against tried and proven methods of production. Due to the increased labor demands of the Rice Intensification System, it might prove more palatable if farmers adopted a small section of the farm for family consumption. In this way, they would be able to compare yields with the traditional system, and possibly have some more land available for high value crops such as fruits and vegetables.

We plan to develop some integrated practices on the Demo Farm wherein we reduce waste and recycle water using the fish pond, vegetables, rice paddies and taro grown in the drainage channels. We also hope to develop an alternate source of cooking fuel in an effort to decrease the dependence on charcoal. This will save the trees that are currently being harvested to produce the charcoal as well as decrease the amount of air pollution that results from the processing operation.

We hope to develop local markets for products produced on the farm as well as offer training seminars and on farm consultations for those farmers interested in the system. There are also several large producers who are interested in incorporating drip irrigation into their operations to permit intercropping fruit trees with vegetables.

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Irrischeduler- a simple device for scheduling irrigations

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Abstract

Farmers do not use any instruments for scheduling irrigations and depend only on their visual judgment of crop and soil conditions. Evaluation of the farmers' decisions revealed 5 to 30 per cent variations from the appropriate soil moisture for scheduling irrigations. Understanding of the farmers' perceptions (through participatory rural appraisal, PRA in village Lakhan, Dist. Hapur, Uttar Pradesh) indicated the complexity of available instruments as the major cause of their non-adoption by farmers. A simple device, namely irrischeduler, was developed to indicate the time for irrigation based on the soil moisture level. The developed device does not require the user to read from a gauge, which was reported by farmers as cumbersome in their perception. Performance evaluation of the developed device indicated that it could be used for most type of soils, excepting sandy and highly clay soils.

1. Introduction

The dominant method of irrigation practiced in large parts of the country consists of diverting a stream from the head of a field into furrow or borders and allowing it to flow down the grade by gravity. Generally under these surface irrigation methods, the crop utilizes only less than one half of the water released. A good part of the applied water is lost in conveyance, application, runoff and evaporation. Accordingly the efficiency of surface irrigation methods is low. Higher irrigation efficiencies can be realized in the farmers fields if, as a first step, amount of water applied and the time of application of available water are fixed appropriately.

Soil in the plant root zone acts as a reservoir for water. Soil texture is the primary factor influencing the amount of water that the soil reservoir can store. Available water is defined as amount of water that plants are able to withdraw from the soil for their use. Fine textured soils, such as clays, silt loams, or loams are able to hold much more available water than sandy, coarse-textured soils. Soil water holding capacity is an important factor to consider in determining the appropriate timing and volume of irrigation water. Tensiometer is a device that indicates the level of soil moisture.

In exclusively canal irrigated areas there is hardly any scope for scheduling irrigation differently from the schedule of the operation of the canal itself. But even in situations where the water supply is in control of the farmers themselves, they depend only on their visual judgment of crop and soil condition for scheduling irrigations and do not use any instrument for the purpose.

Participatory Rural Appraisal was conducted in village Lakhan, Dist Hapur, Uttar Pradesh to investigate the farmers' perceptions for non-adoption of available tools like resistance block and tensiometers for monitoring soil moisture for scheduling of irrigations. Based on their responses existing tensiometer was modified and an irrischeduler was developed. The article presents the details of the developed device, namely irrischeduler, its calibration using a standard tensiometer and discusses its appropriateness in scheduling irrigations under different type of soils.

2. Materials And Methods

2.1 Participatory Rural Appraisal

A village namely Lakhan, District Hapur, Uttar Pradesh was selected to study the irrigation practices followed by the farmers. The village has some cultivated area exclusively under canal command, some cultivated area exclusively under tube well command and some having both, canal as well as tube well irrigation facilities. A detailed participatory rural appraisal (PRA) study conducted to understand farmers perceptions about irrigation scheduling revealed that none of the farmers adopted any tools for scheduling irrigations and depend solely on their visual judgement of crop and soil condition (Rajput and Patel[1]). On discussion with the concerned farmers and on demonstration of the use of tensiometers to them it was found that the farmers considered the reading of vacuum gauge cumbersome and wished to have a simpler device.

2.2 Evaluation of Farmers' Decisions of Irrigation Scheduling

Fifteen farmers having land holdings ranging from 0.15 ha to 5.6 ha were selected for observing their irrigation practices. Soil moisture contents at which the selected farmers actually applied the irrigations in wheat crop (2001-2002) were recorded and were compared with their respective appropriate soil moisture levels for studying the accuracy / inaccuracy in their judgment for scheduling irrigations without the use of any appropriate instruments.

Difference between the Field capacity and the wilting point of a soil is considered as the available irrigation water. The irrigation is scheduled on depletion of a fixed percentage (normally 50 per cent) of the available soil moisture. Soil moisture contents at field capacity and wilting point of the soils of the study area were determined. The soil moisture at the time of irrigation by different farmers were recorded and compared with their respective appropriate soil moistures for irrigation.

2.3 Scheduling Irrigations Using Tensiometers

Tensiometers are one of many tools available for irrigation management. With practice, tensiometers can provide the information required to make proper irrigation decisions (Goldhamer and Synder[2]). A tensiometer consists of a porous cup, connected through a rigid body tube to a vacuum gauge, with all components filled with water. The porous cup is normally constructed of ceramic because of its structural strength as well as permeability to water flow (Michael[3]).

Tensiometers are placed in the field with the ceramic cup firmly in contact with the soil in the plant root zone. The ceramic cup is porous so that water can move through it to equilibrate with the soil water. A partial vacuum is created as water moves from the sealed tensiometer tube. As the soil dries, water potential decreases (tension increases) and the tensiometer vacuum gauge reading increases. Conversely, an increase in soil water content (from irrigation or rainfall) decreases tension and lowers the vacuum gauge reading. In this way, a tensiometer continuously records fluctuations in soil water potential under field conditions (Pogue and Pooley[4]).

The range of operation of a tensiometer is generally limited between 10 and 85 cb. Waterlogged conditions are indicated when tensimeter reads below 10 cb and leaf defoliation begins when reading exceeds 85 cb (Peacock *et.al*[5]) . Above 85 cb the column of water in the plexiglass tube will form water vapor bubbles (cavitate), and the instrument will cease to function (Smajstrla and Harrison[6]).

A tensiometer is placed in the portion of the root zone that represent average depletion level of the entire root zone depth. The general depletion levels are 40, 30, 20 and 10 per cent of the water used by the crop from different quarters of the root zone (Michael *et.al*[7]). Consequently, a tensiometer needs to be placed between the second and third quarter of the root zone or at 63 percent of the depth of the roots in order for it to be placed in the depth of the root zone representing the average extraction level. For example if the root zone is 50 cm the tensiometer should be placed at 31.5 cm (Levin *et.al*[8]).

2.4 Development of an Irrischeduler

A regular tensiometer was modified to develop it in to an irrischeduler. In the irrischeduler a transparent tube (rigid Plexiglass) and a coloured float is used to indicate the level of water in it. The porous cup (ceramic) is used at one end of the tube and the tube is filled with water and is sealed from the other end with the help of a watertight cork. The ceramic cup is installed in the soil at an appropriate depth as discussed in case of tensiometers above. The irrischeduler provides an opportunity to monitor soil moisture fluctuations through change in water level in its tube. It may also enable marking one value on the tube indicating maximum permissible drop of water level to indicate the time for scheduling next irrigation. Characteristic curve of irrischeduler was developed and it was calibrated with the help of a slandered tensiometer. Figure 1 presents a tensiometer and an irrischeduler installed side by in a tomato field.

3. Results and Discussion

Fifteen farmers having land holdings from 0.15 ha to 5.6 ha were selected for studying the variations in farmers' judgment from their respective appropriate soil moistures for scheduling irrigations. Soil moisture contents at which the selected farmers actually applied their irrigations for wheat crop (2001-2002) were recorded and are presented in Table 1. Soils of the selected farmers fields were analyzed to determine their textures (Table 2). Appropriate soil moisture levels in respect of different farmers fields were determined using a hydraulic properties calculator (Saxton[9]) for scheduling irrigation and the same are presented in Table 2.

Table 1 indicates that the farmers having exclusively canal irrigation facility irrigated four times when the canal was in operation and they could have not scheduled their irrigations otherwise. The farmers having tube well irrigation facility did tend to irrigate more frequently than required and allowed much less soil moisture depletion than what was appropriate. Farmers having tubewell irrigation facility irrigated wheat fields 6 to 7 times (Table 3). It may also be noted from Table 3 that the farmers never allowed the soil moisture to deplete upto allowable level and irrigated at soil moistures 5 % to 30 % above the appropriate soil moisture level (Table 3).

Participatory rural appraisal was conducted in village Lakhan involving all the selected 15 farmers. Scoring and Ranking techniques of PRA indicated that farmers schedule irrigatios on the basis of crop condition (Rank I) followed only by soil condition (Rank II). No farmer used any instrument or device for the purpose. Demonstration of the use of a regular tensiometer received the comments from the farmersthat it was cumbersome as it required reading from a gauge. However, farmers wished to have a simpler device but without a gauge for trial in their fields themselves.

An irrischeduler was developed having a transparent plexiglass tube and a coloured plastic ball in it to indicate water level in it. The irrischeduler was installed in a tomato field. A regular tensiometer was also installed nearby (Figure 1). With each passing day water level in irrischeduler started falling tensiometer started showing increasing readings. The relationship between the fall of water level inside the irischeduler tube and the reading of the vacuum gauge of the tensiometer with decreasing soil moisture were developed (Figure 2).

Characteristic curve was developed for the irrischeduler relating the fall of water level inside the irrischeduler tube and the soil moisture level. Based on the estimated appropriate soil moisture for scheduling irrigation for a field (Table 2), its corresponding level of water level in irrischeduler was determined and marked on its body. The farmer then had to schedule next irrigation of his field when the water level in the irrischeduler fallsbelow that mark. On the day of irrigation, irrischeduler tube should be filled with water completely and sealed with its cork.

The values of field capacity and wilting point are a function of soil texture. The range of available soil moisture varies with soil type. Also different levels are allowed before scheduling next irrigation based mainly on the crop type. Figure 3 indicates that for all soils excepting sandy soil and highly clay soils, the range of soil moisture (under allowable soil moisture depletions of 50%, 40%, 30% and 20 % of total available soil moisture) fall within the operational range of the irrischeduler.

4. Conclusion

Irrischeduler is a much simpler device in comparison to a tensiometer but possesses all its positive attributes, therefore it can be used to schedule irrigations effectively. Farmers having their own tube wells or any other source of water may make a good use of irrischeduler and cut down on number and amount of irrigations and save the energy, time and money. The developed irrischeduler can be used to schedule irrigations in most soils except sandy soil and highly clay soils.

5. Acknowledgement

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Table 1 Soil moisture levels at different irrigations of wheat 2001-2002
(Village Lakhan, District Hapur)

SN	Name of farmer	Source of water	Soil moisture contents observed at the time of different irrigations (%)						
1	Gyan Singh	C	10	12	17	10	-	-	-
2	Jagpal	T	20	21	22	20	19	22	-
3	Harchanda	C	15	17	20	13	-	-	-
4	Ramveer Singh	T	21	20	22	21	20	21	-
5	Dinesh Singh	T	21	21	22	23	20	20	-
6	Chhidda Singh	T	22	23	21	20	20	21	-
7	Jagpal Singh	C	12	12	16	11	-	-	-
8	Ompal Singh	T	21	23	20	22	21	23	-
9	Chandar	C	15	14	19	14	-	-	-
10	Bhule Singh	C+T	21	20	20	23	21	20	22
11	Veer Singh	C+T	22	24	22	23	25	22	24
12	Bhagvan Singh	T	21	23	21	23	22	-	-
13	Indraraj	C	15	15	18	14	-	-	-
14	Khoobi	C	16	17	18	14	-	-	-
15	Ranbhool Singh	C	11	13	17	10	-	-	-

C = Canal , T = Tubewell,

Table 2 Appropriate soil moisture levels for irrigation for wheat 2001-2002

(Village Lakhan, District Hapur)

SN	Name of farmer	Size of holding (ha)	Soil texture			Field Capacity (%)	Wilting Point. (%)	Appropriate Moisture for irrigation (%)
			Sand (%)	Silt (%)	Clay (%)			
1	Gyan Singh	5.6	56.5	35.28	8.22	21	9	15
2	Jagpal	5.6	44.5	44.00	11.5	24	10	17
3	Harchanda	5.6	44.5	39.28	16.22	25	11	18
4	Ramveer Singh	3.6	40.5	45.28	14.22	25	11	18
5	Dinesh Singh	3.2	37.78	45.72	16.5	26	11	19
6	Chhidda Singh	3.0	31.78	48.00	20.22	28	12	20
7	Jagpal Singh	2.4	45.78	41.72	12.5	23	9	16
8	Ompal Singh	2.0	36.5	44.28	19.22	27	12	19
9	Chandar	1.2	35.78	48.00	16.22	26	11	19
10	Bhule Singh	1.2	44.5	44.00	11.5	24	10	17
11	Veer Singh	1.1	31.78	50.00	18.22	28	12	20
12	Bhagvan Singh	1.0	36.5	44.28	19.22	27	12	19
13	Indraraj	1.0	33.78	50.00	16.22	27	11	19
14	Khoobi	0.7	32.5	45.28	22.22	28	13	20
15	Ranbhool Singh	0.15	56.5	35.28	8.22	21	9	15

Table 3. Inaccuracy in farmers decisions for scheduling irrigations

SN	Name of farmer	Range of soil moisture at the time of irrigations (%)	Soil moisture appropriate for irrigation (%)	Error in scheduling irrigations (%)
1	Gyan Singh	10 – 17	15	-33 to +13
2	Jagpal	19 – 22	17	+11 to +29
3	Harchanda	13 – 20	18	-27 to +11
4	Ramveer Singh	20 – 22	18	+11 to +22
5	Dinesh Singh	20 - 23	19	+ 5 to +21
6	Chhidda Singh	19 - 23	20	0 to +15
7	Jagpal Singh	11- 16	16	-31 to 0
8	Ompal Singh	20 - 23	19	+ 5 to +21
9	Chandar	14 - 19	19	-26 to 0
10	Bhule Singh	19 - 22	17	+17 to +35
11	Veer Singh	21 - 24	20	+10 to +25
12	Bhagvan Singh	21 - 23	19	+10 to +21
13	Indraraj	14 - 18	19	-26 to - 5
14	Khoobi	14 - 20	20	-30 to +10
15	Ranbhool Singh	10 - 17	15	-33 to +13

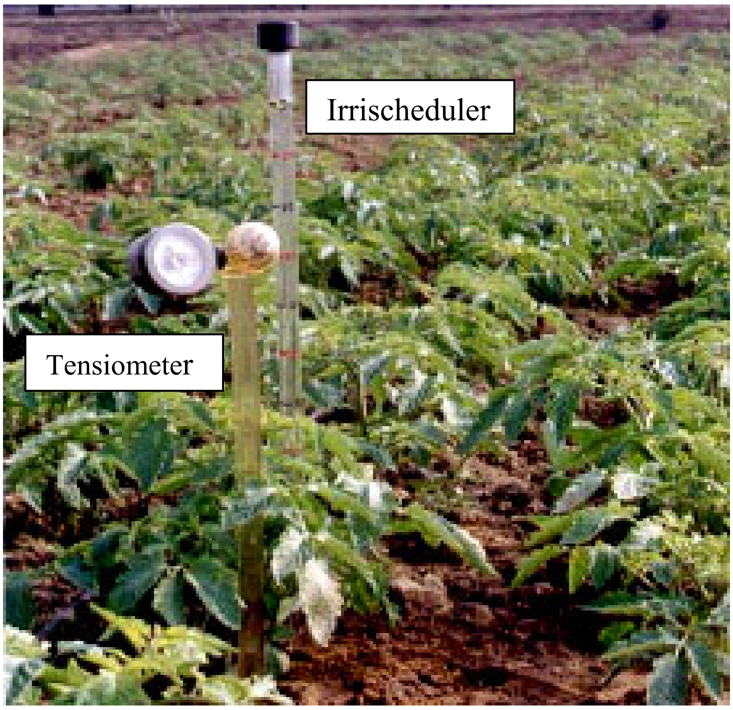

Figure 1. Irrischeduler installed next to a tensiometer in a tomato field for calibration

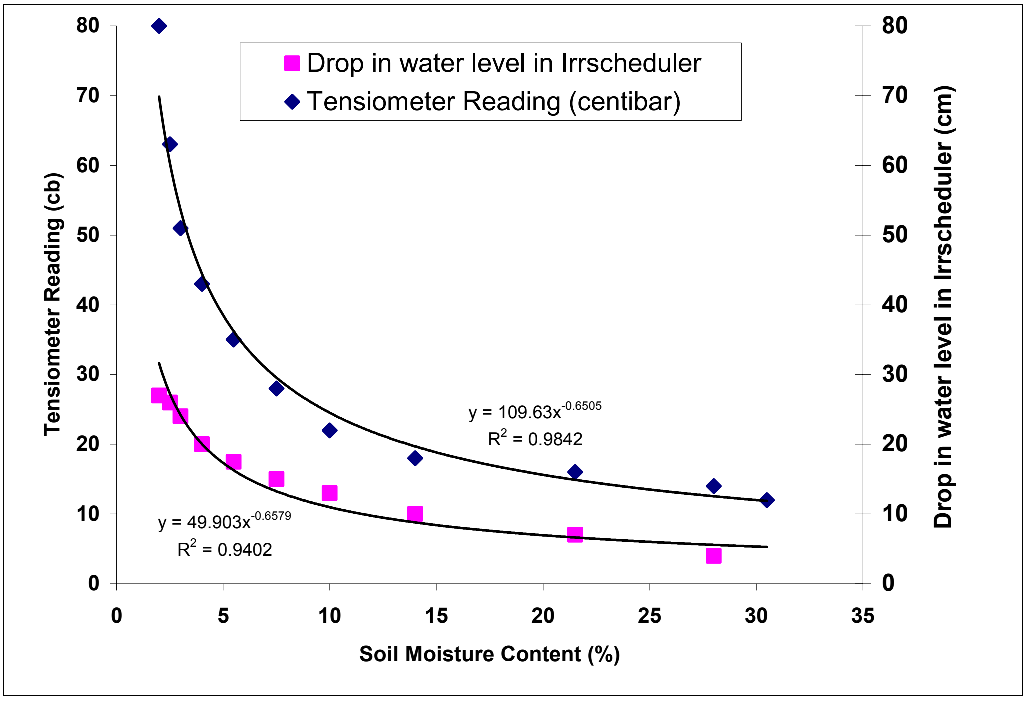

Figure 2 Characteristic curves of a tensiometer and an irrischeduler (Loamy sand soil)

Figure 3 Range of operation of irrischeduler and allowable moisture in different soils

Water Conservation Questions and Definitions from a Hydrologic Perspective

Richard G. Allen, Lyman S. Willardson, Charles Burt, and Bert J. Clemmens[1]

Abstract

Water conservation activities are frequently encouraged within municipalities and irrigation systems, especially during periods of drought. The objectives of many irrigation water conservation programs have been to increase irrigation efficiencies with the expressed purpose of reducing gross diversion requirements. The intent during droughts is that less water will be depleted from a limited resource. In long-term conservation programs the intent is that more water will be made available for other users. However, the reasons for reducing diversion requirements must have both a regional and local interpretation from a hydrologic and conservation of mass viewpoint. Water management principles used to guide society's water use objectives require terms and definitions that clearly describe the effects of various water uses, both consumptive and non-consumptive, within a hydrologic system. Some water use terms such as the evaporated fraction, reusable fraction, nonreusable fraction and consumed fraction are discussed in this paper. These terms are useful to both users and public in developing improved, rational and visual understandings of the hydrologic nature and impacts of water use and conservation programs.

In situations where the nonevaporated components of irrigation diversions return to the fresh water resource for reuse by others, conservation programs may not stretch water supplies or "save" water in the region, especially in the long-term, and especially where the initial source is from ground-water. In some instances, where water is abstracted from streams, irrigation water conservation programs can actually be "ET sustainment" programs, since they may sustain a more "consumable" water supply for one city or project at the potential expense of downstream projects, cities and perhaps the environment. Water conservation programs should fundamentally be evaluated in the context that, in general, the only real loss of water from an irrigation project is by the process of evaporation from open water surfaces, evaporation from moist soil and transpiration from vegetation. Fundamental hydrologic concepts and questions are described that can help planners and managers to establish the context and impact of individual conservation programs in the near and long term.

Introduction

In irrigation systems where return flows reenter a fresh water resource and are of reusable quality, water is only saved over the long run through water conservation where the evaporation or evapotranspiration (ET) components are reduced. However, issues of stream flow reduction and time lags can be important. In cities, the investments in costs for treatment of water and distribution capacity, degradation of ground-water must be considered in addition to when or whether excess water applied returns to a fresh water resource for reuse. Conservation programs may not save "real" water, but only change the distribution of the resource in space and time. In these cases, the public investment is not well spent. Some water use

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terms such as the evaporated fraction, reusable fraction, non-reusable fraction and depleted fraction are discussed that can help the user and the public develop improved visual understanding of the hydrologic context and true impacts of water use and conservation programs. Fundamental questions are provided to help quantify the context of the water conservation program and the impacts from a hydrologic viewpoint.

Appropriate Reasons to Conserve Water by Increasing "Efficiency" (Uniformity) of Water Application

The following are appropriate reasons why cities or irrigation projects or systems should conserve water:

- Reduce costs for treating water
- Reduce costs for pumping water
- Reduce costs for added distribution capacity in an area of growing population or demand
- Reduce leaching of fertilizers and other chemicals and degradation of ground-water
- Sustain flows in specific segments of streams that are threatened by low flows or thermal increases and where "nonevaporated" components of diverted water bypass the stream or return at a less valuable time
- Where "nonevaporated" components of diverted water flow into a saline system (ocean, saline lake, or brackish groundwater) and are therefore nonrecoverable or contaminate streams downgradient.
- Where water is abstracted from a deep, confined aquifer, but the "nonevaporated" components of abstracted water percolate to a more shallow unconfined aquifer, thus changing the distribution of water between the aquifers in an undesireable way.

In agriculture:

- Reduce waterlogging and improve salinity control
- Enhance equity among users
- Maximize the total fraction of water delivered to crops to increase crop yields
- Reduce soil erosion.

Inappropriate Reasons to Conserve Water by Increasing "Efficiency" (Uniformity) of Water Application

The following are inappropriate reasons to initiate a water conservation program:

- To create "new" water downstream in regions where return flows (from nonevaporated diversions) already reenter the water resource at an appropriate time
- To enhance streamflows for long distances downstream where return flows (from nonevaporated diversions) already reenter the water resource at an appropriate time
- To extend the life of an unconfined aquifer where return flows (from nonevaporated diversions) already reenter the aquifer with acceptable quality

Benefits of Low Efficiencies

The following are benefits of low efficiencies of water application (i.e., overirrigation or poor distribution uniformities) that are realized in a number of situations (Allen et al., 1997). These benefits are fortuitous and are not usually designed as part of water management:

- Recharge to unconfined aquifers
- Dampening of flood flows or redistribution of flows over time (due to reentry of return flows with some time lag and dampening)
- Augmentation of streamflows during droughts (due to reentry of return flows created by diversions during periods of higher flow). The augmentation of diffusive return flows by groundwater may help cool streamflow and benefit biota
- Incidental ground-water recharge near oceans may help reduce salt-water intrusion
- Creation of wetlands

Fundamental Precepts

There are fundamental precepts that govern the ability to conserve water and the ability to create "new" water by a conservation program. These are:

- The law of Conservation of Mass. The Law of Conservation of Mass suggests that matter can not be created nor destroyed. In the context of liquid water, the law suggests that liquid water, while remaining as liquid water (and not evaporated) can not be created nor destroyed. Thus all nonevaporated components must be "somewhere" and must reappear "somewhere."

- The reality that 99% of the earth's landmass is underlain by ground-water (Freeze and Cherry, 1979) impacts the "loss" of water. All deep percolation "losses" are not "lost" to the hydrologic system, but seep downward vertically to the groundwater. After entering the saturated groundwater system, the liquid moves with the groundwater laterally, at some velocity determined by hydraulic gradient and geology, until it discharges to a surface water source.

Thus, the only way to really create "new" water is to reduce the water that is degraded to the point where it is not usable by anyone else downstream or to reduce the evaporated component of the diversion (i.e., reduce the evapotranspiration, ET).

The above appropriate reasons for conservation programs are all valid reasons and goals for water conservation efforts, but they should be worth the price paid to obtain them. Many improvements may not conserve water on a regional basis, since ET of irrigated lawns or fields is normally not reduced in these types of "conservation" programs. In fact, ET may actually be increased due to improved uniformity and more careful control of water application. Therefore, water conservation efforts on the local scale may ultimately increase water consumption both on a local and regional scale.

Reality and Efficiency

The primary consumption of water within an irrigation system is by the process of evaporation from open water surfaces, evaporation from moist soil and transpiration from vegetation. The combination of this evaporation and transpiration is termed ET. In addition to ET, water that is returned to a saline water body or that is severely degraded in quality is essentially lost as a freshwater resource. All other water diverted by an irrigation system remains in liquid form and will ultimately return to a freshwater system. The return of diverted water to the system is a natural, diffusive process that is nearly impossible to control, because remaining liquid water must obey the law of gravity and the law of conservation of mass. Gravity brings nonevaporated water back to a stream, ocean or aquifer system.

The term irrigation efficiency (IE) has traditionally been defined as the ratio of the sum of beneficial consumption and leaching to gross diversions. (Jensen, 1967; Bos, 1985). Unless the ideas now associated with the implications of low irrigation efficiency are modified, it will become extremely difficult to properly manage the supply of fresh water in arid regions of the world due to the misconceptions and misunderstandings by the engineering, political, and news communities. For example, much current irrigation literature contains erroneous recommendations to increase irrigation efficiencies in order to create more available water some distances downstream (for example, UN-FAO News Release, 1994; Yaxin and Guangyun, 1993; U.S. Water News, 1995). The economic damage and waste of limited water resource management funds caused by such articles and misconceptions is large.

There are hydrologic systems where nearly one hundred percent of the water is being productively consumed due to natural reuse within the system. Total consumption in such cases cannot be increased past 100%, nor can altered practices designed to "increase irrigation efficiency" in such a system yield additional water to be used by new diverters without reducing the consumption (i.e., evaporation) of current users. Use of the term "irrigation efficiency" has caused a dichotomy between the physical situation of the hydrologic system and the public's and government's perception of the physical nature of water management. These incorrect views are pervasive and strongly held. Billions of dollars have been proposed for investment to correct for low irrigation efficiencies with the intent that water problems will be solved. The public has been convinced that selected investments and penalties imposed on irrigation will free up vast amounts of water for other uses. Only a fully rational approach to water management can minimize the conflicts that arise between municipal, industrial, environmental, recreational, aesthetic, and agricultural uses of the finite fresh water supply.

Importance of Local Hydrology and Location within a River Basin

Some irrigation projects are located close to the ocean or directly upstream of other saline water systems such as saline lakes or saline ground water sinks. In these situations "return" flows from irrigation projects enter these saline systems and are truly lost for additional consumption by humans. In these situations, reducing diversions by enacting water conservation programs may allow upstream users to divert and consume more water, thereby increasing the total beneficial consumption of the water resource.

In areas where excess diverted water percolates through soil profiles and picks up salt, return flows from deep percolation increase the total salt load of the receiving water resource and may reduce its economic usefulness. In these cases, reducing diversions and return flows by increasing irrigation uniformity and reducing excessive applications may increase the effective water supply.

Basic Hydrology and Law of Conservation of Mass

There are saturated ground-water bodies lying beneath the earth's surface almost everywhere in the world. These ground-water bodies have had thousands of years to develop, and have built up to an equilibrium point so that ground water flows freely by gravity, if it is unconfined, to a lake or stream system (or to the ocean, if nearby) where it discharges. Unless they have been overdrafted by pumping, most ground-water systems are in equilibrium with surface water systems. Most streams exist during periods of low surface runoff because a ground-water table feeds the stream. The addition of water to a ground-water system is, over the long term (perhaps tens of years or less), balanced by similar amounts of outflow to a surface system. The flow process is controlled by gravity, is automatic, and is inevitable, i.e. part of the basic hydrologic equilibrium.

A consequence of reducing water diversions is almost always a reduction in return flow back to the resource. Therefore, the quantity of net consumption by an irrigation system may be largely unchanged by a conservation program. To effectively create "new" water in a regional context, unless directly upstream of a salt sink, a conservation program must in some way reduce evaporation or ET or improve return flow quality, and not simply reduce diversions. Reductions in the direct consumption of water are usually in the form of reducing areas of phreatophytes or wetlands along canals, collection ditches, or in areas of shallow, ground-water seepage to the soil surface. Wetlands and phreatophytes created by irrigation are often considered to be of value for wildlife habitat and may be lost when water conservation practices are implemented. Reduction of crop ET will almost always reduce turf quality or crop yields, unless evaporation from soil is reduced without reducing plant transpiration.

It is important that irrigation improvement procedures be evaluated to show when and how water is actually saved by the conservation program. Guidelines for preparation of conservation plans must include procedures for describing hydrologic components and interactions within and beyond irrigation system boundaries, with descriptions and examples of how to assess whether evaporation or ET can be reduced within the system or "return" flows into saline systems can be reduced, thereby achieving real conservation of water and the creation of an enhanced water supply. Unfortunately, it is common to draw "lines" around system boundaries and to neglect the real interconnections between in-system "losses" and existing river system gains.

Definition of Water Consumption Terms

An improved, graphic image of the hydrologic and basin-wide effects of irrigation is possible when the disposition of water within an irrigation project is described in terms of "fractions." Definitions based on fractions have been proposed by Jensen (1993), Willardson et al. (1994), Allen et al. (1996, 1997) and Molden (1997) and Molden and Sakthivadivel (1999) for assessing the impacts of fresh water diversions by users of water resources, including irrigated agriculture, municipalities, industry, and ecological interests.

The new terms are intended to encapsulate clearly the impact of any and all types of water use on actual physical losses of utilizable water from the affected hydrologic system. Unlike most efficiency terms, the proposed methodology and terms (a) are appropriate for evaluating water allocation, water use, and related management options, (b) are consistent and appropriate for all water uses, not only for irrigation and a narrow evaluation of irrigation practices, and (c) can be clearly understood conceptually and in terms that can be correctly applied by people engaged in the water allocation / use / management debate. Application of such terms will help to clarify what the allocation of water to various uses at various locations in a hydrologic system actually means in terms of the total water supply.

A change from using "efficiencies" to using "fractions" to describe water use eliminates many misunderstandings. Fractions are used in many applications to describe what proportion of some quantity has been applied to a particular use. Use of a fraction evaluation instead of an "efficiency" prevents the occurrence of a serious logic error in describing or evaluating the management of water. Jensen (1993) discussed the need for a change in the ways that water use is described, and has also advocated moving away from use of the term efficiency in irrigation.

Figure 1 shows a matrix of uses and disposition of irrigation diversions categorized as beneficial and nonbeneficial and as consumptive and nonconsumptive as described by Clemmens et al. (1995), with enhancements to the water disposition categories by Allen et al., (1996, 1997). The figure illustrates relationships among the following fractions proposed to describe the hydrologic disposition of irrigation diversions. The fraction terms are defined as follows:

Evaporated Fraction.

The evaporated fraction (EF) is the fraction of an irrigation diversion that is consumed through evaporation or evapotranspiration:

$$EF = \frac{Q_{ET}}{Q_{Div}} \qquad \mathbf{1}$$

where Q_{ET} = quantity of diversion consumptively evaporated (or transpired) by the water use process (for example, irrigation) and Q_{Div} is the total diversion of water to the specific process. Besides ET from landscapes or cropped fields, Q_{ET} includes evaporation from evaporation ponds, canals, reservoirs and seeps, and water evaporated from riparian vegetation and wetlands created by irrigation return flow or seepage. EF is similar to the irrigation consumptive use coefficient term introduced by Jensen (1993), except that EF may also include evaporation external to the primary process.

Nonreusable Fraction

The nonreusable fraction (NRF) is defined as the fraction of a diversion that is not evaporated, but is no longer available for reuse by other water users due to entry into a saline system (ocean, brackish water bodies, or saline aquifers) or due to degradation in quality to the point that it is economically nonresuable, or is physically beyond economic recovery:

$$NRF = \frac{Q_{NR}}{Q_{Div}} \qquad \mathbf{2}$$

where Q_{NR} = quantity of diverted water that is still in liquid form, but has been made nonrecoverable due to the physical manipulation by the user (diverter). The NRF represents the fraction of Q_{Div} that could conceivably be made available to other users, in addition to reductions in nonbeneficial ET, through conservation efforts, without reducing crop yields. Nonrecoverable water that results from a particular use should be identified and charged to that use.

Consumed Fraction

The consumed fraction is defined as the fraction of total diversions that are consumed, i.e., no longer available to any other user during any future time period. The consumed fraction includes the evaporated fraction and the nonreusable fraction, since physically, these two fractions are "consumed" in the context of the fresh water resource. The consumed fraction (CF) includes any water exported from the basin:
where Q_{exp} = water that is exported to outside the hydrologic basin. An example is water contained in

$$CF = \frac{Q_{ET} + Q_{NR} + Q_{exp}}{Q_{Div}} \approx EF + NRF \qquad \mathbf{3}$$

fresh fruit that transported from a basin, or in the case of production of bottled water or other beverages, the water contained in the beverage, assuming that the beverage is not consumed within the basin.

In the definition of consumed fraction, the term "consumed" means that the CF fraction of the diversion is truly consumed or otherwise transformed so that it is no longer reuseable by any other future user within the basin. The consumed fraction of diversions either undergoes a phase change (evaporation), is exported outside the basin, or enters a nonreusable state due to extreme salinization pollution, or uneconomically recoverable location, any of which make the water nonreuseable by anyone else. It is important that the reader realize fully that water diverted by an irrigation project or any other user is not "consumed" unless one of the transformations occurs (transformation from liquid to vapor or entry into a nonreuseable quality state). The user should be considered responsible for the quantity of the water resource which, on a basin-wide scale, is the product $CF \bullet Q_{Div}$.

Reusable Fraction

The reusable fraction (RF) represents the fraction of the diverted water that returns to the water resource for subsequent reuse by others:

$$RF = \frac{Q_{RF}}{Q_{Div}} \qquad \mathbf{4}$$

where Q_{RF} is the quantity of diverted water that is reusable by other users. Q_{RF} naturally reenters the fresh water system.

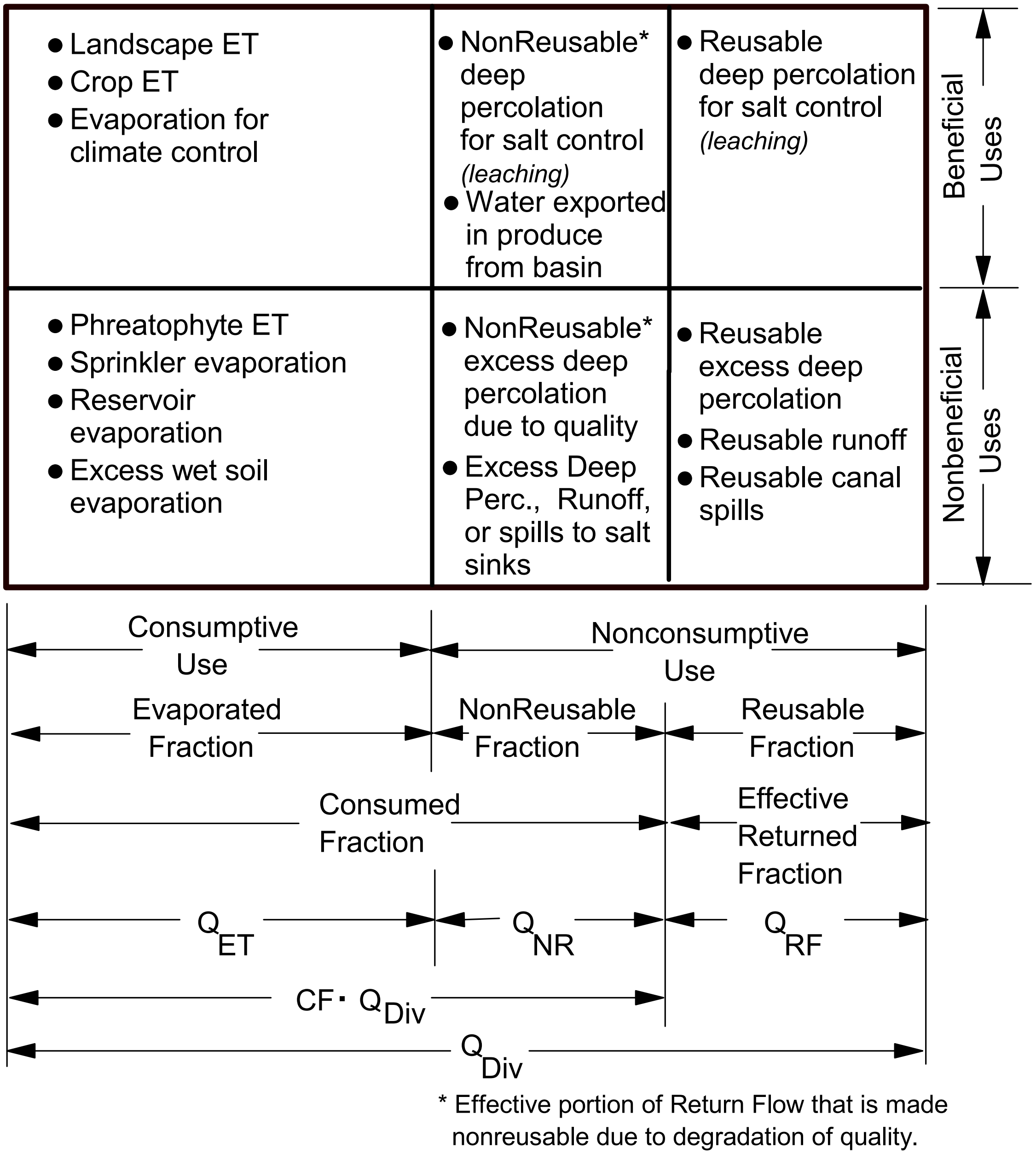

Figure 1. Use categories (consumptive and nonconsumptive and beneficial and nonbeneficial) and fractions describing the disposition of irrigation diversions (after Clemmens et al., 1995 and Allen et al., 1996, 1997).

Impact of the Location within a Basin

Willardson and Allen (1998) recommended the splitting of a river basin into three regions (high, mid and low) to assist in assessing impacts of low "efficiencies" (i.e, consumed fractions) on downstream and other users. In general, the need for conservation programs and impact of such programs increases as one moves downstream (toward the ocean). In low regions of basins, the NRF (nonrecoverable fraction) of diverted water generally increases due to proximity to saline systems.

Nonreusable quantities of water arise in other uses of the water resource besides irrigation. For example, water allocated to "wild rivers" in northern California is in general not recovered for other uses and runs directly into the ocean and becomes nonrecoverable. Such water has a very low evaporated fraction (EF) but has a very large nonreusable fraction (NRF) and consequently, a large CF. Such uses of water should be described in the same terms as for irrigation so that the public understands the impact on total available fresh water in terms consistent with the descriptions used for other uses. A low CF for a city high in a watershed permits a large fraction of the returning water to be reused downstream after natural bioremediation and/or water treatment. A high CF for a large coastal city will result if nearly all of the sewage effluent (reusable under some circumstances) becomes nonreusable when it is discharged directly into the ocean. It does have high benefit, however, if injected to groundwater to reduce seawater intrusion. In some situations, it is "good" to have a "low" CF, since this means that much of the diverted water returns as a fresh water resource for subsequent reuse. However, because a low CF is equivalent to a low "efficiency", the latter term gives a falsely negative impression to the public, in the absence of rational fractional analysis.

Effect of Scale

Fractions can be calculated for any scale of interest. In the case of irrigation, this is typically at the field, subproject, project or basin scale. Generally, the nonreusable or Q_{NR} quantities of water for fields or conveyance systems in upper regions of irrigation projects are small relative to Q_{Div} and Q_{EP}, especially if hydrology and elevation promote convenient and timely reuse of water or return of water to the stream or to a recoverable ground-water system.

An example of this is the Little Willow Irrigation District in southwest Idaho (Allen and Brockway, 1983) where the geology and topography of the long, narrow mountain valley containing the irrigation project promotes rapid reentry and reuse of surface and subsurface return flows within the project boundaries. Irrigation "efficiencies" (or more correctly, stored fractions) of individual farms average only 0.30, but the total project irrigation "efficiency" or consumed fraction is 0.60 due to the reuse of water. The remaining 40% of diversions not consumed by the Little Willow project (i.e., 1 - CF) return to the surface water resource below the irrigation project and are diverted by other downstream water users, making the RF for the basin very high.

The acceptable magnitude for NRF for an individual lawn or field or other use may be different from the system-wide average NRF. Actual NRF may be low for fields or conveyance systems in upper regions of irrigation projects where the opportunity for reentry and reuse of deep percolation, surface runoff, spills and seepage is high. NRF may be high for similarly irrigated fields or conveyance systems near the lower portions of irrigation projects when percolation or runoff directly enters the ocean or brackish water bodies.

Fundamental Questions

There are fundamental questions that one should ask when evaluating the potential impacts of a “water conservation program” on ultimate water savings and impact. These questions are posed from a hydrologic perspective and adherence to the law of conservation of mass.

1. Where does the delivered water come from? (i.e., is it from a stream, ground-water, or lake?) Where is the location of the abstraction?

2. At what time of the year are the abstractions made? (i.e., what does the abstraction “hydrograph” look like?)

3. Where does the nonevaporated component of any applied water go? At what times? (i.e., hydrograph of flows of nonevaporated components)

4. Where does the nonevaporated water reappear as part of a ground-water or surface water system? At what times? In what quantities? With what quality?

5. What happens in the mean time (between the abstraction and the return to the resource)? What are the consequences of this time lag or spatial lag? (i.e., is there local stream dewatering? Are there junior appropriators without water?)

Reasons for Action

1. If there are local instream flow needs that are not being met, then reduce diversions with conservation. However, the conservation program will not create new water for other users outside of the specific system or enterprise. In fact, the conservation program may be an “ET sustenance” program at the expense of downstream users and may reduce downstream flows.

2. If the water use near a saline system (ocean, brackish sink, etc) so that nonevaporated components are impaired or lost via quality change, then a conservation program will have a good hydrologic impact

3. If there are system capacity constraints or if there is large invested treatment (culinary) or energy costs involved, then a conservation program should be considered for local economic reasons and may not result in savings to the water resource

Basic Conservation questions

1. How much of the water abstraction gets consumed or moves beyond local control? (What is the CF?)
2. Who benefits from “wasted” water when it reappears and is recovered?
3. Are current “downstream” users better off by any higher efficiencies created in systems upgradient by a water conservation program? Are the downstream users benefited quality wise?
4. Is other water available by other means?
5. Will conservation make “new” water available to other local or within-system consumptive processes so that the net effect of the conservation is even less water downstream? (this is in the opposite direction intended or purported by many conservation programs, but may be the hydrologic reality).

Conclusions and Recommendations

Irrigation is no longer an endeavor isolated from other users of the fresh water resource. For regional water management, determination of the consumed fraction and reusable fraction is much more relevant than irrigation efficiency, and the use of these fractions may help to eliminate misunderstandings. Emphasizing or promoting conservation program components that increase efficiencies, without strong caution and guidance concerning when and where water can be saved, may harm both users and the economy. Irrigation enterprises contemplating conservation investments must know whether environmental, economic or landscape health and crop yield benefits stemming from a local conservation program are worth the cost. The public and other groups that are interested in freeing up water supplies for new uses must know whether a conservation program will ultimately create new water.

The quantity impact of a given use should be expressed in terms of (a) the fraction of water it directly consumes, (b) the fraction, by virtue of that use, that is rendered unavailable to other users, and (c) the fraction that is returned to the hydrologic system for reuse. It is understood that the hydrology of irrigation projects and their impact on basin-scale hydrology can be complex due to the wide ranges and variations in geology, mineralogy and timing of ground-water flow systems. Therefore, the quantification of Q_{NR} and Q_{RF} may be difficult in some situations. However, the use of simple fractions serves as a good starting point for assembling a clear understanding and definition of the hydrologic destiny of fresh water diversions.

Conservation programs should target reduction of the product ($CF \bullet Q_{Div}$), which requires either reducing Q_{ET} (and thereby potentially reducing crop yields) or reducing Q_{NR}. In reality, many conservation programs target increasing the "irrigation efficiency" (IE), which may be counterproductive, since, as shown in Fig. 1, $IE \bullet Q_{Div}$ contains different terms than are present in $CF \bullet Q_{Div}$. As generally defined (Clemmens et al., 1995), $IE \bullet Q_{Div}$ includes some Q_{RF} and omits some Q_{NR}.

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Comparison of Measured ET from Turfgrass Lysimeters

To Calculated ET During Drought Conditions

Mark A. Crookston[1] and Brent Q. Mecham[2]

Abstract

The Northern Colorado Water Conservancy District (NCWCD) has a network of weather stations throughout its service area to provide reliable crop water use information for both turf irrigation managers and agricultural producers. It also has four small turfgrass weighing lysimeters to compare measured ET to calculated ET. During 2002, Colorado experienced one of its worst droughts and less frequent irrigations were mandated at the location of the lysimeters. The results from comparison of measured ET to calculated ET using the ASCE Standardized Reference Evapotranspiration Equation[3] are presented. The measured ET from the lysimeters agrees well with the ET calculated from weather station data. The knowledge gained is useful in helping irrigation managers make decisions about irrigation practices, including how much water reduction can be achieved without causing severe injury to the turf area in the landscape during periods of drought or water shortages.

Background

The NCWCD constructed four turfgrass weighing lysimeters during the 1998 season. Each lysimeter was 18 inches in diameter and had a 24-inch depth. Three electronic load cells supported each lysimeter. Details on the construction of the lysimeters were presented at the 20th Annual International Irrigation Show of the Irrigation Association[4]. Two lysimeters (LysB and LysC) were filled with a sandy loam soil and two lysimeters (LysA and LysD) were filled with a silty clay soil. All four were established from sod to the same varietal mix of Kentucky bluegrass. It received about three pounds of nitrogen in split applications over the growing season. Mowing occurred weekly at a 3 inch cutting height.

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[3] The ASCE Standardized Reference Evapotranspiration Equation, Environmental and Water Resources Institute of the American Society of Civil Engineers, Standardization of Reference Evapotranspiration Task Committee, December 21, 2001, revised July 9, 2002, Draft

[4] 1999 Proceedings, International Irrigation Show, Irrigation Association

Beginning in 2001, the lysimeters were all installed adjacent to the NCWCD weather station at its former headquarters site in Loveland, Colorado. This site was a 120-ft by 120-ft irrigated plot, surrounded by a hedge of Three-leaf Sumac (Rhus trilobata). This weather station site was in the middle of a field of dry land grasses. The character of the area was urban with office buildings and residences on adjoining properties. Irrigation at the location was accomplished by an automated sprinkler system, typically beginning at 11:00 pm. Seven tipping bucket rain gauges were installed to record rainfall and irrigation information with the top of their collectors flush with the surface of the turf. Their locations were arrayed immediately around and between the four lysimeters. A single tipping bucket beneath each lysimeter was intended to record drainage data but was not fully reliable. Two electronic data loggers were utilized to collect data continuously, recording at 15-minute intervals.

The on-site weather station included sensors for air temperature, relative humidity, rainfall, wind speed, solar radiation and rain. The normal schedule for instrumentation maintenance was to clean, service and re-calibrate each sensor annually or more frequently if needed. Additionally, data loggers were returned to the manufacturer for cold-temperature testing and re-calibration on a five-year or less schedule to insure accuracy and reliability.

The typical growing season starts April 1 and ends October 31 with average grass reference evapotranspiration totaling 33 inches. The time periods selected for this paper were June 24th through July 21st of 2001 and 2002. This four-week period is generally the peak ET time of each season in northeastern Colorado. In addition, data was limited to the time period starting at 5:00 a.m. through 10:00 p.m. Nighttime data was discarded because calculated ET was negligible and it eliminated lysimeter data during periods of irrigation and also when most drainage losses occurred. This simplified and cleaned up the data set.

The 2001 season was characterized by daily watering of the irrigation zone containing the four lysimeters. Lysimeters were well watered during 2001 and soil moisture was consistently maintained near field capacity. In contrast, severe drought conditions precipitated irrigation changes for 2002. Irrigation during the 2002 season was limited to twice weekly watering and soil moisture levels were maintained lower than the previous year. In summary 2001 was representative of well-watered conditions with negligible moisture stress using daily irrigations. The 2002 season represents controlled moisture stress conditions with irrigations occurring every 3 to four days. Turfgrass health and appearance in all lysimeters was excellent both years.

Calculated ET

ET was calculated from the on-site weather station with the ASCE Standardized Reference Evapotranspiration Equation for hourly intervals using both a NCWCD developed computer program and REF-ET[5]. These two Penman-Monteith calculations compared very closely, both hour-by-hour and their 28-day sums as shown in Table 1. However the NCWCD developed program provided

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[5] Reference Evapotranspiration Calculation Software, version 2.01.17, University of Idaho and Dr. Richard G. Allen

hourly ET to the thousandth of an inch while the output from REF-ET was rounded to the hundredth of an inch. This proved significant as calculated peak hourly ET was only 0.034 inches. Consequently, data from the NCWCD in-house program was utilized for the comparison with lysimeter measured ET.

Table 1

	Year	Sum (inches)	Maximum Difference (inches/hour)	Minimum Difference (inches/hour)
REF-ET	**2001**	**6.06**	**n/a**	**n/a**
NCWCD	**2001**	**6.079**	**+0.007**	**-0.007**
REF-ET	**2002**	**6.47**	**n/a**	**n/a**
NCWCD	**2002**	**6.452**	**+0.005**	**-0.007**

Weighing Lysimeter Data

To eliminate data outliers, the weighing lysimeter data was filtered hour-by-hour using upper and lower limits.

Primarily to eliminate outliers from un-measured drainage events, the upper limit was set to 0.05 inches per hour. This upper limit was nearly 50 percent higher than the 0.034 inches per hour maximum calculated by the ASCE Standardized Reference Evapotranspiration Equation. LysC in 2002 especially had trouble with longer than normal drainage delays, often continuing for several hours after irrigation was completed. The effects of delayed drainage could have been minimized with a quicker draining soil medium and/or more reliable operation of the tipping buckets beneath each lysimeter.

Primarily to eliminate outliers caused by under-measured rainfall, a lower limit of -0.005 inches per hour was set. Measurable rainfall occurred five times in 2001 and once in 2002 during the study periods.

The following figures summarize the data obtained from the turfgrass lysimeters for the selected study periods. Figure 1 and Figure 2 show the lysimeter weights during the study periods. Note the higher frequency of irrigations in 2001 versus 2002. Additionally, the lysimeter weights are significantly higher in 2001 than in 2002 indicative of higher soil moisture. Figure 3 and Figure 4 show running sums of lysimeter measured ET versus calculated ET from weather station data during each study period. The lysimeter sums are generally at or above the calculated ET sum in 2001 and below calculated ET in 2002, indicative of more normal soil moisture levels with some controlled water stress.

Figure 1 - Turfgrass Lysimeters at Loveland, CO
June 24 - July 21, 2001

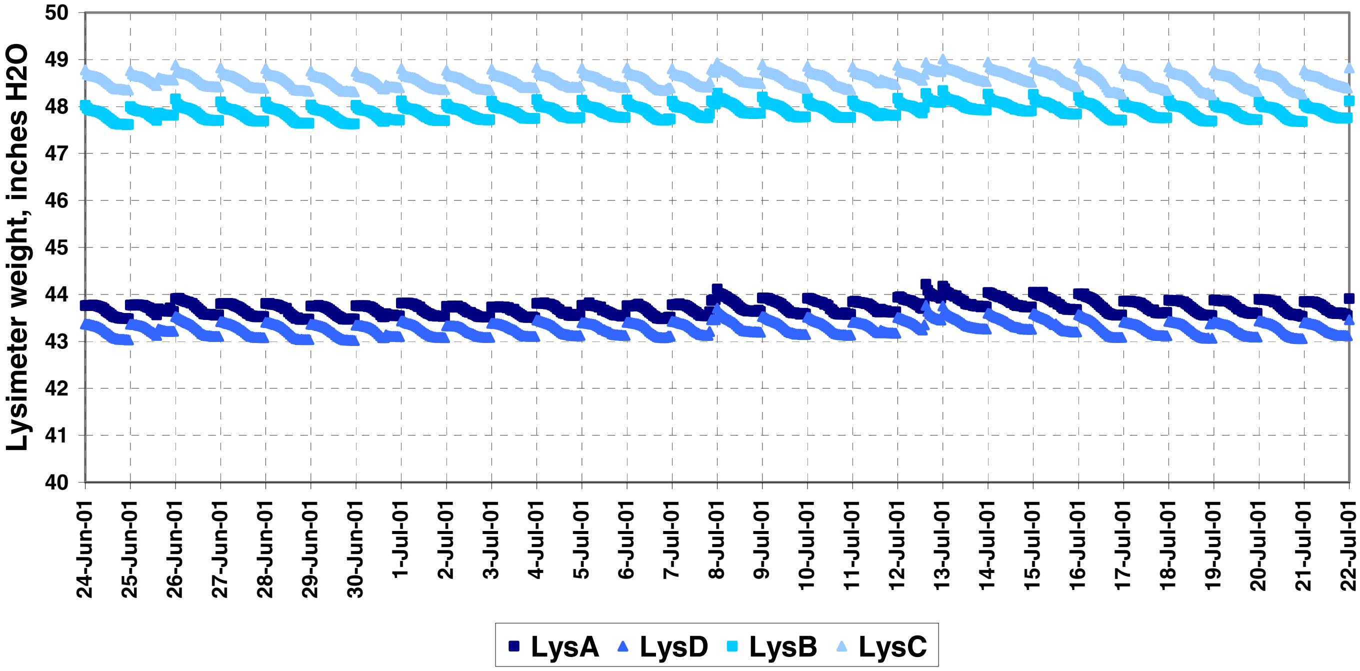


Figure 2 - Turfgrass Lysimeters at Loveland, CO
June 24 - July 21, 2002

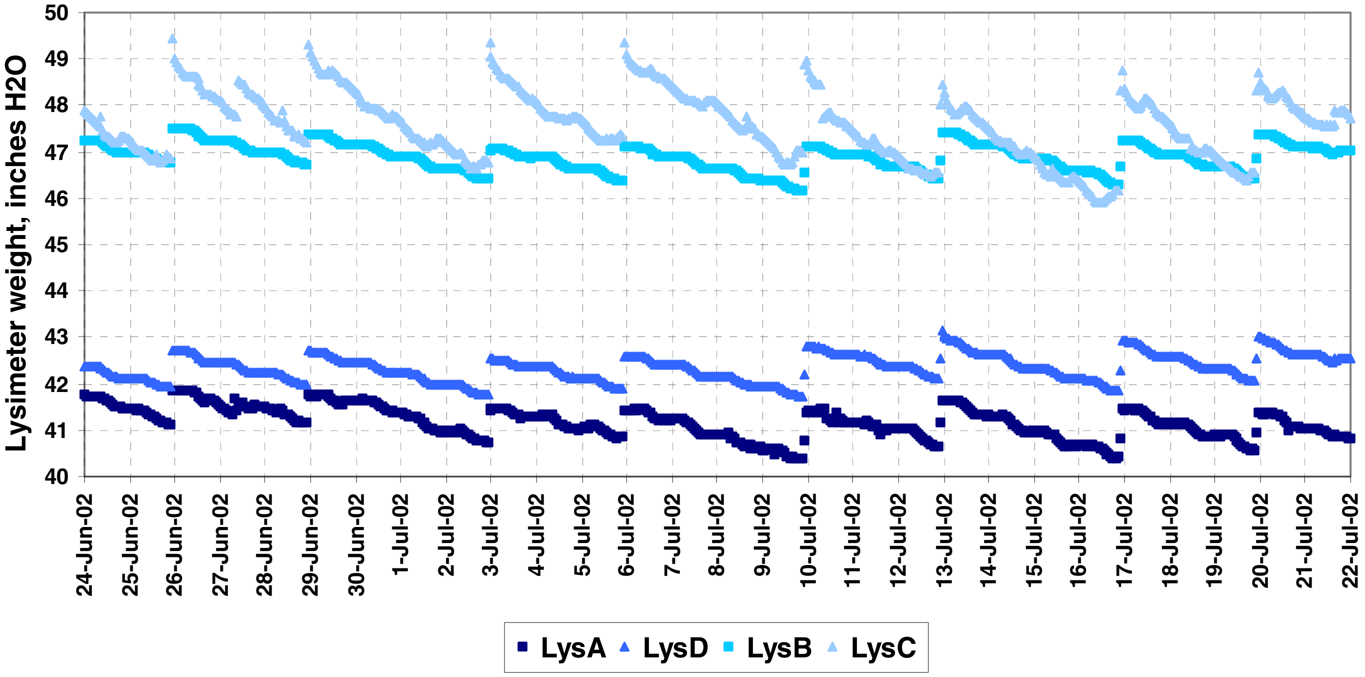


Figure 3 - Turfgrass Lysimeters at Loveland, CO
June 24 - July 21, 2001

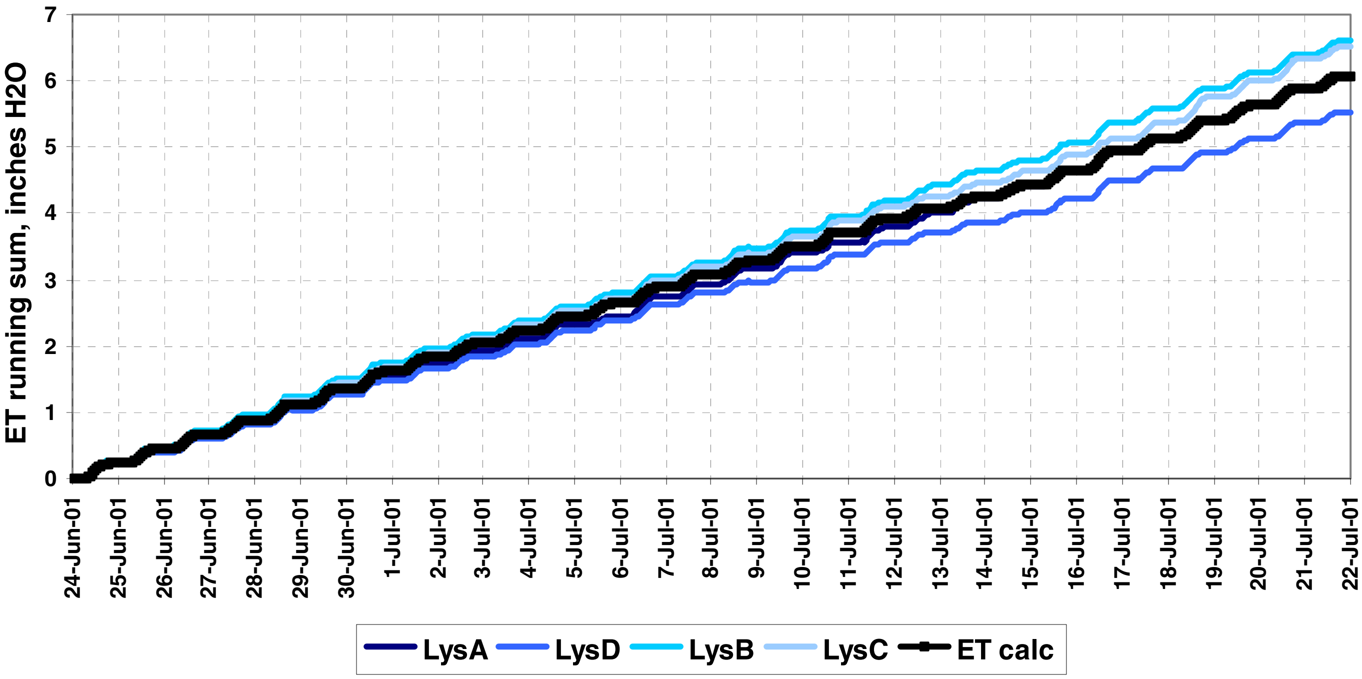
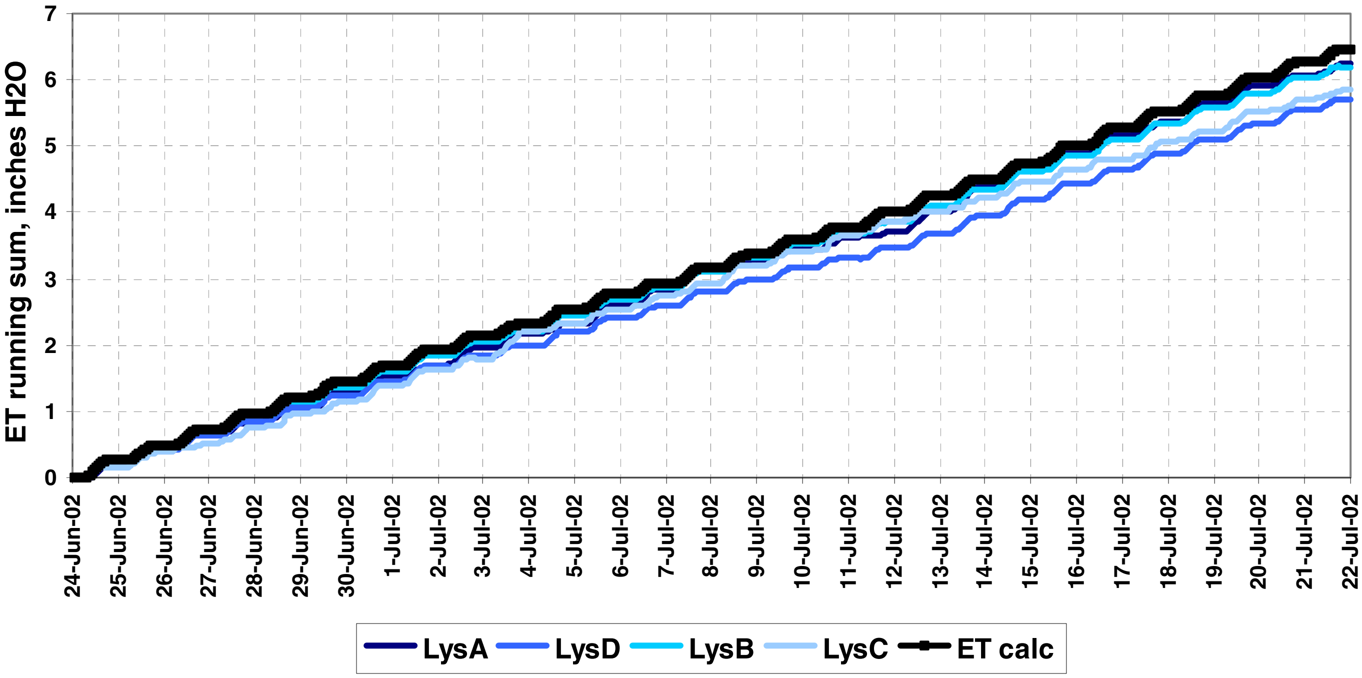


Figure 4 - Turfgrass Lysimeters at Loveland, CO
June 24 - July 21, 2002



Average daily KC ratios were calculated by dividing the measured ET from each lysimeter by the calculated ET from the NCWCD program of the ASCE Standardized Reference Evapotranspiration Equation. The results are summarized in Table 2.

Table 2

	2001 Sum ET (inches)	2001 Avg Daily KC	2002 Sum ET (inches)	2002 Avg Daily KC
Calculated ET	**6.079**	**n/a**	**6.452**	**n/a**
LysA	**6.084**	**1.00**	**6.244**	**0.97**
LysD	**5.526**	**0.91**	**5.705**	**0.88**
LysB	**6.595**	**1.08**	**6.199**	**0.96**
LysC	**6.527**	**1.07**	**5.844**	**0.91**
Avg Lysimeter Difference	**+2%**		**-7%**	

Conclusions

It was anticipated the measured ET from the turfgrass lysimeters would be 90 percent of the ET calculated using the ASCE Standardized Reference Evapotranspiration Equation and data from the adjacent weather station. This reduction was expected due to the lower mowing height. The lysimeter site was cut to 3 inches weekly while the ASCE Standardized Reference Evapotranspiration Equation assumes a turf height of 0.12 meters or nearly 5 inches.

The more frequent irrigation interval and higher soil moisture levels during 2001 resulted in increased measured ET from turfgrass lysimeters. Measured ET was 2 percent higher than calculated ET, a minor difference.

The less frequent irrigations of 2002 and lower soil moisture levels did not appear to significantly decrease the measured ET from the turfgrass lysimeters. Measured ET was 7 percent lower than calculated ET from weather station data, reasonably close to the anticipated 10 percent reduction due to mowing height.

Further analysis of the available data sets from the NCWCD weighing lysimeters should provide additional information regarding turf water use and appropriate irrigation management strategies.

Changing Watering Restrictions Bylaws to Reflect Advancements in Irrigation Technologies:

The City of Calgary as a Case Study

Gillian Skeates, The City of Calgary Waterworks
Denis Gourdeau, The City of Calgary Parks

Abstract

In October 2001, The City of Calgary Waterworks took one of its two municipal water treatment plants offline. Unseasonably warm and dry conditions caused the city's demand for water to remain higher than expected due to ongoing residential landscape watering.

The emergency section of the water utility bylaw was invoked, mandating a ban on all outdoor water use. Recognizing that the existing bylaw primarily targeted the landscape industry, Waterworks undertook a review and update of the bylaw. Waterworks drew from the outdoor water use expertise of Calgary Parks in order to complete the revision. The updated bylaw reflects technological advancements in the irrigation industry and incorporates the Irrigation Association's draft Best Management Practices.

The paper highlights the old bylaw and discusses the processes, evaluations and decisions leading to the establishment of the new bylaw sections and a certified water managed property program for all utility customers.

Background

Calgary is located in the southern part of the province of Alberta, in Canada. It is situated 100 kilometres (60 miles) east of the Rocky Mountains and 300 kilometres (180 miles) north of the border between the United States and Canada. Calgary has a population of approximately 1,000,000 and covers an area of 722 square kilometres (278.5 square miles). The city is a major financial and commercial centre and is home to a variety of industries including Canada's oil and gas industry. Tourism also plays a large role in the economy of Calgary. The climate is semi-arid with an average of 400 millimetres (16 inches) of precipitation annually. The average frost-free period is from May 25 to September 15 (The Calgary Horticultural Society). For all of these reasons, in addition to generally variable weather, outdoor watering in Calgary is important in order to sustain plant life. The City of Calgary Parks has developed over 3000 public landscaped areas, more than 2000 are watered on a regular basis during the summer season.

Calgary has two sources of raw water, both surface sources. The Elbow River serves the Glenmore Water Treatment plant and the Bow River is the source for the Bearspaw Water Treatment Plant. In addition to this, The City of Calgary Waterworks operates 19 finished water storage reservoirs. These reservoirs have a combined holding capacity of 600 Megalitres (158.5 Million US Gallons), which is an appropriate volume for fire protection at any given time, and for acting as a buffer for days when demand outstrips plant production capacity. In 2001, average daily demand for all utility customers was 503 Megalitres (133.1 Million US Gallons) and peak day demand was 850 Megalitres (224.9 Million US Gallons). This is typical of the relationship between average and peak daily demands in Calgary.

Conditions/Situation

In October 2001, the Glenmore Water Treatment Plant was shut down for one month to complete a major infrastructure upgrade. The shutdown had been planned for a period in the fall when daily water demand was expected to be less than the production capacity of the Bearspaw Water Treatment Plant (Voss). An unseasonably warm, dry and long fall resulted in a higher than expected demand for water. Identifying that Bearspaw Water Treatment Plant would not be able to service the entire city at those levels of demand, Waterworks requested that utility customers voluntarily restrict their water use. A drop in demand did occur, however not to the degree that was required. In order to maintain the safety and integrity of the water system, mandatory watering restrictions were implemented from October 12 to November 15, 2001. Prior to this, mandatory restrictions had not been imposed since the early 1960's.

The emergency section of the Water Utility Bylaw did not provide any options for varying levels of restrictions. A total ban on outdoor water use was the only option available. From the bylaw:

> "no person shall water any lawns, garden, yards or grounds or use a hose or other similar device to wash motor vehicles or the exteriors of houses or other buildings or for any other use during [periods of shortage]"(The City of Calgary Bylaw 22M82).

As a result, customers who were still using water for outdoor purposes were adversely affected by these restrictions.

The watering restrictions also impacted The City of Calgary Parks. Their Urban Forestry division could not continue its fall tree-watering program. Trees were still being watered well into October in order to mitigate the impacts of drought-like conditions in the area, and minimize tree losses, which could have been as high as $3,000,000 (CDN), 1 percent of Calgary's tree inventory (Friesen).

Irrigation contractors who were still installing irrigation systems and landscapers who continued to plant in order to fulfill contracts both for The City and for residential and commercial customers could not use outdoor water to test systems or to maintain new plantings. It is estimated there were 50 acres of new landscaping under construction at the time.

Realizing the Need for Change

It was clear to Waterworks that there was a need to develop an updated watering restrictions strategy, communicate with customers in a more integrated fashion, and increase public education around the use of water resources. Furthermore, a member of Calgary's City Council requested that Waterworks consult with customer groups affected by the watering restriction in the fall of 2001, and bring forward amendments to the Water Utility Bylaw with respect to watering restrictions (The City of Calgary Motion NM2001-36). Minimizing the impacts on any one group of customers in the event of future watering restrictions was to be a key outcome of amending the bylaw. Partnering with Calgary Parks would help to identify ways that the irrigation industry has responded to increasingly scarce water and ways that new technology in landscape irrigation could be incorporated into a restrictions strategy.

In the summer of 2002, Waterworks again needed to curb customer demand. The review of the mandatory watering restriction policy was not yet complete and instead of burdening customers with a mandatory restriction per the inequitable existing bylaw, Waterworks requested that customers voluntarily reduce their water use. This experience reinforced the need to have a more flexible mandatory watering restriction strategy to accommodate customers who use water outdoors in the course of operating a business, and those who use highly efficient irrigation systems as well as those who need to water in order to establish new plantings.

Review Process

The review process began by examining watering restriction policies and current literature on the subject from across North America. The findings showed the following similarities among approaches to watering restrictions (Capital Regional District) (The City of Austin Texas):

1. Various stages of restrictions are typical. The stages become increasingly restrictive as conditions worsen. There is generally no expectation that implementation must be in the order of number; the stage that most appropriately provides a solution to the shortage is the stage that is implemented.
2. There are typically exemptions for specific conditions. For example, commercial and industrial customers, who would suffer financial hardship in the event that their water use is restricted, or who rely on the use of water for reasons of health and safety, would be exempt in the earlier stages. The watering of recently installed landscaping is typically exempt, also in earlier stages.
3. There are various methods of imposing watering restrictions. An odd/even-watering schedule is common, though another option is to implement restrictions based on larger geographic zones. For example, a watering restriction according to garbage day pickup, community, quadrant of the city or postal code zone is also commonly used.

Based on the experiences of other municipalities in implementing watering restrictions and subsequent research, there are advantages to the geographic zone watering approach. Zone watering increases the flexibility that the utility has over areas where water use will be restricted, as it breaks the area down into more than two groups and minimizes the number of customers who will water on any given day. It also brings about the desired effect of a reduction in demand. Experience has shown in other municipalities that odd/even-watering can result in increases in demand and artificial peaks (Gregg).

Customer Consultation

Many customers groups were consulted during this investigation into watering restriction amendments. Focus groups and meetings were held to present ideas for a revised approach and to solicit feedback and customer support for the revisions. The specific groups consulted included representatives from Community Associations on behalf of residential customers, the Calgary Horticultural Society, and commercial and industrial customers including representatives from the linen, car wash, and food and beverage industries. Also the Irrigation Association, the Building Owners and Managers Association, the Urban Development Institute, Landscape Alberta Nursery Trades Association and regional customers outside of city limits were consulted. The City of Calgary business units consulted included Parks, Roads, Fire Services and Recreation.

Residential customers stated that information from The City about watering restrictions should be communicated clearly, in a consistent and timely manner using an integrated strategy. Industrial and commercial customers indicated that they would be unable to assist in the event of restrictions, as the cost of using water in their business has already motivated them to be as water efficient as possible. During shortages, landscapers and developers would be willing to help out, although they do require water for the purpose of establishing newly developed sites. When it is possible to provide advance notice of a watering restriction to these customers they would work with Waterworks to mitigate the impact. It is also critical to customer groups that The City of Calgary lead by example, and, when approached, business units were responsive and willing to co-operate. In most cases, internal and external stakeholders were pleased that they had been consulted with during the watering restriction review process.

Calgary Parks wanted some acknowledgement of users who are conservative with their water use throughout the irrigation season. Parks operates 430 locations that have centrally controlled irrigation systems installed, and those technologically advanced systems were treated in the same way as archaic systems that inherently waste water. Parks' centrally controlled irrigation systems use upwards of 44 percent less water than traditional systems (Gourdeau and Marter).

Proposed Changes

The proposed changes to the bylaw, which were approved by Calgary's City Council on September 9, 2002, include a four-staged approach where a schedule is established based on a geographic area. Watering according to postal code prefixes, on a one per seven-day schedule, allows more flexibility, can be used to isolate districts if the problem and restrictions are needed locally, and helps to bring about the desired reduction in demand. It also facilitates by-law enforcement.

The stages of restrictions were developed based on typical Calgary demand patterns, municipal water utility standards, typical Calgary climatic conditions and the Irrigation Association's draft Best Management Practices. They are used to progressively lower the city demand as the stage increased. Stages apply to all customers including residential, non-residential and The City of Calgary business units. Under this approach, specific activities are restricted for various groups of customers. Exemptions are granted for water uses that are required for the purpose of operating a business, or that protect the health and safety of the public.

Table 1: Restricted Activities during Periods of Shortage

Activity	Application Method	Stage One	Stage Two	Stage Three	Stage Four
Watering of gardens, trees and shrubs	Hand-held containers	Allowed	Allowed	Allowed	Complete ban on all activities listed in Activity column. The City of Calgary Waterworks instructs all customers to reduce water consumption inside and outside their homes and businesses.
Watering of gardens, trees and shrubs	Hose connected spring-loaded automatic shut-off devices	Allowed	Allowed	Not Allowed	
Watering of lawns, gardens, trees and shrubs	Irrigation through Tier One Water Managed System with certification from City	Allowed with certificate from City. Must reduce watering programs by 10%	Allowed with certificate from City. Must reduce watering programs by 20%	Allowed with certificate from City. Must reduce watering programs by 30%	
Watering of lawns, gardens, trees and shrubs	Irrigation through Tier Two Water Managed Systems with certification from City	Allowed with certificate from City. Must reduce watering programs by 15%	Allowed with certificate from City. Must reduce watering programs by 25%	Allowed with certificate from City. Must reduce watering programs by 35%	
Watering of New Plantings (sod or seed) with reasonable evidence of recent installation: *Sod within 21 days* *Seed within 45 days*	Any	Allowed	Allowed	Allowed	
Watering of lawns, gardens, trees and shrubs	Irrigation with hose-connected sprinkler or Non Water Managed Irrigation System	Based on postal code prefix One day per week **2 hours per day** within the hours of 4-7 am, 9-11 am or 10-12 pm	Based on postal code prefix One day per week **1 hour per day** within the hours of 4-7 am, 9-11 am or 10-12 pm	Not Allowed	

No customer is allowed to use water in fountains and other decorative or recreational features, throughout the stages of restrictions. Washing down sidewalks, walkways, driveways, exterior building surfaces, or other outdoor surfaces, is not allowed throughout the restrictions. The City of Calgary operations cease non-essential hydrant and main flushing, street and bridge cleaning as well as non-essential washing of city vehicles throughout the restrictions. Any City landscaped property that is watered with a non-water managed irrigation system also ceases with the exception of those that fall into a category of exempted groups or activities (The City of Calgary Bylaw 22M82).

The watering restrictions strategy meets three objectives with respect to exempted groups. Industrial and commercial customers are treated equitably as a group i.e. no particular group is more burdened than another is. Groups that require water for uses that protect the health and safety of the public are exempt and furthermore, groups that would experience financial hardship in the event that their water use was restricted are exempt as well (The City of Calgary OE2002-24).

The following businesses or specific activities are exempt from watering restrictions that would impact water used in their course of doing business, except when a stage 4 water restriction is in effect.

(a) Commercial car or truck wash,
(b) Washing vehicles for health or safety regulatory compliance,
(c) Childcare facilities,
(d) Kennels or animal-care facilities,
(e) Food and beverage establishments,
(f) Nurseries, garden centres, turf and tree farms,
(g) Snow or ice making,
(h) Pesticide or fertilizer application,
(i) Power or window washing enterprises,
(j) Testing irrigation systems,
(k) Integrated Pest Management Test Sites,
(l) Farming operations and
(m) Water use for construction purposes, including grading, compaction and dust control.

These groups are expected to comply with respect to landscaped areas on their property.

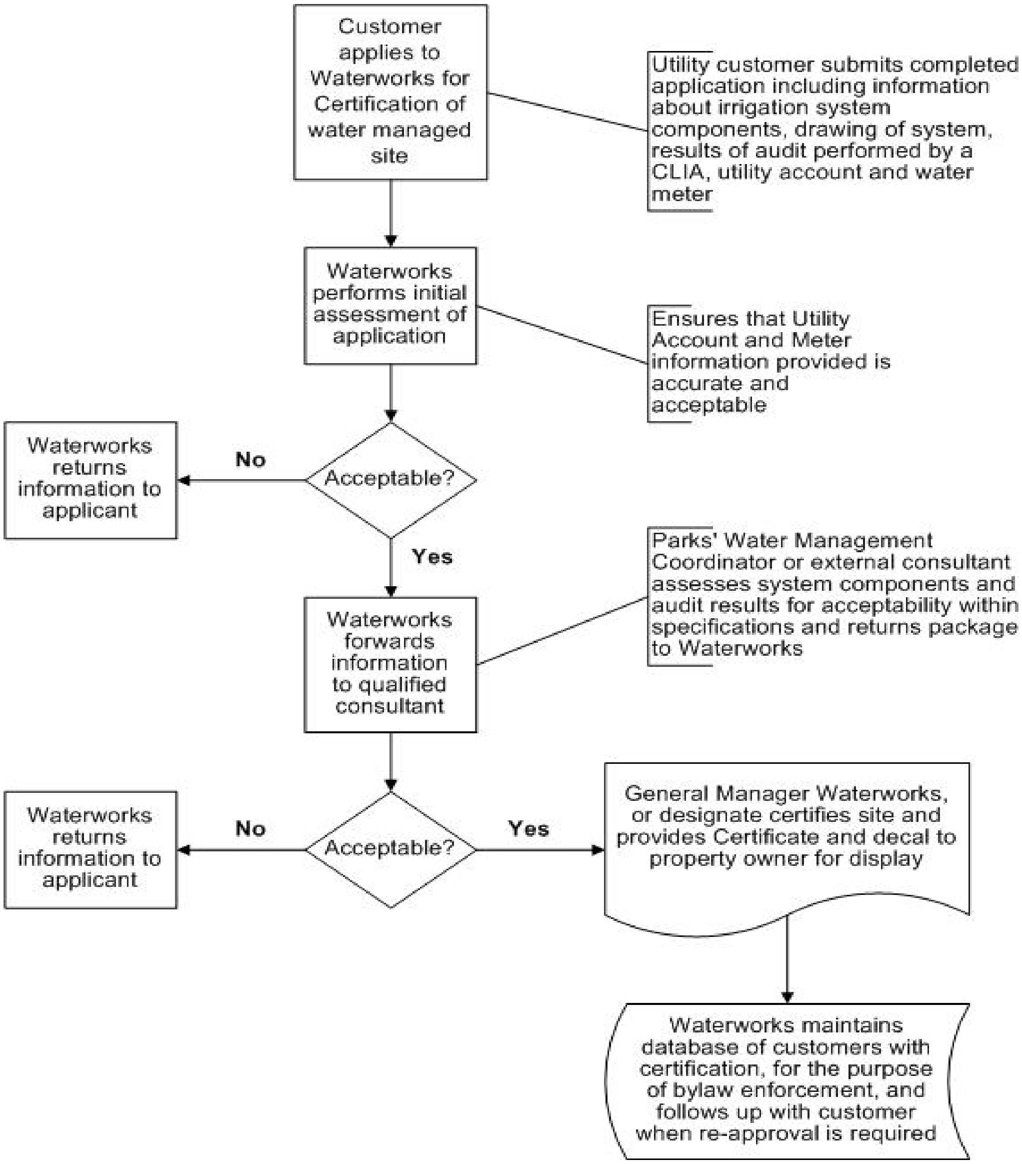
Water Managed Sites

The strategy also includes a benefit for sites that incorporate true water management. Water managed sites use current technology and work towards incorporating weather conditions when applying water to the landscape. They also must comply with a landscape irrigation audit schedule in order to maintain certification of the site. An Irrigation Association Certified Landscape Irrigation Auditor must complete the irrigation audit. When watering restrictions are imposed, water managed sites are required to reduce their watering practices by a designated percentage, which is less restrictive than what non-water managed sites are required to do. This provides a benefit for those property owners who have demonstrated their long-term commitment to water efficiency, by installing and maintaining these systems (The City of Calgary OE2002-34).

All water managed sites must meet the minimum system requirements for installed components. The systems must include a rain switch, a master valve to secure the system if a leak is detected and a metering device. Once all the above requirements are met, water managed sites will fit into one of two tiers of efficiency. A tier one water managed site irrigation system must be centrally controlled, with evapotranspiration based scheduling using real climatic data. A Certified Landscape Irrigation Auditor must audit it for system efficiency and distribution uniformity, prior to certification and once every two years thereafter. A tier two water managed site irrigation system must be automatically controlled with evapotranspiration based irrigation scheduling using historical climatic data and audited for system efficiency and distribution uniformity, prior to certification and annually, by a Certified Landscape Irrigation Auditor (The City of Calgary OE2002-34). Waterworks identified a need to increase the number of Certified Landscape Irrigation Auditors in the market in order to meet the potential demand for irrigation audits in Calgary. To achieve this, the Certified Landscape Irrigation Auditor course was offered in Calgary, in co-operation with the Alberta Chapter of the Irrigation Association, on two occasions with 50 percent of the fees, for eligible registrants, subsidized by Waterworks.

All segments of customers can apply for their properties to be certified as water managed sites and must follow the process below in order to become certified.

Chart 1: Process for Certifying Water Managed Sites



Penalties reflect the severity of the situation, are aligned with other bylaw penalties within The City of Calgary and the penalties for watering restriction violations in other municipalities.

Table 2: Summary of Penalties for Watering Violations

VIOLATION	PENALTY
Stage 1 First offence	$200
Stage 2 First offence	$300
Stage 3 First offence	$400
Any subsequent offence in Stage 1, 2, or 3	$1000
Stage 4 First offence Any subsequent offence	 $500 $2000

Communication Plan

In order to prepare for times of shortage, Waterworks has developed a comprehensive rollout strategy and communication plan. When watering restrictions are required, an integrated approach to communicating with the public is implemented. The goals of the communication plan include:

- To provide customers with the information they need, to comply with the mandatory restriction and ultimately reduce their water demand,
- To maintain public confidence in the operation of the utility during a time of water shortage,
- To inform employees of Waterworks and The City of Calgary that watering restrictions are in place and to ensure that our staff are the most knowledgeable spokespeople,
- To respond effectively to needs for information from all stakeholders – the public, employees, media, and City Council and
- To position The City of Calgary in a leadership role by demonstrating wise use of precious resources.

One of the first steps taken to inform customers of the changes to the watering restriction portion of the bylaw, was to produce a brochure called “Your guide to the watering restrictions bylaw – For Residential Customers” and provide it to all single family residential premises in the city.

The Waterworks website (www.calgary.ca/waterworks) has proven to be a valuable tool to convey messages to customers. In addition, the internal City of Calgary websites are a means of informing employees, both of changes to the existing policy, and changing conditions that might necessitate a mandatory restriction. A list of frequently asked questions, and their respective answers was developed for use on all websites.

Conclusion

After experiencing effects of recent watering restriction events and working through the process of revising the emergency measures section of the Water Utility Bylaw, The City of Calgary has developed an innovative solution, flexible enough to be implemented in emergency situations that may be caused by a variety of conditions.

General acceptance of the new bylaw, and especially the benefit of having certification as a water managed site, has been high. The consultative approach that was taken in these revisions has resulted in greater buy-in from stakeholder groups. Customers acknowledge that The City of Calgary is leading by example through changes in its own operations and water conserving initiatives that Parks and Waterworks have implemented.

The solution balances the needs of utility customers and the business needs of the utility, while incorporating practices that allow for sustained growth of landscaped areas and acknowledge the benefits of advanced technology in irrigation systems. It meets the utility's need with respect to flexibility, demand management and ease of enforcement, while creating equitable stages for all customers and allowing for the protection of landscaping and the city's urban forest areas.

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Controlling Excessive Residential Irrigation – A Case Study

ABSTRACT:

Santa Monica, California is a completely built out city, primarily composed of high-value residential properties. Irrigation water use on many of these properties is three to five times ET. The City is trying a combination of high-tech equipment and regulatory methods to reduce this excessive residential irrigation including:

~ A program to subsidize and encourage the use of weather-based controllers
~ A program to subsidize and encourage the use of water-efficient plants
~ Restrictions on the use of spray irrigation next to hardscape
~ Requirements for on-site retention of runoff
~ Administrative fines imposed by patrolling Code Enforcement Officers

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BACKGROUND:

In 1994 the City of Santa Monica, California declared itself a Sustainable City joining Seattle, Austin, Toronto and others in a dedication to meeting its needs without compromising the ability of future generations to do the same. In 2000, as part of its sustainability programs, the City set a goal to reduce water consumption 20% by 2010. And, in 2002, the City commissioned a far-ranging study of water use resulting in a document called the Water Efficiency Strategic Plan. Research for this plan found that previous conservation measures had largely exhausted the potential for water savings inside single and multifamily dwellings and established new goals for water savings in commercial processes and residential landscaping.

Santa Monica is an eight square mile, completely built-out city. We have no golf courses and virtually all large landscapes are City-owned and irrigated via a central control system operated by experienced irrigation managers. The City is primarily composed of high-value residential properties many of which are owned by absentee landlords. Irrigation control on these properties is poor. It is estimated that the average home is irrigating for an ET of 0.4 in a city where the average daily ET is 0.12.

Beyond the water waste issue of whether too much water is being applied, is the issue of runoff. In 2000, confronted with rising pollution levels in Santa Monica Bay and a determination that urban runoff was a primary contributor, Santa Monica constructed the Santa Monica Urban Runoff Recycling Facility (SMURRF). The SMURRF captures 97% of the City's dry-weather storm drain flow and recycles it for use in irrigation and toilet flushing. On average, the SMURRF intercepts 325,000 gallons per day in dry weather. That's, roughly, one acre-foot per day dumped, literally, in the street.

So where does this water come from? Car washing, a little; gardeners washing down sidewalks, a little more. But our analysis says the big one for Santa Monica is misdirected and misapplied residential irrigation.

THE PROGRAM:
So what are we doing about it? We have a five-part program:

~ Grants and Rebates for Irrigation-Related Improvements
In October of this year the City's Environmental Programs Division established a competitive grant program which gives selected applicants grants up to $20,000 for landscape projects that reduce water use in Santa Monica. $80,000 in grants will be awarded every six months.

~ The City plans to participate in Metropolitan Water District's Turf Replacement Program which is similar to the one currently in place in Las Vegas. However, Santa Monica's program imposes additional requirements for concurrent irrigation system improvements.

~ Ordinance Enforcement
The City has a group of ordinances which prohibit specific forms of water-wasting activity. The one most frequently violated prohibits irrigation overspray onto hardscape and irrigation runoff. In 2002 the City Council increased the fine for violations of this ordinance to $250 for the first offense with increasing fines for subsequent offenses. In April 2003, City Code Enforcement Officers began 4AM to midnight patrols specifically targeting water waste violations. 500 citations were issued in the first five months, most for irrigation-related issues.

~ Weather-Based Irrigation Controllers
The city offers a rebate for the installation of weather-based irrigation controllers. In addition, residents who receive citations for landscape water waste through our enforcement program can make an equivalent investment in a weather-based controller in lieu of paying the fine.

~ Promotion of Water-Efficient Plants & Irrigation
The City operates three demonstration gardens, conducts tours of water-efficient residential gardens and holds workshops for residents and landscape professionals specifically to promote the use of California-friendly plants and efficient irrigation systems.

~ On-site retention of runoff
Santa Monica is one of the first cities in the nation to require runoff retention as part of all new construction, residential and commercial. System requirements are based on the total square-footage of buildings and hardscape on the property. The first 0.75" of any water application to these surfaces must be directed to and retained in an on-site facility. While intended primarily for rainfall events, misdirected irrigation or irrigation runoff to on-site hardscape is also recovered.

HOW'S THE PROGRAM DOING:
Visit us at http://www.santa-monica.org/environment/policy/water/ for an update.

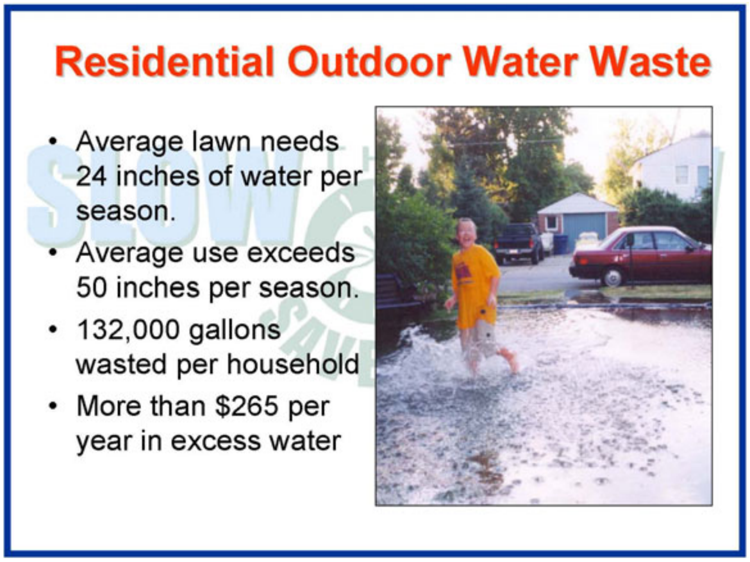
SAVING UTAH WATER IN THE FIFTH YEAR OF DROUGHT

Earl K. Jackson, Professor, Utah State University Extension
Paula Mohadjer, Water Conservation Officer, Jordan Valley Water Conservancy District

ABSTRACT

Utah is the second driest and one of the fastest growing states in the nation. Residents have enjoyed inexpensive water for many years but the current water supply will not meet future demand. In 1999, the “Slow the Flow, Save H2O” water conservation education program was initiated by Jordan Valley Water Conservancy District. TV and radio ads taught correct irrigation scheduling, water wise landscaping, and a toll-free telephone number was established for scheduling a free irrigation water audit at their home. This program is now in its fifth year and irrigation system audits and water use records of over 4,500 residential and 120 large water user sites have been completed by Utah State University Extension interns. The average resident uses twice as much water as a healthy lawn requires. Parks, churches, apartments and schools studied were more wasteful than homeowners, using nearly three times as much water than required. The year following a site evaluation, participants were able to reduce their water use by 20-60%. The turf water requirement (net evapotranspiration, ET) for the Salt Lake City area was confirmed at near 24 inches of water per season at the Demonstration Gardens located at the Jordan Valley Water Conservancy District Headquarters and is the value used for percent waste calculations.

Participants in this six-county Utah study use culinary water for both lawns (67% outdoors) and drinking water (33% indoors). The average distribution uniformity (DU) of the irrigation system was 52% with a precipitation rate (PR) of 1.4 inches per hour for fixed popup spray heads (range of 3.7 inches to 0.7 inch per hour at the 95% confidence level). For rotor heads, the average distribution uniformity was 58% with an average precipitation rate of 0.7 inches (range of 2.3 inches to 0.1 inch per hour). The average root depth of the bluegrass lawns was only 5.6 inches. The average residential hose connection has a water pressure of 73 pounds per square inch with a hose output of 8.2 gallons each minute.

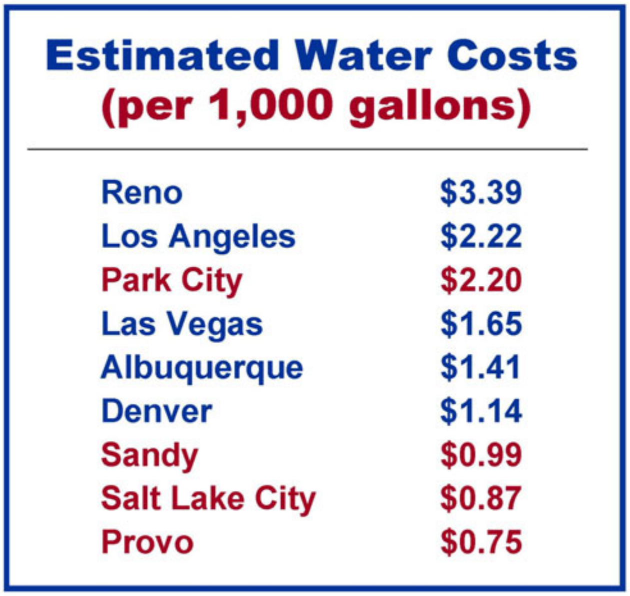


Residential Outdoor Water Waste

- Average lawn needs 24 inches of water per season.
- Average use exceeds 50 inches per season.
- 132,000 gallons wasted per household
- More than $265 per year in excess water

INTRODUCTION

Utah is one of the fastest growing states, while also being the second driest state in the nation. Enough people are added to the population to make a new city the size of Salt Lake City (160,000) about every three years (Utah Division of Water Resources, 2003). It is also the third most urban state in the nation with about 80% of the population living along the Wasatch Mountain Front in six counties (Wahlquist, 1981). With wise planning by the pioneers and several reservoirs completed by the U.S. Bureau of Reclamation (usually with a two year irrigation supply), Utah has enjoyed inexpensive water for many years. The Utah Division of Water Resources indicates that the national average cost per 1000 gallons of culinary water is $1.96 while in Utah it is only $1.15 per 1000 gallons (Utah Division of Water Resources, 2003). The price of water in 2002 varied greatly between cities as shown in the accompanying Table. With cheap water and a pioneer heritage of making the desert bloom, citizens have a passion for green lawns with gardening as the number one hobby in the state. Consequently, residents have developed poor watering habits for the landscape without regard to conservation and the water requirement for healthy turf. Many residents give their lawns a shallow watering every day and have little knowledge of the problems caused by overwatering the landscape. Much of the extra water either runs off the hardscape into the nearest storm drain or percolates down through the soil carrying fertilizers and pesticides into the shallow aquifers. As a result of the population growth, water demand is increasing in a state that has a limited new water supply. The current water supply will not meet future demand of the growing population. Because of this, there is a strong need for citizens to develop a long-term water conservation ethic to assure enough water for future generations and to reduce non-point source water pollution. The **'Slow the Flow, Save H_2O'** water conservation program including the residential water check procedure was designed to help Utah citizens use water more wisely in the landscape.



Estimated Water Costs (per 1,000 gallons)

Reno	$3.39
Los Angeles	$2.22
Park City	$2.20
Las Vegas	$1.65
Albuquerque	$1.41
Denver	$1.14
Sandy	$0.99
Salt Lake City	$0.87
Provo	$0.75

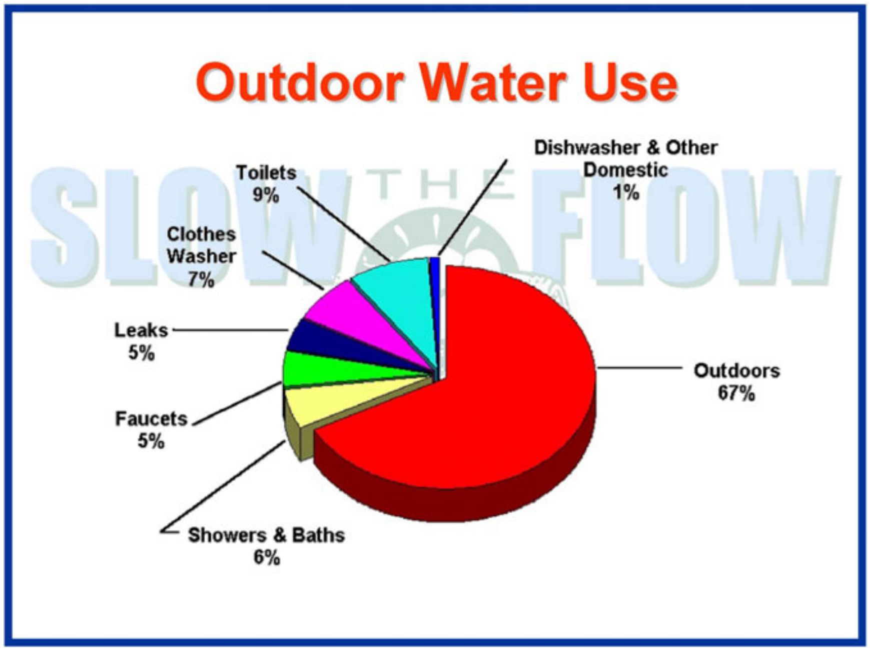
Water Conservation Education

Outdoor water use clearly represents the greatest opportunity for residential water savings. In 1998, the Utah State Legislature passed the "Water Conservation Plan Act" which required all water conservancy districts and water retailers with over 500 service connections to submit water conservation plans to the Utah Division of Water Resources. Most of the conservation plans focus on outdoor water use since about 67% of the culinary water along the Wasatch Front is used in the landscape. In 1999 the Jordan Valley Water Conservancy District initiated the "**Slow the Flow, Save H_2O**" water conservation program in Salt Lake County. They were joined by the Central Utah Water Conservancy District, Salt Lake City Public Utilities and Utah State University Extension in magnifying this program. As part of the overall conservation effort, the Water Check program is a personalized water conservation education program. We found that conservation efforts can be most effective when consumers are well informed from a one-on-one session at their own home.

RESULTS FROM RESIDENTIAL SITES

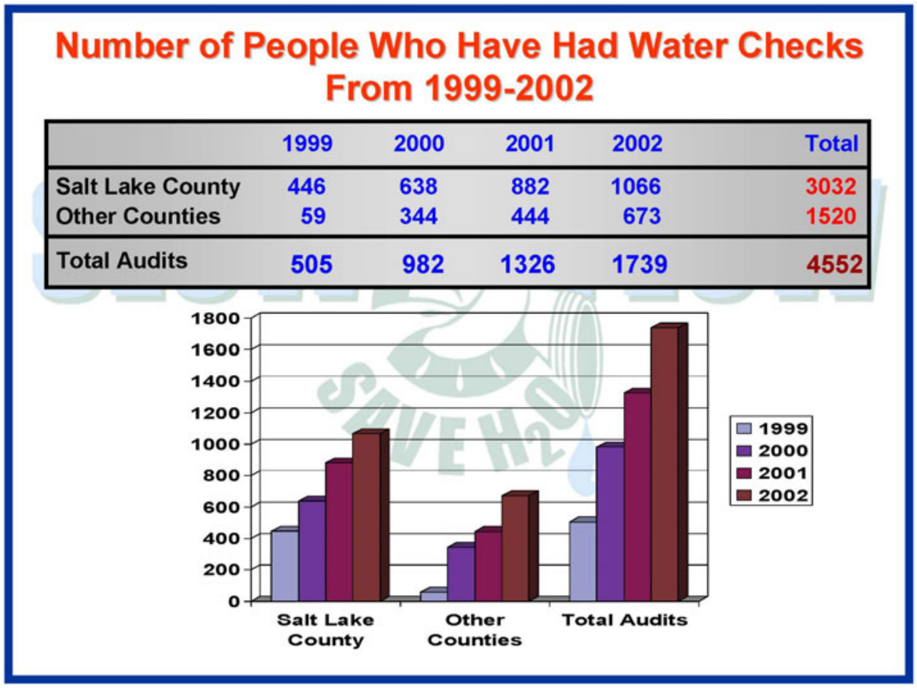
Outdoor Water Use

Most residential properties along the Wasatch Mountain Front use drinking water for irrigating lawns, flowers and other outdoor plants. Many random surveys of residential properties before 1999 indicated that about 50% of a household's water is used outdoors; but these included properties that may not have maintained a green lawn in the back yard. In the water check program where citizens asked for help in maintaining their landscape (front and back), we found that 67% of residential water was used outdoors. The average landscape size in Salt Lake County was 8,555 square feet on a lot of 12,941 square feet. For this size property, the average household used 257,539 gallons of water per year or 706 gallons per day per household. This equates to using 9.48 acre inches per year instead of the commonly number used by the public of one acre foot per year (12 acre inches) for a family of four. With this amount of water used in the landscape the water check program wanted to document the amount of water wasted and concentrate on outdoor water conservation education of the public.



What Is a 'Water Check'?

The **'Slow the Flow, Save H_2O'** water conservation program includes the 'Water Check' program which is a personalized evaluation of the landscape and irrigation system by a trained Utah State University Extension Intern at the request of a home owner. The landscape water evaluation is a free service to the public funded by the Central Utah Water Conservancy District (CUWCD), the Jordan Valley Water Conservancy District ([JVWCD), and their partnering water districts and state Agencies. Appointments are scheduled by calls to a toll free **'Slow the Flow, Save H_2O'** telephone line. Television and radio advertising is professionally created and changed each year. The Water Check


Number of People Who Have Had Water Checks From 1999-2002

	1999	2000	2001	2002	Total
Salt Lake County	446	638	882	1066	3032
Other Counties	59	344	444	673	1520
Total Audits	505	982	1326	1739	4552

educational program is promoting a new ethic of efficient outdoor, culinary water use. A landscape 'Water Check' evaluation of a residential sprinkler system results in a customized watering schedule for the resident. It is a modified water audit following the methods and terminology of the Irrigation Association (The Irrigation Association, 2002). Site evaluation takes about an hour depending upon the lot size and number of irrigation zones. After the initial walk-through, turning on every irrigation zone and evaluating evident problems, a series of tests are conducted on the watering system to determine how much water the system puts out (precipitation rate), the soil type and absorption rate (infiltration rate), and the evenness of the water application (distribution uniformity or efficiency). The resident then receives a personalized lawn watering schedule for the entire growing season. Residents are encouraged to perform routine maintenance on the irrigation system to optimize efficient and uniform operation.

Data for Homeowners

- Root Depth
- Soil Type
- Precipitation Rate
- Distribution Uniformity
- Hose Pressure
- Spray Pressure
- Watering Schedule

Water Checks Accomplished

The water check program has become very popular in Utah. Citizens realize that it is a great bargain to have a person come to their home and evaluate the irrigation system and the landscape resulting in a personalized watering schedule. The water check program was started in Salt Lake County which contains over 45% of Utah's population (Wahlquist, 1981). Since 1999, trained Utah State University Extension Interns have accomplished 4,552 residential water checks in 48 cities within six urban counties. Residential data has been compiled on location, people in household, lot size, irrigated landscape size, hose water pressure, hose water flow, soil texture, root depth, precipitation rate, distribution uniformity, pressure at head (both fixed popup and rotor), and calculated irrigation schedule (Rosenkrantz, 2003).

Inefficient Sprinkler Systems

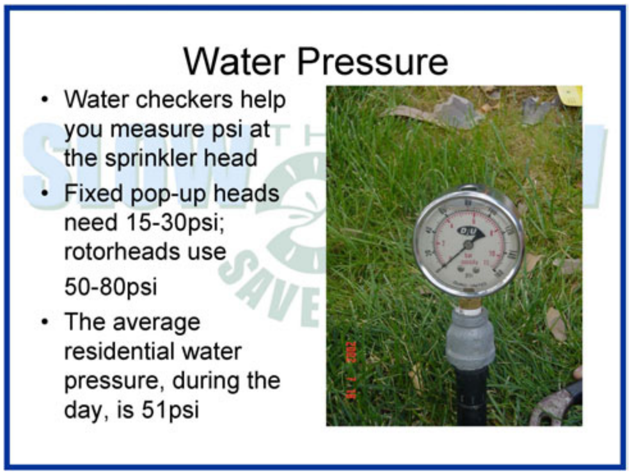
Efficient irrigation is an important water conservation goal. Overwatering not only wastes water, but it weakens and kills more plants than underwatering. Another wasteful practice seen all too often is misapplication of water, resulting in rotted fences and house siding, flooded sidewalks and rivers of water wastefully flowing down gutters. The average distribution uniformity (efficiency) of both fixed popup heads and the larger rotor heads on residential properties is near 56%. A properly installed irrigation system should be a minimum of 70% efficient. An efficient irrigation system is also based on zoning plants with similar water needs together and using the irrigation method that waters each zone most efficiently. Turf and non-turf areas need separate zones because of the differing water needs. As a rule of thumb, shrub areas require about one-half as much water as turf areas.

Data for Water Districts

- Lot Acreage
- Landscape Acreage
- Hardscape Acreage
- Water Use Records
- # of People in Household

High Water Pressure

We found high water pressure to be a major problem in every city and county. Homes with in-ground sprinkler systems should have pressure regulators installed. The average residential water pressure measured during the day at a sprinkler head is 51 pounds per square inch (psi), which is too high for the typical fixed popup sprinkler head and increases misting and evaporation. Nearly all fixed popup sprinkler heads are manufactured for use between 15 and 30 psi of water pressure. With the fixed popup heads, misting and evaporation was evident on most residential systems. On the other hand, the large rotor sprinkler heads usually work best at pressures greater than 60 psi. The average hose connection has a water pressure of 73 pounds per square inch with a hose output of 8.2 gallons each minute. If you use the hose to wash down a driveway for 15 minutes, you have sent 123 gallons of culinary water down the storm drain.

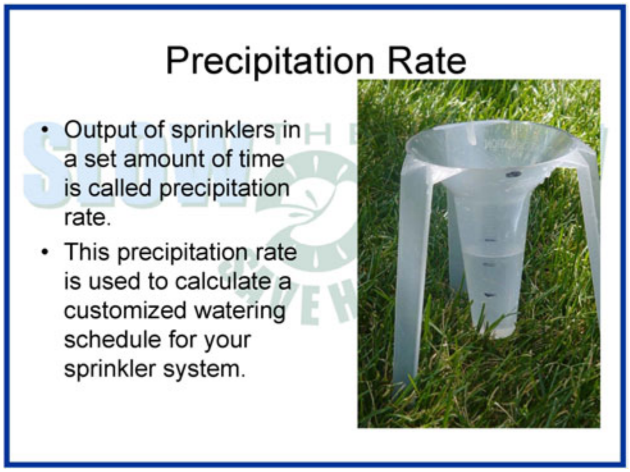


Water Pressure

- Water checkers help you measure psi at the sprinkler head
- Fixed pop-up heads need 15-30psi; rotorheads use 50-80psi
- The average residential water pressure, during the day, is 51psi

Precipitation Rate

Precipitation rate is a measurement of how much water is emitted from a sprinkler head over time. It is measured either in inches of water per hour (like a rain storm) or in gallons per minute. The average residential fixed popup head puts out 1.4 inches of water per hour. We found a range in precipitation rates from 3.7 inches per hour down to 0.7 inch per hour. Most soils can not absorb water at this fast of an application rate. Sprinklers generally apply water faster than a very heavy rain storm (classified by weathermen at 0.5 inches/hour). It should be determined how long it takes each sprinkler zone to put out ½ inch of water. The average system output is 1.4 inches/hour, therefore the sprinklers need to run for 21 minutes on sandy or loam soils to put out ½ inch of water. With a clay soil, split the 21 minutes into three cycles of 7 minutes applied about one hour apart. The larger rotor type heads on the average have a precipitation rate about half (0.7 inches per hour) the rate of fixed popup heads. Citizens are also encouraged to select watering times that maximize availability to the turf (recommended watering between 6 p.m. and 10 a.m.) and minimize evaporation and drift losses from wind and high system pressure. Initial catch cups (cone with metal stand) used in this program were from the Irrigation Association. During the last two years the cones with plastic legs (U.S. Bureau of Reclamation) were used. There was very little variation in water measurement when the two styles of cups were compared side by side as shown in the picture above.



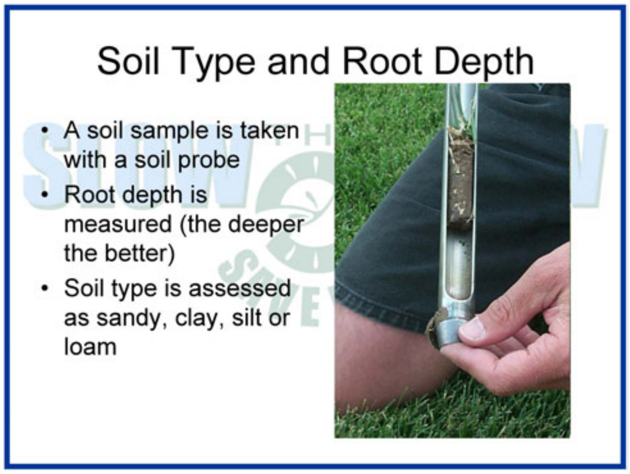
Precipitation Rate

- Output of sprinklers in a set amount of time is called precipitation rate.
- This precipitation rate is used to calculate a customized watering schedule for your sprinkler system.

Households that water with hand-held hoses generally use less water outdoors than households with in-ground sprinkler systems and automatic timers, and tend to water when the grass needs water. They usually use only one sprinkler head at a time so they have less water running onto the hardscape. They also tend to water infrequently and deep into the root zone. We tested twenty different hose-end sprinklers and compared their precipitation rate and distribution uniformity at 50 psi. Most of these sprinkler heads were in the range of 0.2 to 0.5 inches per hour. The homeowner would therefore be able to leave the hose sprinkler on for about an hour to deliver the 0.5 inch of water required in the above watering schedule. We also found most distribution uniformities to be above 60%, with one brand toping the list at 85% efficiency.

Poor Watering Habits

The importance of deep roots should not be overlooked. A shallow watering every day is about the worst thing you can do for your lawn because it keeps the roots short, which then forces watering every day in July and August to keep the lawn from going dormant. Citizens are taught to irrigate turf infrequently and deeply to promote deep healthy root systems. Deep roots have a major impact on water conservation and the ability of turfgrass to grow well in dry weather. Promoting deep rooting gives plants a much larger water reservoir from which to draw. This allows irrigation frequency to be reduced as in the schedule outlined below. With a uniform soil and proper irrigation, a bluegrass lawn should have a root system 12 to 18 inches deep. The average residential lawn has a root system only 5.6 inches deep. The deeper the root system, the more days you can wait between irrigations. The great majority of the residents do not understand the turf water requirement (evapotranspiration, ET) and how to change their timer/controller based on this.

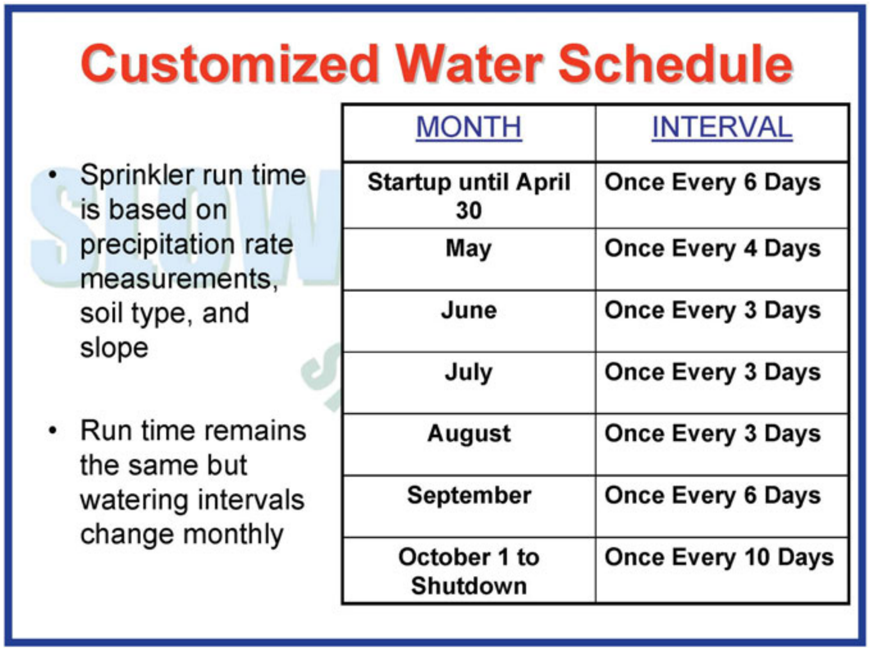


Soil Type and Root Depth

- A soil sample is taken with a soil probe
- Root depth is measured (the deeper the better)
- Soil type is assessed as sandy, clay, silt or loam

Landscape and Soil Types

The type of landscape one has can be an important determinate for the amount of water used outside. Salt Lake County landscapes are about 75% turf or more. Most homeowners have considerable investments made in the design and establishment of home landscaping, and take considerable pride in it. Unfortunately, the typical home owner pays little attention to soil preparation before establishing the landscape. There appears to be no uniform soil texture for a residential yard in Salt Lake Valley. Homes are built on the benches and hills with sandy soils and in the valley where clay-type soils dominate. For soil textures, this study found that 53.2% of the residential sites had clay-type soils, with 34.3% sandy-type soils and only 12.5 % had silty-type soils. A soil that is predominately sand can have water retention problems, while a clay-dominated soil will have problems with water infiltration. As part of the watering schedule, water cycling was promoted for those sites with slopes and/or clay-type soils. The amount of water applied during an irrigation event is dependent upon the application (precipitation) rate and the run time. Where infiltration rates are low, multiple run cycles may be required to avoid excessive runoff. Multiple run cycles should be



Customized Water Schedule

- Sprinkler run time is based on precipitation rate measurements, soil type, and slope
- Run time remains the same but watering intervals change monthly

MONTH	INTERVAL
Startup until April 30	Once Every 6 Days
May	Once Every 4 Days
June	Once Every 3 Days
July	Once Every 3 Days
August	Once Every 3 Days
September	Once Every 6 Days
October 1 to Shutdown	Once Every 10 Days

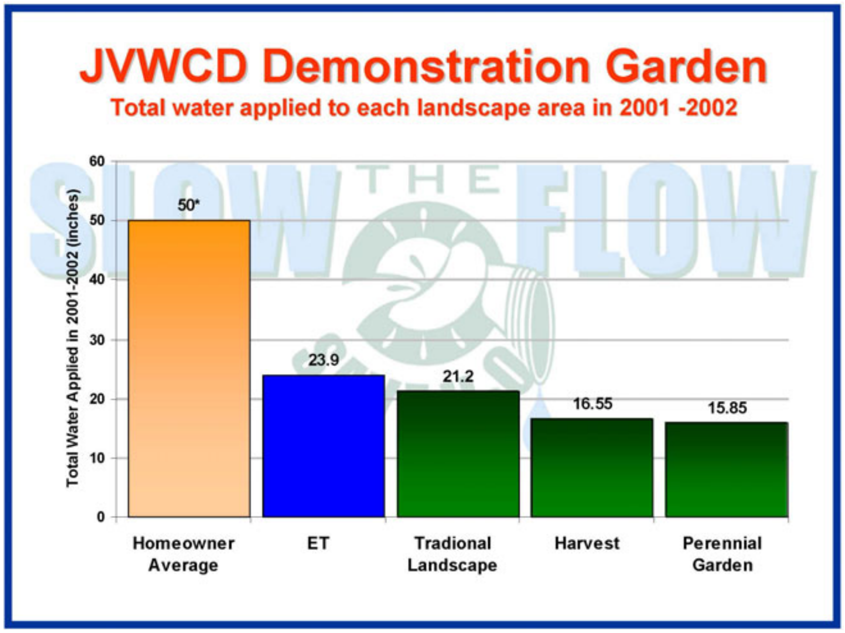
separated by soak times lasting about an hour each. Residents were taught that soils have a modifiable water-holding capacity and practices like aerification and adding amendments help promote deep rooting.

Recommended Watering Schedule

In order to simplify a watering schedule for the homeowners, a schedule was developed based on an interval between deep irrigations (with the accompanying recommendation that at least ½ inch of water be applied at each irrigation) and ET values over the past thirty years. This makes it so that ET calculations need not be made on a daily or weekly basis by the residential participants. Adjusting the timer monthly to better follow this demand curve will save water and money. It took two years of discussions with various agencies and water districts before everyone could agree to the schedule based on interval between irrigations. Now, during the fifth year of drought, all agencies recommend this schedule. If followed, this schedule will bring the homeowner's water use down near the turf water requirement (net ET of 24 inches per growing season). As with any irrigation schedule, there is a need to know the precipitation rate of a zone.

Demonstration Gardens at JVWCD

The Conservation Demonstration Gardens located at the Jordan Valley Water Conservancy District headquarters was designed and built to be an educational tool for the community. The Neighborhood Garden emphasizes proper landscape design, irrigation technologies, and low water use plant selections. The Neighborhood Garden features six themed landscapes demonstrating water efficient practices. Each theme yard has its own water meter that monitors the actual amount of water being used. The challenge was to water efficiently for the typical Utah landscape demonstrating that it is possible to irrigate at the turf evapotranspiration level (ET), called in this paper the 'turf water requirement'. The graph at the right indicates that the Traditional Landscape yard which is mainly bluegrass lawn, can be kept green and healthy with less than 24 inches of water a year. If some of the lawn area is replaced by various types of plants, water use can be reduced significantly.

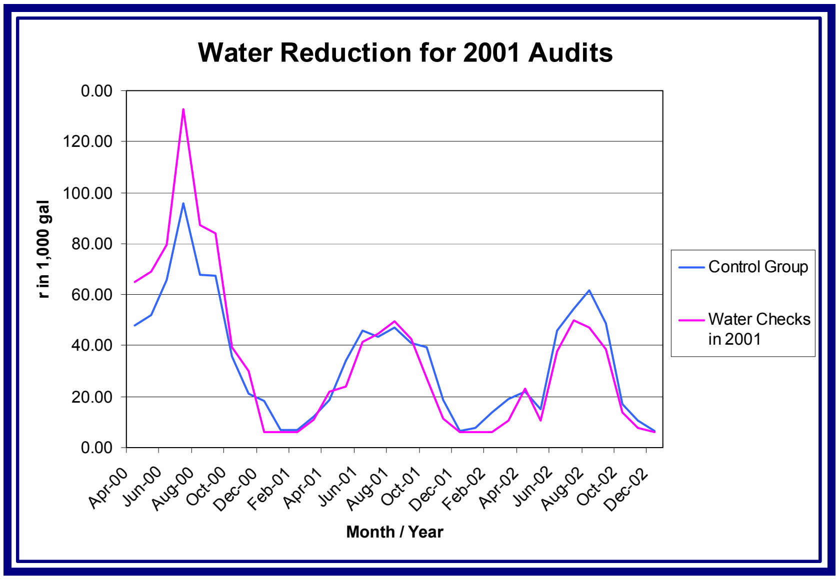


Xeriscape Type Landscapes

A series of workshops was advertised to the public on reducing residential grass areas and establishing areas of native plants - Xeriscape type landscapes. A total of 76 participants from Salt Lake City gave permission for us to follow their water use records (Jackson, 2000). All of them indicated an interest in water conservation both for the lawn and gardens. The average outdoor water use by this group over a five year period was 28.2 inches for the growing season (April 1 through October 15th). With the 30 year average turf water requirement at 24 inches (net ET), the group was only 12% over net ET. Only twelve residents went through the expense of renovating their lawn area into a true Xeriscape landscape. Before the landscape conversion, the group's average was 25.9 inches of water per season indicating irrigation at only 5% over net ET. After the landscape conversion, the average resident reduced their water use by 32% (significantly below the turf water requirement). The average lot size in Salt Lake City is 12,941 square feet with an average landscape area of 8,555 square feet. This average landscape, if all in grass, would require 131,918 gallons of water over the season to maintain a green healthy lawn. At Salt Lake City 2003 prices, the water would cost $415.43. Each of the citizens converting their landscape to a Xeriscape type landscape saved an average of $99.60 per year by saving water.

Culinary Water Waste at Residential Sites

Along the Wasatch Front, a green healthy lawn requires about 24 inches of water either from rain or irrigation, evenly spread out during the growing season which is usually April through about October 15th. Application of irrigation water should follow the recommended irrigation schedule above. The standard is known as the turf water requirement (called ET for evapotranspiration) which is 24.7 inches of water or 15.42 gallons per square foot of turf for the entire growing season. After four years of drought conditions in Utah during 1987 to 1990, we had normal to wet years without any lawn watering restrictions. The average resident applied nearly 57 inches of water to the lawn during 1996 and 1997 (Jackson, E. K. and Hinton A. C. 2002). This is 224% of the standard lawn water requirement (ET = 100%). In 1999 another drought cycle started and 2003 is the fifth year of this cycle. During the last three years, the average resident in this water check program used 50 inches of water or 201% of the standard. This is less water used than during the wet cycle but still very wasteful. This means on the average, residents use twice as much water as the turf-based landscape requires.



Residential Water Savings

The percent of water saved after a residential water check varies by the customer group, the year of the water check and the location along the Wasatch Front. The year following a water check, the group served by Salt Lake City Public Utilities reduced their water use by 12.3%. Those having a water check during 1999 served by the retail section of Jordan Valley Water Conservancy District reduced, (usually with larger landscape size than in Salt Lake City) reduced their water use 28% during 2000. Residents having a water check during 2000 (982) over a three county area had an average reduction of nearly 18% the year following the water check. Those residents who took out part of their front lawn and put in perennial plants or shrubs (a Xeriscape type landscape) reduced their water use by 32% on the average. If each resident in this early study reduced their water use again this year by just 15%, it would save 70,210,140 gallons of water (215 acre feet).

The water reduction graph (on the preceding page) represents the continued drought situation in Utah and the response of the citizens having a water check. The blue line represents a randomly selected residential control group that reduced their water use during 2001 and 2002 from their 2000 level. The red line represents the 882 citizens in Salt Lake County who received a water check by the USU interns during 2001. When we evaluated the water use records the year before the water check (red line in 2000), they used more water than the average citizen (random selection of 300 homes without a water check) represented by the blue line. Those who called the water check hot line for help the following year (2001) used 35% more water during 2000 than the control group. The water check program reached the target high water user resident.

The water check group used slightly less water during 2001 than the control group, but since the group received water checks May through August it was difficult to document an immediate reduction in water use. The drought continued into a fourth year (2002) and all of the residents (water check group and control group) reduced their total water use from the 2000 level. The following year, the water check group used 31% less water than the control group with the major savings coming during July and August. Most of the savings came from paying attention to irrigation scheduling, tuning up the sprinkler system to improve the distribution uniformity, and purchasing more modern controllers with a rain delay devise and cycling their 0.5 inch water application.

Effects of Over Watering a Landscape

The following four photographs document the deterioration of a landscape over a two year period due to inefficient irrigation and over watering. The lawn was green and the trees healthy when the first picture was taken early spring. This homeowner turns on the sprinkler system every morning. Too much water is being applied too quickly (high precipitation rate), causing excessive runoff and shallow rooting of turf. Shallow rooting of turf often results in drought stress during hot summer months. Turf can be "trained" to grow deeper roots. Every irrigation should moisten the soil to a depth of 8 to 12 inches but then given time for the surface to dry. Give your lawn the footprint test; walk across the grass and if your footprints are visible, your grass needs watering. Water starts running off this property 16 minutes after the sprinklers start and continues to run down the gutter for 14 minutes after the sprinklers are turned off. By the end of the season the fertilizer and pesticides used had either been washed off into the storm drain, or washed down through the soil into the ground water.

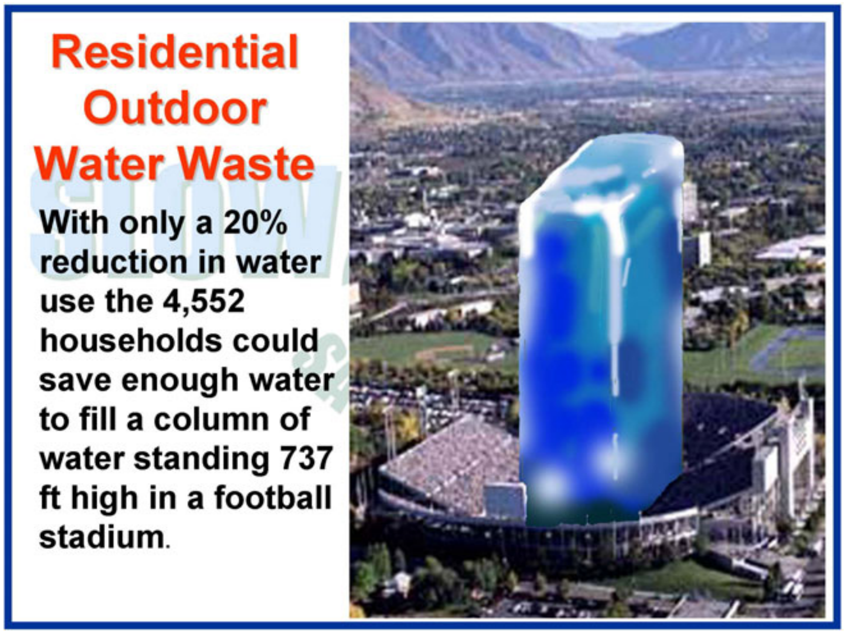
Weeds then invaded the lawn shown in this picture taken the following spring. Weed seeds germinate and establish quickly in an over-watered lawn. When properly irrigated and fertilized, most turf will out-compete weeds. Unsightly bleaching and salt accumulation on wood fences blemish a landscape. Sprinkler heads must be properly adjusted to avoid spraying fences and buildings.

Trees and shrubs have different water requirements than turf. Ideally, sprinkler systems are designed with distinct watering zones for lawn areas versus garden and tree areas to accommodate different water demands. Trees need less frequent irrigation than turf. In this landscape both the pine tree and the maple tree died from over watering. The shrubs then became chlorotic.

Besides plants, other elements of a landscape suffer from improper irrigation. This concrete sidewalk cracked due to frost heave in an overly wet subsoil. The homeowner continued to over water during the late growing season, when watering should be tapered off. Efficient irrigation saves more than water. Proper watering saves money, time, fertilizer, pesticides, effort, and frustration.

Residential Water Savings through the Water Check Education Program

The playing area of a football field is about the size of one acre. The total amount of water that could be saved by the participants in the Water Check program during the past four years, is graphically portrayed as a column of water in a football stadium. If all the participants (4,552) reduced their water use by only 20% next year, the combined water saved would be 737 acre feet.



FUNDING

CENTRAL UTAH WATER CONSERVANCY DISTRICT

[CUWCD, www.cuwcd.com]

The Central Utah Water Conservancy District is a water wholesaler conveying water supplies from high mountain sources to storage facilities and treatment plants. From there, the water is sold and distributed among the many municipal and irrigation water user companies throughout the District. This District represents the citizens of a ten county area in the administration, sale, and delivery of water developed by the federal Central Utah Project. As part of the Central Utah Project Completion Act, the District was given the charge to conserve 49,000 acre-feet of water per year. CUWCD contributes funding to "Slow the Flow, Save H2O" including the Water Check program as part of its continuing commitment to wise and efficient water use.

JORDAN VALLEY WATER CONSERVANCY DISTRICT [JVWCD, www.jvwcd.org]

Jordan Valley Water Conservancy District (JVWCD) is the largest municipal water district in Utah, serving most of Salt Lake County outside of Sandy City and Salt Lake City. JVWCD is primarily a wholesaler of water to other cities and improvement districts within Salt Lake County. The water district recently adopted a new aggressive water conservation goal of reducing per capita water use 25% by 2025. In order to meet this goal, JVWCD has implemented several water conservation programs under the slogan "**Slow the Flow, Save H_2O**". The water check program for both residential and large water use properties is part of this conservation program.

UTAH STATE UNIVERSITY EXTENSION [USU, www.extension.usu.edu]

Our mission is to provide a link between Utah State University and the citizens of Utah that enhances the economic, educational, and environmental quality of life. Extension "Extends Utah State University to You". The genius of the USU Extension Service is embodied in the unique educational delivery system. Our Extension Agents focus on the needs and problem of the people in each county, which make the programs relevant to critical community issues. We specialize in giving people the tools they need to sustain independence by making educated choices. Education is our top priority. We have worked diligently to preserve the enviable reputation of providing unbiased, factual information. USU Extension agents and trained college interns service the 'Water Check Program' for the many water districts and their partners.

METHODS AND MATERIALS

The term 'water check' was used because the general public was wary of the term audit. Water audit methods determining the distribution uniformity, precipitation rate, water pressure, etc. follow the guidelines established by the Irrigation Association (*IA Handbook, 1996*). The guidelines are summarized in the "Landscape Irrigation Auditor Training Manual. The procedures were originally developed by the Irrigation Training and Research Center (ITRC) at California Polytechnic State University as part of their landscape water management program.

Catch cups used during 1999 and 2000 were from ITRC supplied in the water audit kits. Catch cups supplied by the U.S. Bureau of Reclamation were used in the later water checks.

The Utah Division of Water Resources has calculated the Net ET for the past 50 years at a Salt Lake County weather station maintained by Utah State University Extension along with weather records from the Salt Lake City Airport. The average net ET for the area is 22.9 inches of water during the growing season. Our net ET value averaging three weather stations along the Wasatch Front local term for Utah Mountainous area with the urban population) is 24.7 inches. A typical Utah lawn has an irrigation water requirement beginning in mid-April, rises to a peak in July, and then falls rapidly until mid-October. The summer rainfall pattern for the past ten years averages 8.4 inches during the growing season and the rest of the lawn water requirement is through irrigation, usually using culinary water. The turf water requirement used to compare water use in the water check program has been estimated using a 30 year average of three weather stations in Salt Lake County. Data is summarized by county in Research Report 145 by the Utah Agricultural Experiment Station. The average evapotranspiration for turf is calculated at 24.7 inches of water required for the growing season of April 1st through October 15th to maintain a green lawn. Water use in this report compares the residential consumptive use to 24.7 inches.

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Conservation Strategies for Lawn Irrigation During Drought
A Colorado Experience

Brent Q. Mecham[1]
CID, CIC, CLIA, CGIA

Background:

Colorado experienced its worst drought in recorded history during 2002. Based upon tree ring studies conducted by Hydrosphere in Boulder, Colorado the last drought of this magnitude was 1725 in the Boulder Creek watershed. 2002 was a year of extremes with very low snowpack resulting in very low runoff and streamflows, low precipitation and record hot temperatures. Most Colorado municipalities faced difficult choices to stretch limited water resources focusing on restricting or eliminating lawn irrigation. Many had plans with various actions items that were triggered by reservoir storage levels. However, few if any plans had ever been tested to see if the desired results could be achieved and was complicated by a drought that was worse than anyone had ever experienced or planned for.

In Colorado, the annual demand for water in many municipalities is roughly 55-60% for the indoor or base use and the other 40-45% is for outdoor water use. For the typical single-family residence, a little more than half of the water used is for irrigation of lawns and landscapes.

The most successful conservation programs will place an emphasis on both indoor and outdoor water conservation. Indoor conservation should be practiced by the whole community and can be practiced everyday all year long. Outdoor conservation impacts those who have landscapes to maintain and therefore only a portion of the community is involved. The water saved by indoor conservation efforts becomes available to help meet outdoor needs.

It is suggested that a water provider clearly identify how much water needs to be conserved and what portion of that should be realized by restricting lawn watering. The following conservation strategies for lawn watering come with several options to achieve similar results. *It is highly recommended that local communities consult with members of the green industries to determine the strategy that will work best for local circumstances and needs.* Perhaps none of these suggestions will work just right but can become the catalyst to create other ways and ideas to stretch water resources during difficult times.

Effective landscape water management can use current evapotranspiration rates (ET) to create irrigation schedules on a real time basis, but for planning purposes historical ET is used. The following conservation irrigation strategies could be used when water supplies are insufficient to meet the water requirement of the landscape whether the shortage is caused by drought or is a delivery problem. They are based upon the historical ET calculated using the ASCE / EWRI Standardized Penman-Monteith equation.

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Base information:

The following chart lists how ET information is used to determine the amount of water that needs to be applied to the landscape.

Inches of water per month for Northeastern Colorado

	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
ET_o	4.02	4.95	6.17	6.62	5.51	4.05	2.77	34.09
K_c	.90	.90	.90	.90	.90	.90	.90	.90
PWR	3.62	4.46	5.55	5.96	4.96	3.65	2.49	30.69
Rain	2.06	2.32	1.53	1.29	.99	1.30	.67	10.12
Eff. Rain	2.06	1.16	.77	.65	.50	.65	.34	6.13
IWR	**1.95**	**4.13**	**5.98**	**6.64**	**5.58**	**3.75**	**2.69**	**30.72**
Gal / s.f.	1.2	2.6	3.7	4.1	3.5	2.3	1.7	19.1

Where:

ET_o = Historical Grass Reference evapotranspiration for the growing season of April 1 to October 31
K_c = Crop coefficient for cool season turfgrass mowed at 2.5 to 3.0 inches
PWR = Plant Water Requirement PWR = ET_o x K_c
Rain = Historical rainfall
Eff. Rain = Effective rainfall 100% for April, 50% all other months
IWR = Irrigation water requirement IWR = (PWR – Effective Rain) divided by 80% irrigation efficiency

Effective landscape water management will use current ET to create irrigation schedules on a real time basis, but for planning purposes historical ET is used. The following conservation irrigation strategies could be used when water supplies are insufficient to meet the water requirement of the landscape.
Implementing any of these can have an overall impact upon the landscape depending upon the condition and health of the plants and turfgrass when these strategies are implemented. Continuous deficit irrigation over a long period of time will have debilitating effects on the landscape, but when water resources are scarce, there are only a few alternatives and they mostly have negative impacts on landscapes. **When changes in irrigation management are introduced, changes in other horticultural practices must be implemented at the same time**.

The following conservation strategies with accompanying options that could be used to reduce irrigation demand are based on the typical growing season of April 1 to October 31 and assume near normal rainfall. If rain is lacking, the impacts upon the landscape will be even more severe**.** The reduction listed is only for the amount of water reduced that is used for outdoor irrigation. The number in parenthesis is the overall demand reduction based on a typical annual delivery of 60% for indoor usage and 40% for outdoor usage. Water providers should apply their unique demand split (indoor and outdoor usages) to determine potential overall demand reduction.

Conservation Strategy # 1 @10% Landscape irrigation reduction

		Inches	gal/s.f.	Reduction
A)	A 10% reduction in irrigation run times	27.65	17.2	10% (4%)
B)	Irrigation May 1 to Sept 30	26.08	16.2	15% (6%)

A) A voluntary measure without convenient ways to verify if there is compliance.
B) Option B is easier to administrate and verify results. Saves water early & late.

Conservation Strategy # 2 @20% Landscape irrigation reduction

		Inches	gal/s.f.	Reduction
A)	A 20% reduction in irrigation run times	24.58	15.3	20% (8%)
B)	Irrigation Apr 23 to Oct 7 @ 1" per week	24.00	15.0	24% (10%)

A) Hard to verify compliance
B) Option B is easier to administrate. Irrigation schedule remains the same throughout the season. Works well with Twice-A-Week Watering, Quality of the lawn will change over the course of the season looking stressed during the hottest periods.

Conservation Strategy #3 @30% Landscape irrigation reduction

		Inches	gal/s.f.	Reduction
A)	Irrigation May 1 to Sept 30 @ 1" per week	22.00	13.7	28% (12%)
B)	Irrigation May 1 to June 30 @ IR NO IRRIGATION July 1 to July 31 Irrigation Aug 1 to Oct 15 @ IR	20.79	13.0	32% (13%)

A) Levels out distribution, less demand early in the irrigation season when reservoirs are lowest, controller times stay constant; grass will change in appearance and quality during growing season. If the results don't materialize see strategy #4, option B.
B) Better for the plants and turf, but irrigation schedules will change frequently to irrigate properly. This is the biggest challenge to get the changes needed to save the water. A 30 day period of no watering will have minimal impact on the turf overall. It has time to be healthy before the restrictions start and enough time afterwards to revive.

Conservation Strategy #4 @40% Landscape Irrigation reduction

		Inches	gal/s.f.	Reduction
A)	Irrigation May 1 to Oct 15 @ .75" per week	18.00	11.2	43% (17%)
B)	Irrigation May 1 to June 30 @ 1" per week NO IRRIGATION July 1 to July 31 Irrigation Aug 1 to Oct 15 @ 1" per week	18.00	11.2	43% (17%)
C)	Irrigation Apr 15 to June 15 @ IR NO Irrigation June 15 to Aug 15 Irrigation Aug 16 to Oct 31 @ IR	17.33	10.8	44% (18%)

D)	Water diet.			40% (16%)
E)	Water budget			40% (16%)

A) Levels out distribution with less demand in early spring when water supply is uncertain. Controller times are set for the season. Turf will most likely remain in a stressed condition for the entire year. Winter desiccation and death of some lawns the following spring, especially lawns with shallow root systems. Trees and shrubs will not receive sufficient moisture and they will compete with the grass for the moisture.
B) Same base schedule as option A in Conservation Strategy 3 with no watering for the month of July. It has the advantages of option A listed above and could be implemented if the desired reductions were not being achieved in Conservation Strategy 3 using option A. Run times will be consistent throughout the season.
C) Better for the natural growth cycle of the cool season grasses and many trees and shrubs. Healthy lawns and other plants should be able to go 60 days without additional water, but that will be pushing the threshold for many landscapes. Big challenge to communicate effectively the on-off times to water with controller times needed to be changed at least monthly to water to ET. Technology could assist in facilitating customer's need for better irrigation management. Extending irrigation into October will help replenish lost soil moisture and benefit trees and shrubs for the winter months.
D) See Item D in Conservation Strategy #5
E) See Item E in Conservation Strategy #5

Conservation Strategy #5 @50% Landscape Irrigation reduction

		Inches	gal/s.f.	Reduction
A)	Irrigation Apr 15 to Oct 15 @ .50" per week	13.00	8.1	58% (23%)
B)	Irrigation May 1 to June 15 @ 1" per week NO Irrigation June 15 to Aug 15 Irrigation Aug 16 to Sep 30 @ 1" per week	13.00	8.1	58% (23%)
C)	Irrigation Apr 15 to May 31 @ IR NO IRRIGATION June 1 to June 30 1" of irrigation for month of July 1" of irrigation for month of Aug Irrigation Sep 1 to Oct 31 @ IR	13.55	8.4	56% (22%)
D)	Water Diet			50% (20%)
E)	Water Budget			50% (20%)

A) Levels out distribution with less demand in early spring when water supply is uncertain. Controller times are set for the season. Turf will be in a mostly stressed condition for the entire year. Winter desiccation and death of lawns and other landscape plants the following spring will be noticed, especially lawns with shallow root systems. Trees and shrubs will not receive sufficient moisture and they will compete with the grass for the moisture. **Once-A-Week watering** would be a better use of the water to encourage deeper soaking of the water into the root zone rather than Twice-A-Week watering of only .25" per watering.

Frequently most lawns will have a higher weed infestation because the weeds can thrive on less water than what the grass needs to effectively compete against weed growth. Additional hand watering of trees and shrubs will affect overall reduction and in older more established neighborhoods almost all of the water would be used for keeping trees alive.

B) Better for the natural growth cycle of the cool season grasses and many trees and shrubs. Healthy lawns and other plants should be able to go 60 days without additional water, but that will be pushing the threshold for many landscapes. Big challenge to communicate effectively the on-off times to water with controller times needed to be changed at least monthly to water to ET. By the end of the growing season the many plants and lawns will have not recovered sufficiently to go through a dry winter. Technology could assist in facilitating customer's need for better irrigation management. Extending irrigation into October will help replenish lost soil moisture and benefit trees and shrubs for the winter months.

C) A variation on option B. Start irrigation earlier in the season at ET rate to help get turf areas healthier and make available more moisture for trees and shrubs. The "no watering" period can be longer with by adding @ .50" of water every other week for the months of July and August. This becomes very confusing to communicate to customers. This amount of water is critical for better survivability of the grass and is not meant to wake it up out of dormancy. A longer period of watering at ET in the fall when ET rates go down will help get lawns, trees and shrubs more water to go into winter dormancy.

D) Water diet sets a percent reduction based on past historical usage. This needs to be communicated if it is on an annual basis or per billing cycle basis. In either case it is difficult for the customer to know how they are doing without an effective way to measure water usage. Water Diets reward poor irrigation mangers that have been water wasters. They could still overuse water even though they are cutting back on past over usage. Good water managers will have stressed looking landscapes when the goal is an across-the-board reduction by percentage. Compliance is usually achieved by imposing surcharges on the amount of water that exceeds the targeted goal or reduction. Water diets are not sensitive to current weather conditions that create the demand for water.

E) Water budgets treat all landscapes fairly by setting a target amount of water to be used based on size of property. Clearly defining the goal of staying within the budget places the responsibility of wise water management upon the property owner. Rain gauges could be used to measure irrigation application and place the burden on each property manager to track his water usage. It takes time and information to establish a fair and equitable water budget for each property. Water budgets work best when coupled with tiered rate structures that will penalize poor water management with higher rates for excess water used or reward those who are able to live within the water budget. Water budgets would hopefully preclude the need for any other type of watering restriction.

Alternative Conservation Strategies or Management Practices

Water Budgeting

Water budgets or allowances, or allotments are terms used interchangeably to determine the amount of water in gallons or CCF to meet the needs of the landscape. Correctly done it should be fair and equitable for each individual property. One of the major advantages is that the water provider can place the burden of responsibly using the water on the water user. It takes considerable effort on the part of the water provider to set up, but so does enforcing watering restrictions. Water budgeting should remain in place always and not be used during times of water shortages.

Education instead of restrictions

This will focus on conservation education with voluntary efforts by people to reduce water usage both indoors and outdoors. Target amounts of water should be suggested that would focus on small changes in lifestyle or to invest in water saving appliances and technology to aid or facilitate in conserving water.

The overall goal of water savings needed by the utility from the community could be stated with specific suggestions such as the number of gallons per day per person for indoor use or amount of water per week to be applied to the lawn. Restrictions should become guidelines to help minimize peak loads on the distribution system. Keeping the public informed on a very regular basis on how well they are doing with the water resources should improve performance by increasing awareness. This strategy works well with the watering budgeting concept to put the burden of responsible water usage on the user.

Prioritizing the Landscape

This concept involves making a management plan that looks at what parts of the landscape are most important and needs the water and what parts of the landscape can be put into a low-maintenance mode and use the water on the higher priority parts. Sometimes the water is taken from one project and applied to another because of its importance or use. Parks departments or school districts are good examples of looking at all of the opportunities there are and maximizing the water resources for the greatest benefit. This strategy can be combined with any of the above conservation strategies to reduce overall demand for water on the system and allows the manager to make the best decision on how to use the resources instead of the water provider.

Restrictions

The water provider with the hopes of reducing water usage puts restrictions into place, but frequently usage goes up. Restrictions as to which days to water and / or hours to irrigate perhaps help with distribution issues, but they seldom change habits or behavior. Restrictions that are coupled with very strict recommendations for irrigation can achieve the desired goals, but money and time are spent in enforcement. Hoarding & Splurging describes a likely behavior that can occur as people will go into a “panic” mode applying more water than they should going into a “dry” period and then into a “greedy” mode by over-watering when irrigation resumes after the dry down period. This behavior reduces the overall effectiveness of this strategy concept. Each of these scenarios will have an impact on the water provider’s ability to deliver water effectively because of the high demands that will be placed upon the treatment and distribution system.

If restrictions are used, then the following strategy is recommended to achieve results. With any of the restrictions, horticultural considerations are mostly ignored.

Run Times Per Zone

A big debate over how to enforce the watering restrictions comes with a specified number of hours to irrigate or time limits per zone. A specified number of hours is equal for everyone, but does not address needs. Large properties get the same number of hours as little properties. Little properties can probably get by on the number of hours stated, but large property managers are frustrated with insufficient time to water all of their property. By setting a time limit per zone based upon the type of sprinkler head, properties are treated more fairly but there will still be discrepancies because many sprinkler zones will be different than the average used to determine the suggested run times. Because of the variability in individual sprinkler systems and how they perform, the water providers takes on a role of being landscape water manager in addition to water provider.

As a general rule of thumb, sprinkler heads that are fixed spray, meaning they don’t have any rotating or moving parts when the water is being sprayed out apply water at a rate of 1.5” per hour. Sprinkler heads that have moving or rotating parts when the water is coming out have an application rate or precipitation rate of one-half (.50”) inch per hour. One of the biggest mysteries for most people is to know how many minutes to set the sprinkler for to apply a target amount of water. For most landscapes, a half-inch application of water works well. It is a sufficient amount of water for soaking deeply into the root zone. It may need to be divided into a couple of applications on the same watering day to minimize runoff and to improve the infiltration into the soil. To apply a quarter inch of water would require a run time of 10 minutes for spray heads and 30 minutes for rotor-type sprinkler heads. A half-inch application would then require two start times. With twice a week watering two start times per irrigation day would apply one inch of water for the week.

Summary:

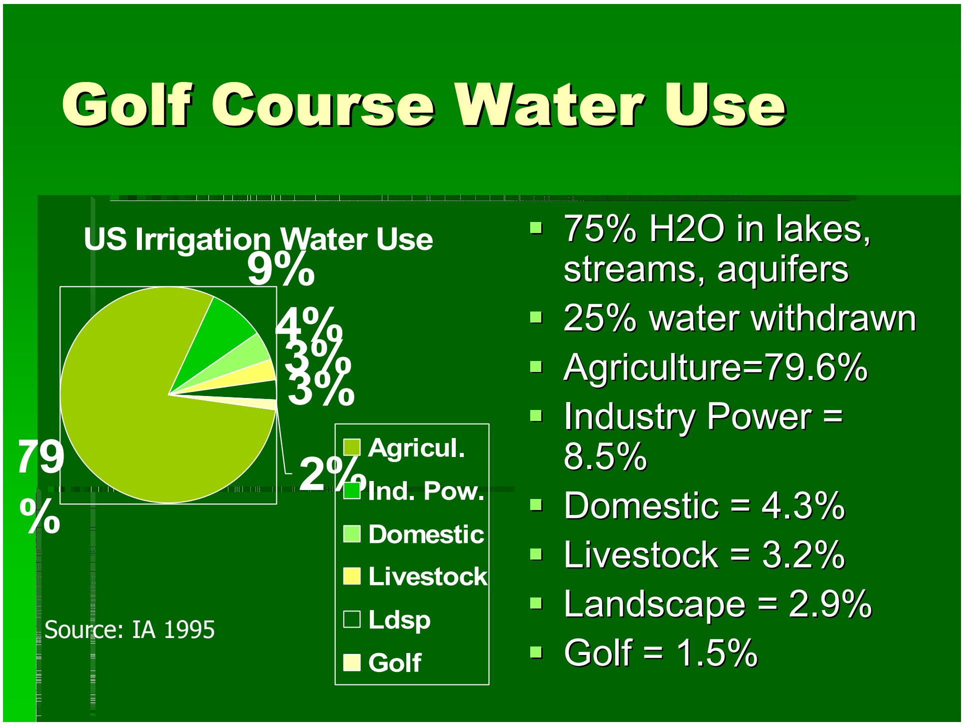
When communities face water shortages, creating a plan with input from green industry leaders can achieve positive results for water savings. The strategies presented can sometimes be combined or they can be a catalyst for creating new strategies that might even be better. There is not one perfect plan for every community because of all the many variables of where the water comes from, who has rights to it, and how it gets delivered. In the end, the best strategy is to allow water purveyors to do what they do best and that is deliver water. Allow customers to manage the water and make them accountable for using it wisely.

Water Conservation Management Case Studies From Southwest Golf Courses – Horticultural and Regulatory Challenges

By David L. Wienecke, USGA Green Section, Southwest Region

Overview - We have spent decades developing procedures for growing high quality turfgrass to meet the demands of discerning golfers. These skills include proper fertilization, mowing, grooming and cultivation, and of course irrigation water. Today due to drought conditions throughout the western United States regulatory agencies and golf courses managers are struggling to find ways to meet the sometimes competing goals of providing water for all users without making it impossible to irrigate golf courses. This paper will illustrate the regulatory and horticultural challenges and solutions seen in golf course irrigation.

Terminology - Based on surveys conducted by the Irrigation Association golf course turfgrass irrigation constitute the smallest portion of irrigation water used in the United States (i.e. 1.5% of the total compared to 79.6% of the total used for Agriculture).



Golf Course Water Use

Source: IA 1995

- 75% H2O in lakes, streams, aquifers
- 25% water withdrawn
- Agriculture=79.6%
- Industry Power = 8.5%
- Domestic = 4.3%
- Livestock = 3.2%
- Landscape = 2.9%
- Golf = 1.5%

Where do these numbers come from? How do they compare to the amount of water the turfgrass needs? What is the difference between the regulatory allotments for golf course turf and actual turf requirements?

Many states use Acre Feet (i.e. amount of water needed to cover 1 Acre (i.e. 43,560 square feet) 1 foot deep) measurements to calculate irrigation allotments. 1 Acre Foot = 32,585.78 gallons. Typical golf course irrigation systems will use 150,000 to 250,000 gallons of water per 24 hour period for 85 Acres of turf. Annual irrigation allotments are based on the square feet or acreage of irrigated turf. Using one 18 hole Arizona golf course with 147 irrigated acres (landscape and turfgrass) as an example, the Arizona Department of Water Resources (ADWR) allocates 690.68 Acre Feet of annual irrigation water, (i.e. 0.213 Acre Feet per Acre). Irrigation systems and ET calculations apply precipitation rates in inches. Pumps apply water in gallons.

Modern golf course irrigation systems use evapotranspirational (ET) models programmed into on site weather station integrated computers that regulate the amount of irrigation applied. The goal of these controllers is to provide only the amount of water needed by the plant to replace water lost the preceding 24 hour period by evaporation from the soil and by transpiration from the plant leaves. The water manager calculated the % of ET that will be used to apply water each night for maintaining plant health. The ET and pump models use gallons of water and inches of precipitation measurements to apply the irrigation water.

Average monthly rainfall minus the potential Turf ET surplus or deficit*

Location	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
PHX, AZ	0	-0.4	-1.8	-3.8	-6.3	-8.2	-9.1	-7.4	-5.9	-3.5	-1.3	-0.2	-47.9
LAX, CA	2.3	2.4	0.5	-1.5	-3.8	-4.9	-6.1	-5.6	-4.3	-2.5	-0.6	2.0	-22.1
SFO, CA	3.3	2.7	0.9	-1.2	-3.1	-4.3	-5.0	-4.5	-3.7	-1.9	0.2	3.0	-13.6
DEN, CO	0.5	0.6	1.0	0.7	0.3	-1.8	-2.7	-2.3	-1.3	-0.3	0.6	0.5	-4.2
LVG, NV	0	-0.3	-1.5	-3.2	-5.4	-7.4	-8.8	-7.6	-5.4	-2.9	-1.0	-0.2	-43.5
ABQ, NM	0	-0.2	-1.0	-2.3	-4.0	-5.7	-5.7	-4.8	-3.2	-1.7	-0.6	0	-29.2
PDX, OR	7.3	5.5	4.6	1.1	-0.6	-2.0	-4.7	-3.9	-1.5	2.9	6.4	8.1	23.2
SLC, UT	1.6	1.2	0.8	-0.2	-2.0	-4.0	-6.3	-5.2	-3.0	-0.5	0.8	1.3	-15.5
SEA, WA	5.2	3.9	2.8	0.4	-1.4	-2.4	-4.1	-3.4	-1.1	2.3	4.8	5.8	12.8

Source: Rainfall-ET Data. The Toro Co. Minneapolis, MN, USA. 1966, 63 pp.
*Potential turf ET rate calculated from modified Blaney-Criddle formula.

Irrigation application uniformity (Coefficient of Uniformity or CU) is calculated to determine the precision of the water distribution (based on nozzle performance, sprinkler spacing, pipe and head pressure, sprinkler turning speed, etc.). Using the golf course example above, CU is calculated yearly and ranges from 77% to 85%.

Best Management Practices – Now that we have covered terminology we can look at specific case histories from golf courses and regulatory agencies to see how these factors function in the real world.

- Increasing the CU is the best way to reduce water usage by reducing waste water and increasing precision of irrigation application. The catch can test is the best way to accomplish this. (Cite water savings studies Center for Irrigation Technology, CSU Fresno).
- Individual head control (VIH) provides increased precision compared to block controlled sprinklers (i.e. 2 to 10 sprinklers controlled concurrently per station). Comparing VIH sprinkler irrigation to block systems shows 7,458,885 gallons of used Jan-Jul with VIH compared to 10,382,399 gallons used Jan-Jul with block system controls (i.e. Block control sprinklers used 2,923,514 gallons more in the same time within the same city, a 28.16% water savings). Individual sprinkler control also provides better turf quality with firmer playing conditions.
- Ensuring sprinkler spacing, head pressure, and nozzle performance is consistent with design specifications is another way to ensure precision application.
- Installation of part circle sprinklers to reduce excess irrigation of naturalized areas can save significant irrigation water and improve turf quality. (Desert Forest e.g.).
- Golf courses in Arizona, California, and Nevada are not overseeding to save water. The city of Phoenix golf courses stopped overseeding last year and golf courses in Las Vegas are considering it due to water allocation restrictions.
- Golf courses throughout Colorado were required to stop irrigation all together due to three years of successive drought and low snow fall levels. (E.g. City of Denver, City of Aurora, City of Pueblo, City of Golden)
- Use of drought tolerant turf reduces water requirements. Perennial ryegrass requires more irrigation water to stay green compared to bermudagrass in a warm season climate. (i.e. Comparison of ET°)
- E.g. of core aeration, wetting agents, sand topdressing, pre-wetting, turf growth regulators, mowing height, composting as water conservation procedures.
- Salt affected turf management issues – TDS, bicarbonates, sodium. Leaching requires 5 to 15% more water to grow healthy turf. The advantages and disadvantages of effluent reclaimed compared to well or potable water.
- Regulatory Updates: Las Vegas (NDWR), Arizona (ADWR), California (CDWR).

Conclusion – Based on observations from golf course irrigation throughout the west there are serious future challenges ahead. Regulatory agencies and golf course turf managers need to collaborate and learn about each other’s goals, needs and perspectives to develop workable plans for the future. Planning agencies, reclaimed and water resource managers need to work with industry to develop realistic management guidelines. Research must continue to help us find the water and cultural limits for turf management and find ways to maintain optimum precision and water conservation from our irrigation systems.

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Using Recycled Water in Drip Irrigation in Commercial and Residential Applications

Water supplies are under assault from all fronts. The quality of ground is getting progressively worse. Contamination of water supplies limits the usability water. The availability of water fluctuates depending on the areas of the country, rainfall, etc. New sources of water are needed where groundwater supplies are lacking. Water districts and states are involved in court cases spread out over many years to determine the ownership and usage of water sources. Thus, using recycled water and dispersing it in a safe manner has become even more imperative. Technology has been developed that is using water from waste plants and septic systems. This water is used for commercial, industrial, and residential uses. Water quality is a vital issue whether in small (200-400 gpd) to large systems using 10-15 million gpd. Using recycled water is becoming more necessary.

Drip irrigation is one of the methods of irrigation for tree farms, row crops, nurseries, and other applications. Drip irrigation may become the preferred method for discharging the water into landscape.

Before using recycled water several issues must be addressed. (1) Preparing the water for discharge and use meeting or surpassing government guidelines (2) filtration (3) controlling the level of pathogens and organic growths, and (4) keeping drip irrigation lines open to keep the flow consistent and continuous.

As the population grows, the volume of water in waste plants increases and this increase results in a reduction of water quality effluent from these plants. While growth in population increases the revenue, the increase in water throughput can result in a poorer water quality which has had detrimental effect on recycled water being used. There are various types of processes in waste treatment plants, but when the throughput is increased beyond the capacity of the plant, water quality suffers.

Filtration for recycled water should always consider sand media filters. Problems generally encountered with recycled water are organic contamination and the rich nutrient base. Sand filters have proven to be better at trapping and removing organic contamination. Filtration should be in the range of 100 - 200 mesh or 80 to 165 microns.

Organic materials are the major threat in using recycled water in irrigation systems. Algae, bacteria, viruses, molds, mildews, slimes, and other organics can grow within the system. Drip tubes can easily plug with organic matter. Another situation occurs when a small piece of organic matter snags somewhere in a valve, fitting, emitter, or sprinkler. The organic matter by itself may not be large enough to be a problem. But soon another piece comes along and gets caught in the first. Then a very small grain of sand or organic particle that would normally have passed through the system without problems becomes caught in the organic matter. Soon a large build-up of crud forms and the flow is blocked. Have you ever had the hose on your vacuum cleaner clog up with a wad of hair, small objects, and dirt? Each one of those objects went into the hose, so they should have made it through to the canister. But they didn't because they all got caught together. The same thing happens in your irrigation system.

Using recycled water in irrigation has increased the amount of organic growths in they system. This is due to the higher volume of organics and the rich nutrient base in the water. Chlorine, UV, and ozone have been used in these waste plants in an attempt to disinfect the water. They have all been poor in removing and preventing organic growths. Using the same processes in the field will not provide any better results. Products have been developed for cleaning and removing organics from the irrigation system and these products can be injected into a system to prevent growths from forming in the first place. Dosages vary depending on the quality of water, volume, amount of contamination, temperature, layout of system, pH, and other factors.

Efforts have been made to treat the water mechanically to remove more of the nutrients before being introduced into the irrigation system. Softening, RO, and other processes have proven to be costly. The disposal of the backwash, the use of brine solutions, and acid and austic regeneration solutions present their own problems. Some growers have tried using several different types of filtration in the same field. This has worked fairly well with ground water, but not with recycled water.

State guidelines vary from state to state and are constantly change due to federal, state, and local regulations being updated and revised. Trends in the industry have changed from adding ammonia compounds in combination with chlorine to discharge water to today’s standard of chlorinating and then de-chlorinating before discharge. Disinfection methods have changed and are implemented in the field. Some methods of disinfection work well in the laboratory and then perform poorly in the field.

In some areas of the country, fish are not even considered safe to eat that are caught in rivers, ponds, and oceans. Fish have sought farther off shore. Off shore fishing boats now go 25 to 50 miles offshore in search of fish. There may be a link with lower water quality of discharge from waste treatment plants.

With the poorer water quality, recycled water is more of a problem to use. More treatment is required in the field to make the water usable. There are more problems with drip lines plugging. When the drip lines plug, the pressure increases and the volume of output decreases.

Case Study Large Tree Farm

Results using recycled water have been promising as a method of discharging waste water into the ground and restoring the aquifer. The plant is under federal mandate to begin eliminating discharge into the local river. This tree farm is to begin to reduce the discharge into the river and begin alternative disposal method.

This tree farm irrigates 720 acres of cottonwood and sycamore trees. These trees were selected because of the large volume of water that the trees can consume and their ability to withstand the water discharged. Trees are grown with the idea of selling the wood after 7 to 10 years. The agency is hoping to break even with the project (cover costs with the proceeds from the sale of the timber). The tree farm has been in operation for four years. Trees now range in height from 10 to 25 feet tall, average circumference of tree is 6 to 8 inches. Trees have proven to be hardy, resistant to disease and less than 3 % have died in four years.

Tree Farm Data
1,250 gpm flow rate
720 acres total
16 zones of approximate equal size
2 zones water per day for 24 hours, then rotated to other zones
90 acres per day irrigated, approximate
1,800,000 gals per day of irrigation water for 90 acres
20,000 gals per acre per day

Water for this tree farm is from a regional waste treatment plant. Currently irrigating with 1.8 mgpd and will eventually grow to 5.6 mgpd of waste water recycling. The water for the tree farm is chlorinated at 5 to 6 ppm at the plant, fed through a sand filter, then pumped six miles to the receiving plant. The chlorine level drops to 0.3 to 1.5 ppm on the way to the receiving station. De-chlorination occurs before being sent to the tree farm.

This tree farm has run exceptionally well for the four years of operation. Maintenance of equipment has been low and after the initial cost of set up, costs of operating the system is low with few employees required to maintain the system.

Results have been very good and have been what was as proposed by the engineering firm that designed the project. Organic material is starting to build up and become a problem. Algae is visible on the ground where the drippers are open. The majority of drippers are open and working properly although 30% and 40% are blocked with organic growths. When the end of the drip tubes are opened, a black liquid is expelled that has a putrid odor. This liquid is a combination of fecal material and organic growths. In order to continue the tree farm in the future, removal of the organics with a product such as Line Blaster will be necessary. If not, the drip lines will need to be replaced within the next year. The cost of replacing the drip lines is tenfold higher than cleaning up the existing system. Studies are ongoing and recommendations are being made to clean up the system. The agency is weighing costs and treatment options. Results will be reported as ongoing treatments are implemented.

Case Study Small Package Plant

The small package plant was designed to handle a maximum of 25,000 gpd waste stream from a golf and country club restaurant, clubhouse, and office building. Plant throughput is currently 6,000 to 8,000 gpd. Discharge up to 25,000 gallons per day from the holding pond. The holding pond before discharge can contain up to 3.8 million gallons of water. Currently holding 1.4 million gallons in holding pond. Plant has Ultra Violet (UV) light installed as disinfection before final discharge. The plant has excellent controls and the operator is very well trained in handling the plant.

The final stage before discharge to a holding pond is the mixing chamber. The mixing chamber measures 8' x 12' x 20'. UV light is employed as the final step before discharge to the holding pond.

The holding pond is 65' x 480' and depth varies between 6 and 12 feet. At the far end of the pond, the discharge valve is on the bottom of the pond. Discharge is to drip lines buried in the ground in a wooded are along side of the golf course. There are 8 zones and discharge to the different zones is controlled by timer. The drip lines used contain a “disinfection” lining that is claimed to prevent the growth of organics.

This small package plant has performed fairly well as designed, but several problems have arisen that need to be addressed. In the mixing chamber, a large mass of algae had coated the walls, floor, vessels, equipment, piping, etc. Visibility in the chamber was only to a depth 2 to 4 ft. as the algae’s color tinted the water a bright green. The mass had grown so large that at times the UV bulbs were covered with algae that light was not able to be transmitted into the water. The bulbs had to be physically cleaned to remove the build up. Chlorine tablets were added to the chamber to control the algae. Tubes were installed in the inlet flow that would slowly dissolve the tablets. This was still ineffective and did not control the algae. The operator at times would add powdered pool chlorine in a “shock” treatment to remove some of the algae. The treatment would be effective for 7 to 10 days, then the algae bloom would occur again and it wouldn’t be much better than before. After two weeks, the mass was thick enough to cover the bulbs again and require treatment.

The algae was a problem not only in the mixing chamber, it has spread to the holding pond and growth of algae has been prolific. The holding pond was a bright green color from one end to the other. It had gotten so bad that the discharge pipe was plugged with algae. Another pipe was installed to by-pass the previous suction pipe. It was laid on the ground and over the bank and run to the irrigation pump. This was not approved by the state, but was added until the normal discharge pipe could be cleaned or replaced.

The drip lines also had a green growth in the tubes. It has not gotten to the point where it has plugged the drippers.

After assessing the situation and observing operations at the plant, several options were recommended to begin feeding an organic cleaner to remove the algae. Treatment was determined to require 200 ppm of treatment to be fed once per day in a dosage of 18 ozs. fed as the water entered into the mixing chamber. On the first day of treatment, masses of algae began sloughing off the sides and floating on the surface. After several hours, the masses began turning an off-white greyish color and then they would disappear after 24 hours. In six weeks, the chamber had been completely cleaned and the bottom of the mixing chamber was easily visible. In fact, the operator collected a set of keys that he had dropped into the chamber several months before.

The next step was clean up the discharge tube and to clean up the drip lines. There were several options available:

1) Add a large amount of treatment into the pond to remove the algae in one quick clean up operation, then begin a maintenance dosage to keep the pond from regrowing as quickly, this option would take a week to clean up the pond and it would also be the more expensive option

2) Add a moderate amount of the treatment around the discharge valve to clean out the pipe and to clean out the drip lines. The increase the dosage by a factor of 3 and feed 2 times per week to clean up the pond. This would take 3 to 4 months and is the median cost.

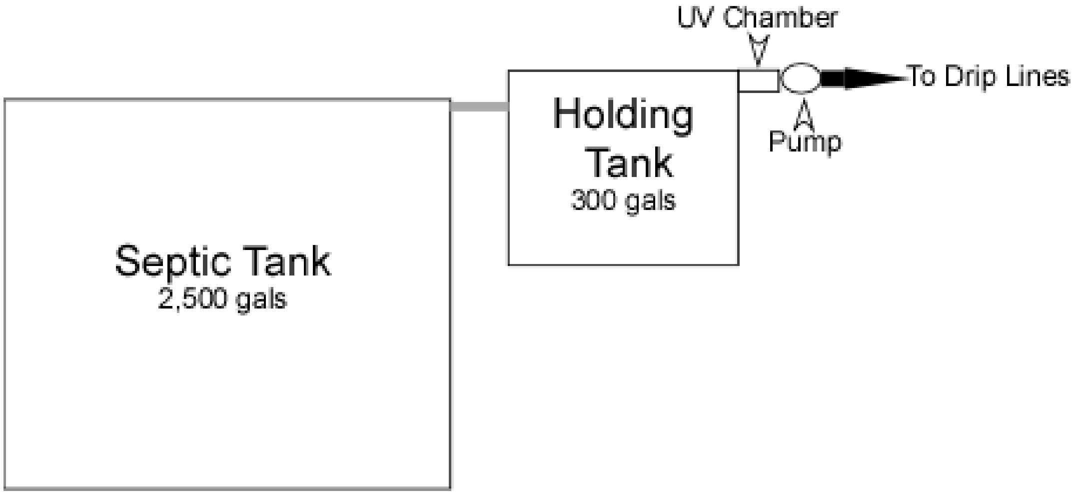
3) Increase the treatment level by a factor of 5 and feed the product six times per week to clean up the pond and drip lines. This treatment would take 6 to 12 months to be successful. Lower cost, longer clean up period.

The operator has recommended option #1 to his company and they are reviewing the options and the costs. Clean up will begin once the recommendation is accepted and results of the clean up should be available in the next 30 days and reported at the IA meeting in Nov.

Case Study Residential Septic System

The first of this type of recycled water system has just been installed and has begun operations. The prototype has been approved by the State of North Carolina and has been in operation for less than a month. It is too early to know any results as far as the operation's success, but it is the beginning of a trend to move away from traditional septic systems with drain fields and beginning to use drip irrigation for dispersal of water. Currently it is not approved for use in landscape irrigation, but after proving to be successful, the state will consider approval for landscape irrigation after 2 years of operation.

The septic system consists of the standard 2,500 gallon septic tank which is placed lower in the ground than the standard tank, a 300 gallon holding tank that is above the level of septic tank, and float sensor that empties the tank whenever it reaches 80% of capacity, a UV light for disinfection, and a pump that sends the water into the drip lines buried 18" below the ground to ensure that is doesn't freeze in the winter.



TYPICAL RECYCLED WATER ANALYSIS

7-05-95

Temperature	77°F	
	Recycled Water	Domestic Water
P Alkalinity (as $CaCO_3$)	0.0	0.0
M Alkalinity (as $CaCO_3$)	164.0	124.0
Chlorides (as Cl)	261.6	120.0
Total Hardness	256.0	120.0
Calcium (as $CaCo_3$)	160.0	108.0
Magnesium (as $MgCo_3$)	96.4	12.0
Silica (as SiO2)	17.3	13.5
Sulfate (as SO_4)	78.2	0.0
pH	6.85	7.68
Conductivity	1200	250
Iron (as Fe)	0.4	0.5
Phosphate (as PO_4)	4.5	1.6

Wednesday is NOT a Good Reason to Irrigate

Bruce Carleton – The City of Moreno Valley

We in the landscape industry owe much to those that pioneered the irrigation industry, they being the growers of agricultural commodities. Many of the chemical tools we use in managing healthy, attractive landscapes come from their work. Further, many of the irrigation parts we work with were adaptations of agriculture parts. Until the development of the gear driven rotor, it was pretty much a one-way street; we did all the taking.

Once upon a time, most landscape systems were laid out like agriculture systems; the acreage was smaller but they had one thing in common, they both began at a gate valve. Manual irrigation systems were common into the '70's, especially residential systems. While considered a total bother by many who managed them, they had one advantage that no one appreciated; typically the plants thrived.

Back to the Future

I recognize the impracticality inherent in this approach to current-day commercial maintenance, but let's look at what was sacrificed when the horticulture community parted ways with our agricultural heritage in terms of irrigation scheduling. The key element to successful water management in the production agriculture setting is carefully managing the irrigation interval. In a field of Alfalfa the grower doesn't wander about wondering how long to irrigate the crop, the key element is when to start the pump. This equates to deciding how best to manage the irrigation interval. They make this decision through experience and the use of a shovel, or some other device to check the moisture content of the soil that supports the crop.

Although we are not growing Photinia to maximize vegetative production (likely, just the opposite), we do influence the health and appearance of the ornamentals under our care precisely by how well we manage the soil profile in terms of moisture. The innovation that revolutionized landscape management (the automated controller) also placed an obstacle in our path, one that has yet to even be recognized by many in the trade.

The nature of the obstacle is this; we have been numbed to the importance of whether irrigation is actually needed at a site each Wednesday (and Monday, Friday and probably Saturday as well!). The needs of the plants have been set aside to maximize the convenience for those maintaining the system. The calendar has become the inflexible dictator of when the landscape would receive irrigation, whether it needed some or not. In reality, we are likely placing undue stress on the plants when we fail to consider how our irrigation practices affect the plant physiologically.

Know The Law

Most plants can tolerate extremely frequent irrigation if the soil is reasonably well drained; so what's the problem you may think. There are two results of this attitude that will run you afoul of what I call *the law of landscape management*. Simply stated this law says that any poorly conceived or implemented action (or lack of action) will have unpleasant ripple effects.

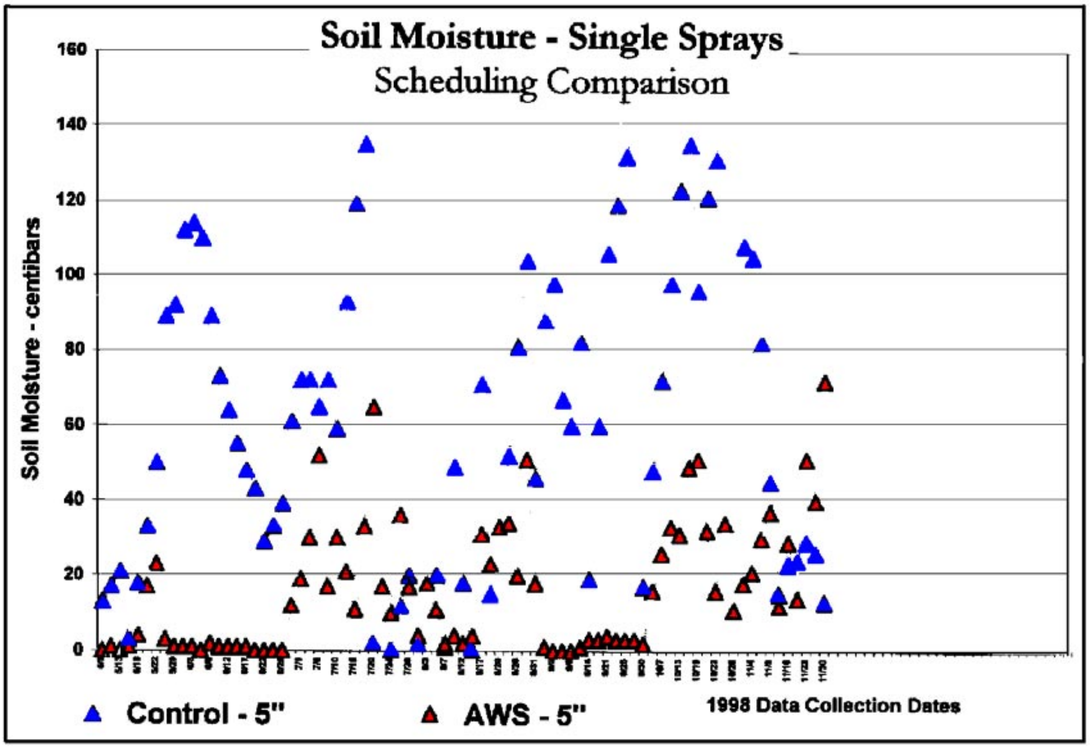
First, suppose there is a mainline break or other interruption in supply (the term drought comes to mind) which means you can't give the plants the daily dousing they've come to rely upon. The plants have adapted to the 'bath tub' irrigation schedule by establishing all the absorptive root hairs at the soil surface where they can get everything they need. Here, and nowhere else, can the roots find moisture AND air. Since they have an effective root depth of about two inches, this zone is quickly depleted of moisture by the plant and direct evaporation. It won't take long before the plants show the effects of even a brief interruption in irrigation.

Second, this attitude will become costly as more focus is placed on water consumption by governmental and supply agencies. Anyone who manages a site that falls under the guidelines of AB 325 (the landscape conservation ordinance mandated by the California state legislature in the early '90's) already has a flavor for what commercial maintenance will be like in the future. There is a process beginning in the California State Legislature to revisit AB 325 and make it more conservative, and influence more total acreage (older landscapes will likely be included) to help address the pending water shortage facing California with the loss of 'surplus' Colorado River water.

Since abandoning irrigation controllers is not an option, how can we improve our performance by using the controller more wisely? That is the dilemma I faced in Moreno Valley six years ago when tasked to improve the conservation performance of nearly 70 small parkway systems that were too small and scattered to be feasibly controlled with a central control system.

The first avenue explored was the use of 'canned' irrigation schedules generated by a software program developed for the California Department of Water Resources. A comparative study was constructed to measure the performance of the computer schedules versus 'artistic' scheduling done by an experienced technician. Both approaches were monitored to measure water use, turf quality and soil moisture levels during the seven heaviest irrigation months.

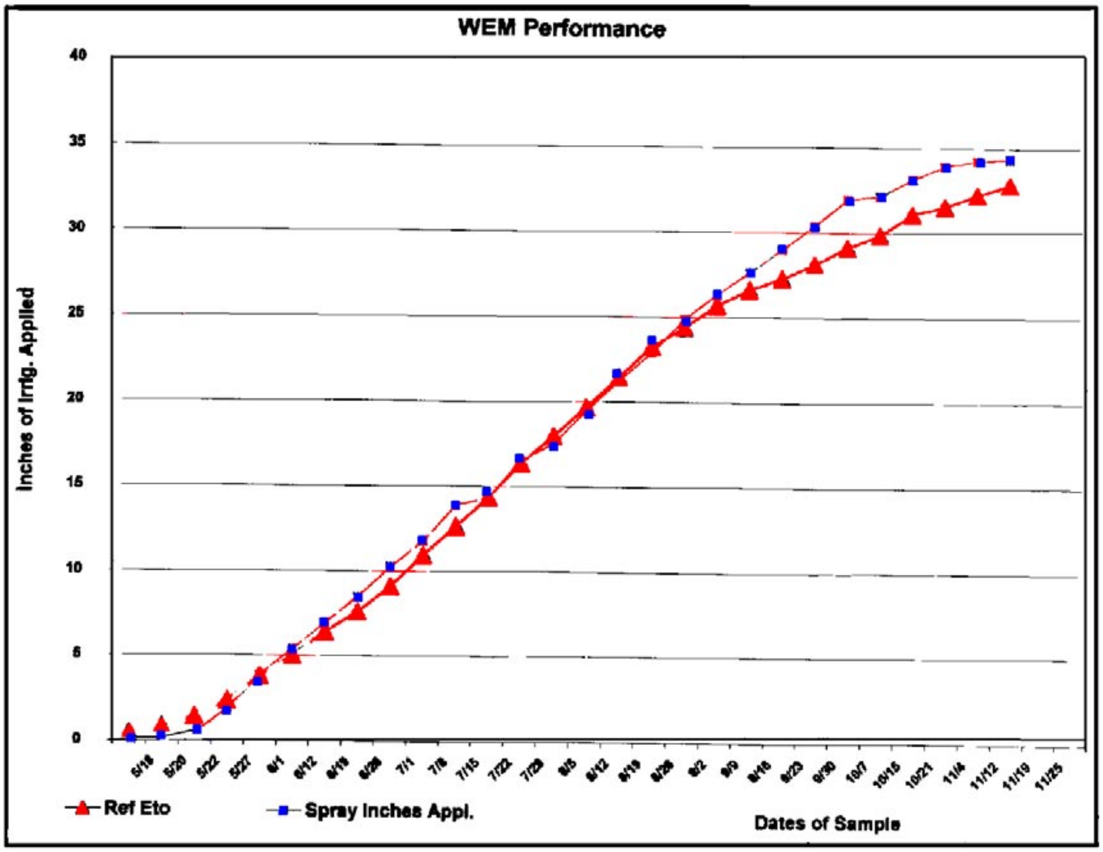
We used Watermark^{TM} moisture sensors to measure the moisture content of the soil profile at the 5 and 10-inch depths. We found that typically the computer scheduled sites (denoted as AWS) irrigated too often, particularly in the spring and fall months. The profile was near saturation below the 5-inch depth for periods up to two weeks at a time. Clearly water was being applied before the profile could even begin to dry out enough to approach field capacity, let alone the wilting point. Not surprisingly, this approach applied an average of 118% of ETo (over three sites); not exactly the level of conservation I had hoped for.



Conversely, the manual schedules (control) had the opposite problem, for most of the summer the soil at was at, or above, the wilting point at the 5-inch depth. Very small, frequent water applications were made so that below 2 inches into the soil profile, there was essentially no available water. Despite this apparently meager irrigation program, 101% of ETo was applied. So while the 'wing-it' approach proved more conservative, the root zone was in rather precarious shape through much of the irrigation season. So for different reasons both scheduling approaches resulted in shallowly rooted turfgrass, and less than optimum growing conditions for the roots.

Paradigm Shift

As a part of this study we equipped two out of the way valves with the Watermark^{TM} moisture management hardware (WEM). We found that at the end of the study these valves were irrigating very efficiently, tracking with reference evapotranspiration (ETo) with amazing accuracy. But best of all, we paid almost no attention to these two isolated areas and seldom changed the irrigation schedule through the entire growing season.



Although this result was based on only two valves, this approach clearly warranted further consideration; particularly in light of the less than adequate performance of the 'canned' schedules that I had hoped would become the foundation of our water management program.

Like many in the trade, I too had a less than pleasant experience with an older soil moisture control system that showed up in the Southern California market in the 80's. And while there are some legitimate concerns associated with the use of soil moisture sensors, I have found that modern systems have evolved that can lessen these risks.

While our comparative study demonstrated that fundamentally, the hardware could perform well, there were some application conflicts that we encountered as we considered a more aggressive pilot project. A more serious effort took shape meant to evaluate how the system would perform in the real world, over the long haul.

Building A Better Mousetrap

One of my first concerns was the possibility of having the system over-ridden for testing, and then left that way at the end of the test. If only highly responsible people have access to the system, this may never be an issue. Since typically these systems are common interrupts, it is usually necessary to over-ride the sensors to test the system. This problem was defeated by installing a relatively inexpensive mechanically timed switch, such as those used in public facilities in lieu of normal toggle light switches so lights wouldn't be left on for hours. This was dubbed the 'egg timer' by staff and allowed us to protect the system from human forgetfulness.

Another common knock on sensors is that you can't properly represent a large area with a small patch of ground. This has not proven to be a major obstacle for our program, although the more diverse the landscape is, the more sensors that must be employed. One advantage enjoyed in the case of Moreno Valley is that parkway landscapes tend to be repetitive as a rule. This tendency toward monotony bodes well to success as it means finding a 'representative' sensor site is easier to do. If a site is properly hydro zoned in terms of irrigation layout, then the task of placing sensors is not particularly difficult.

Perhaps the biggest challenge is in planter beds, since the sensor must be within the active root zone of the plant(s) being monitored, while also being in a location that receives full irrigation applications. Obviously a sensor cannot be placed at the crown of a mature Wheeler's Pittosporum (at least with overhead irrigation), nor so far away from the ornamental that root influence on the sensor is lost. Fortunately, most established ornamentals have a root zone that exceeds the 'drip line' of the plant by a significant amount.

Our program is based on having the field wiring for the sensors protected by electrical conduit to keep any furry rodents from wreaking havoc with the sensor circuits. This is very easy to accomplish with new construction where open trenches allow the sensors to be located anywhere on the site. Under retrofit conditions, the wiring is obviously the big obstacle to installation. A vibratory plow or slit trencher can facilitate these projects on longer runs. Sensors can be placed more than 2000 feet from the control module if adequately sized wire is used. See manufacturers recommendations as a very long wire run adds resistance to the circuit that can affect the accuracy of the equipment.

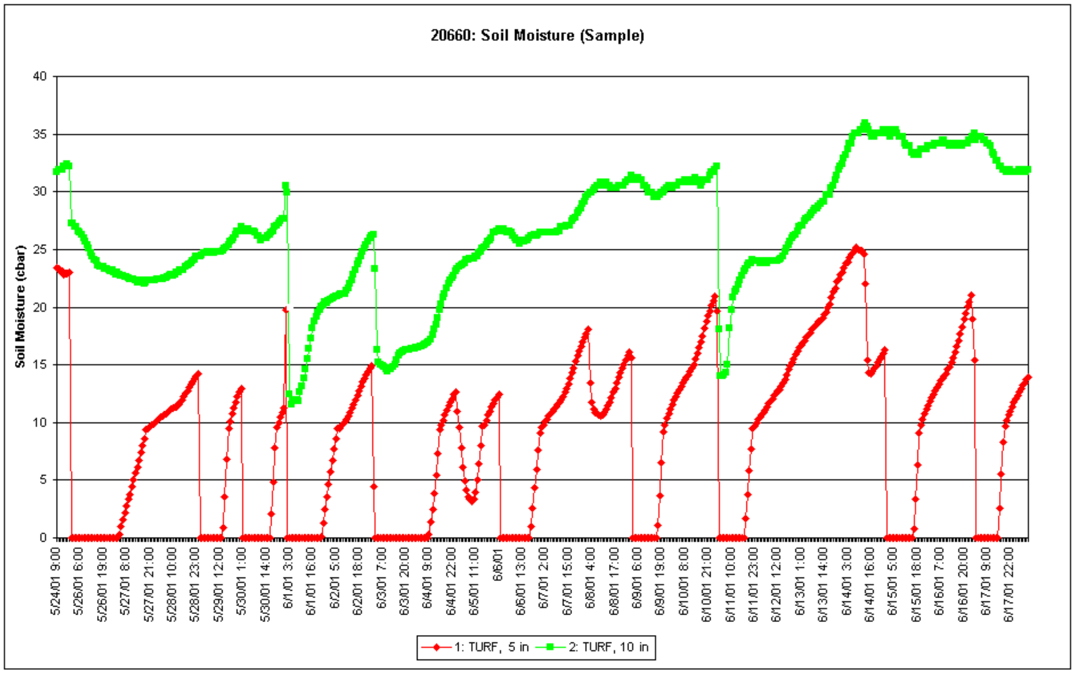
Perhaps the most obvious difference in managing a soil driven control system is how the controller is scheduled. The basic structure of the schedule changes dramatically. Currently the prime focus is on tweaking the run time to try to meet the ever-changing water needs of the plant. As was illustrated above, this is often not the best approach from the perspective of the root. The soil moisture approach turns the process around by switching the main focus toward tailoring the timing of irrigation events to the needs of the landscape. By introducing the hardware, the problem of guessing which nights to water is eliminated. The controller must be set to attempt to irrigate every night (except prior to mowing of course). This may or may not be a big change from normal for an irrigator. The other part of the equation is the runtime; this value will stop changing from month to month, eliminating the need to guess about how to tweak it.

Fill'er up!

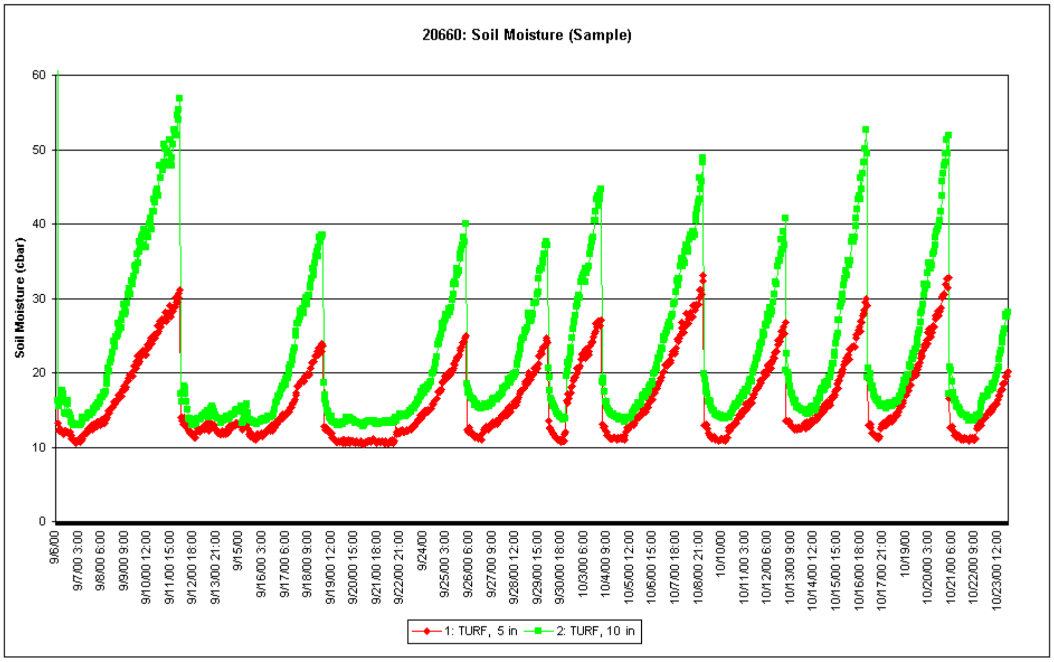
The underlying philosophy of interval driven irrigation is this, fully hydrate the root zone so the plants can exploit as large a volume of soil as possible. This accomplishes two things. First, we encourage the development of an extensive root system; more roots lead to more robust and durable plants. The impact of a temporary loss of irrigation will be greatly minimized. Second, when practiced on a regular basis, thorough irrigation helps facilitate root zone leaching, and encourages the proliferation of beneficial soil organisms that ultimately can improve the soil structure.

I'll use a car analogy to illustrate the process. The soil is to a plant what the fuel tank is to an engine. The soil is the 'tank' where water is stored until absorbed by the plant. Our first objective is to determine how much water must be applied to 'fill the tank'. Once we learn that value, it makes sense that we apply that much water each time it needs to be filled. Thus the valve run time becomes essentially a static value.

Now the run time part of the irrigation equation is satisfied (specifics will be covered below) and the challenge becomes knowing when that 'refueling' should occur. This is where the sensors and control hardware come into play. By tuning the interval with the control module it is possible to tailor the interval to real-time site conditions. The following charts were derived from data logger feedback.



This chart tracks soil moisture trends (in centibars of tension) for an established turf area (fescue) after retrofitting with the moisture control hardware. Note that moisture was not reaching the deeper portion of the soil profile after irrigation. At the same time, the shallow portion of the root zone was remaining soggy for two or more days at a time. This indicates that two adjustments are needed. First, the irrigation interval must increase. This is accomplished by increasing the set point on the control module. To drive moisture deeper into the profile, more runtime was added to the schedule on the clock.



The indicated adjustments had a beneficial result, eliminating the excess shallow moisture while improving deep profile moisture reserves. By monitoring soil moisture on a continuous basis, it is possible to use the base irrigation schedule and the control module to establish irrigation practices that provide consistently beneficial root zone moisture conditions. And these benefits occur regardless of the time of year and without monthly manipulation of the runtime or water budget. It is not essential to constantly log sensor data to derive benefit, but the fine-tuning process is accelerated if your system is so equipped.

Time is on Your Side

There are two ways to set up a base irrigation schedule to use with sensors. A theoretical approach that uses software to determine an approximate runtime based on a collection of field data and irrigation system performance. Some manufacturers have such a tool available. The Watermark^{TM} system features WaterPerfect^{TM} software, an excel spreadsheet, that is designed to work in concert with that manufacturer's hardware. The other is more labor intensive, but can be very accurate (without the use of even a calculator).

Briefly, the software approach involves using field measurements of soil texture, root zone dimensions, sprinkler precipitation rate (PR) and distribution uniformity to project how much runtime will be needed to fully hydrate the root zone of the landscape in question. If you have site audit data on hand (and the necessary technology) this can be a simple way to get going.

If you don't have a stomach for the math, fear not, there is another method just for you, the empirical approach. All you need is a soil probe and a watch. Evaluate the soil profile with the probe to determine if the soil profile is in need of irrigation. Depending upon the season, this may be two days since the last irrigation or two weeks. The key is probing down to see how deeply active roots exist, and whether you can squeeze any free water out of the sample. If you can extract water, the plants will likely also be able to. This is a rather subjective approach, and it will take daily observation to find the right time to conduct your test (I warned you this would be labor intensive!).

When the time is right, simply start irrigation for the area where you predict you will set a sensor. Note the time and constantly observe the system during irrigation. Two key pieces of information will be derived. First, determine how long each valve can run continuously without any run off (if more than one valve serves an area, alternate between them). Second, determine how many total minutes of irrigation are needed to drive water deep enough to sustain roots at the low end of the effective root zone. By probing the soil periodically during irrigation you can determine how many minutes the valve(s) must run to deliver enough water to hydrate *the entire* root zone. Note that you will likely need to interrupt irrigation periodically (at least with spray systems) to prevent ponding and run off. On sandy soils a cycle and soak approach may not be necessary. Keep good notes as this will define your cycle length and soak allowance. Once your probing shows that water has moved to a desired depth into the root zone, you have defined the optimum runtime for the valve(s).

If you have a very repetitive landscape, that same data can be used for several valves. However, if there is significant variability in the PR or soil conditions etc., then an independent test will have to be performed for those systems as well. For even a relatively small commercial project, this process could easily take more than half of the workday.

Once you have defined how long the valve(s) must run to drive water down well into the root zone, and if there is a run time limitation to prevent run-off, you are ready to schedule the site.

Show Time

As I mentioned, the form of the irrigation schedule will likely appear pretty exotic to staff compared to traditional sites. For sites without turf, the controller should be set to irrigate *every night.* If there is turf, the evening before it is mowed obviously should be left off the schedule so you aren't leaving ruts all over the site.

Once the base irrigation schedule is in place, you must adjust the knob on the control module. Depending upon the system there will either be a scale of wet to dry or 1 to 12 or something of the sort. Regardless of the scale used, the point is to understand that the knob dictates how often the system will irrigate. Wet means it will run often, dry means it will go longer between irrigation events.

The goal is to continually try to stretch the interval by incrementally increasing how dry the soil should get before the sensor module allows irrigation to be applied. Obviously the season will influence this interval. If your making the switch to sensors in the summer proceed with caution, chose a setting near the 'wet' end of the scale. In the cooler months keep pushing the envelope to see if you get to a point where you see stress but the system isn't allowing irrigation to occur. That will usually define the highest setting you will ever want to run.

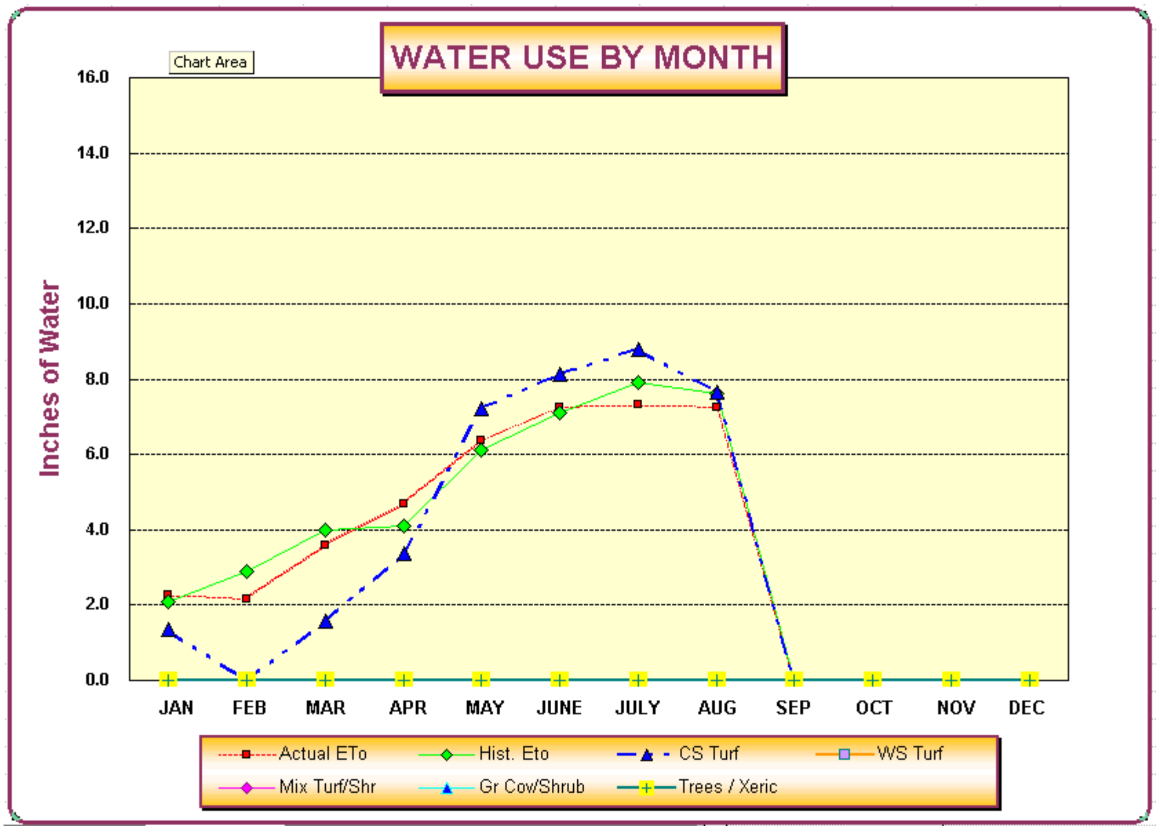
The key to success is to watch the site carefully the first two months. Don't panic at the first sign of stress; monitor consistently to see if stress worsens before succumbing to the impulse to dump water on it for a week.

Besides tuning the sensor module, you need to balance the applied irrigation between valves on the site. Some areas get reflected heat while others get none. Hopefully the sensor is your 'worst case' scenario, and other valves in the hydro zone require somewhat less water. By watching and probing the entire site, you soon will learn how to make subtle adjustments in the schedule (up the runtime here, cut it a little more there) until the site has a consistent look.

The next step is to begin monitoring water use at the site. That means reading the water meter each month, and comparing consumption with expected water use for the site. The WaterPerfect software incorporates such a feature. If you don't already know how, drop me an e-mail (brucec@moval.org) and I will send you the specifics of how it can be done. You need to know the area irrigated by each point of connection with a fair degree of accuracy, and what units your meter measures to complete the calculation.

The report card

Once you have determined how many inches of water your system applied, you can quickly grade the performance of the system in terms of plant need. If you've been in this business for very long you have probably heard of Reference Evapotranspiration (ETo). This ten-dollar term simply defines a value of expected water loss from a landscape based on the water use of a plot of well-watered tall fescue (probably) that is monitored by a weather station. Universally, ETo is reported in inches of water. This value is easily available for many parts of California through the California Irrigation Management Information System (CIMIS), operated by the State of California. For other parts of the country this data is becoming more common, but you may have to dig a little harder to find it.



Here's the utility of CIMIS, you gather the ETo value (inches) for last month, you calculate the applied inches your system applied last month, and viola; you have a ready made comparison that illustrates how well water has been managed at your site. Rarely will the values agree exactly, but if your site uses 100% or less of ETo, you can feel secure that the system is working well. What better way to illustrate your commitment to excellence than to have records that show how effectively your management program works. If on the other hand your site is consistently above 115% of ETo, you have some work to do.

The first area to check to find the waste is to carefully review the hardware, are there blown wiper seals, missing nozzles, cracked fittings, lateral breaks and/or stuck valve(s)? If so, these obviously kill system performance. Make sure the low and leaning heads are re-positioned so they can do the job. Replace or service clogged nozzles and really watch the system run. Do you have head-to-head coverage and operating pressure reasonably close to manufacturers recommendations? If not, you have some serious work ahead of you. You can't expect excellent results from a marginal (don't blame control hardware for poor maintenance practices) system.

Closing

In Moreno Valley we have automated nearly 30 sites with sensors and the results have been excellent. The key has been consistent monitoring of water use, and quickly reviewing system performance when water use jumps above typical levels. Sometimes a nozzle adjacent to the sensor gets clogged, or a shrub isn't trimmed quite soon enough and the spray pattern is blocked. The hardware itself has been to blame for erratic performance in only one case in the nearly three years we have been using the system. I am convinced that if system installation is thoughtfully planned, and post install observation is adequate, the chances for failure are quite low. This means monitoring the water use at the site must be done consistently. If it is, problems with the control system or the irrigation equipment in the ground can be identified quickly. In our pilot project, we experienced an average irrigation management labor savings of 35% over traditional methods where schedules were modified twice each month according to weather conditions.

Staff has gained a high degree of confidence in the sensor system, and will continue to expand the scope of tracts irrigated this way as budgets permit. I encourage anyone in the industry to learn more about this alternative to artistic irrigation scheduling. As water becomes a more highly valued commodity, it will become essential that those of us in the green industry be able to prove to the outside world that we know how to manage it wisely. Soil moisture sensing is one very straightforward method of achieving that goal.

Title: **Development of a Standardized Testing Protocol for Soil Moisture Sensors: Current Status and Preliminary Test Results**

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Suggested Topic Category: Water Conservation in Turf
Sub Category: Precision Irrigation

Abstract

Soil moisture sensors are an important component of some sensor based irrigation system controllers. The sensor provides information critical to the effective and efficient management of turf and landscape irrigation systems. At the Center for Irrigation Technology (CIT) a testing protocol standard is being established to verify the accuracy of commercially available soil moisture sensors. This protocol will characterize the ability of the sensor to provide reliable results when comparing individual units during multiple wetting cycles for various soil types, soil temperatures, and water salinity levels. In 2003, while initial tests were conducted on a commercially available sensor at CIT, a draft copy of the protocol was posted on the Irrigation Association (IA) website for comments. We propose to present results from the tests to date, such as calibration curve plots of the sensor reading versus the measured mass and volumetric moisture content. In addition we will summarize the comments and suggestions received via the internet to the draft protocol that was posted on the IA website.

Introduction

In January 2003, researchers at the Center for Irrigation Technology began testing a soil moisture sensor in accordance with the draft protocol formulated after joint discussion with industry personnel. Subsequently, the following two draft protocols were posted on the Irrigation Association website for public comment.

PROTOCOL A: **The Center for Irrigation Technology Draft Testing Protocol**

Turf and Landscape Irrigation Equipment – Soil Moisture Sensors

FIRST DRAFT

Reference No.: (CD/3/03) **Date: 03/03**
File: 1000-8 (SEN/03) **CIT/CSUF**

A1.0 Scope

Soil moisture sensors are an important component of some sensor based irrigation system controllers. The sensor provides information critical to the effective and efficient management of turf and landscape irrigation systems. This testing protocol standard is being established to verify the accuracy of commercially available soil moisture sensors. This protocol characterizes the ability of the sensor to provide reliable results when comparing individual units during multiple wetting cycles. This protocol also tests the sensors over the range of conditions encountered in typical field installations. This includes a range of soil types, a range of soil temperatures, and a range of irrigation water salinity levels. The sensor's ability to provide useful performance information when exposed to this range of conditions will be evaluated. Specifically the sensor's calibration curve will be determined and analyzed for stability when subjected to varying on-site conditions. The calibration curve is a plot of the sensor reading versus the mass or volumetric moisture content.

A2.0 Normative References

(Gravimetric Methods for Determining Soil Moisture Content)

A3.0 Terms and Definitions

For the purpose of this draft testing protocol, the following terms and definitions apply.

A3.1 Available Water

The portion of water in a soil that can be readily absorbed by plant roots

A3.2 Bulk Density, Soil

The mass (weight) of dry soil per unit bulk volume

A3.3 De-Ionized Water

Conductivity is 0 dS/m

A3.4 Evapotranspiration (ET)

Water transpired by vegetation plus that evaporated from the soil

A3.5 Field Capacity

The amount of water remaining in the soil after it has been saturated and allowed to drain away

A3.6 Fine Texture

A general term to indicate a soil with large portions of clay and silt

A3.7 Mass Water Content

The water content expressed as the weight of water in the soil divided by the oven-dry weight of soil

A3.8 Mass Water Percentage

The mass water content times 100

A3.9 Oven Dried

Placed in an oven and dried at 105°C for 48 hours

A3.10 Permanent Wilting Point (PWP)

The largest content of water in a soil at which plants will wilt and not recover when placed in a humidity chamber

A3.11 Siemens

The SI unit of electrical conductance

A3.12 Soil Texture

The relative proportions of the various soil size separates

A3.13 Volumetric Water Content

The ratio of the volume of water in a soil to the total bulk volume of the soil, in decimal form

A3.14Volumetric Water Percentage

Volume water ratio multiplied by 100

A3.15 Water Salinity Level

An electrical conductance measurement characterizing the level of soluble salts that can interfere with the growth of some crops

A4.0 Symbols and Abbreviations

dS - deci-Siemens

A5.0 Sampling

A5.1 Sampling Test

A representative of the testing agency shall select test specimens for each test at random from a sample of at least 20 units supplied by the manufacturer. The number of specimens selected for each test shall be as listed in Table 1.

Table A1

Clause or Sub-Clause	Subject of Test	Number of Test Specimen
A6.2.1a	Calibration in a fine textured soil	2
A6.2.1b	Calibration in a medium textured soil	2
A6.2.1c	Calibration in a coarse textured soil	2
A6.3.1a	Calibration at 20°C	1
A6.3.1b	Calibration at 30°C	1
A6.4.1a	Calibration when wetted with water with a conductivity of 1.5 dS/m	1
A6.4.1b	Calibration when wetted with water with a conductivity of 3.1 dS/m	1

A6.0 Test Method

A6.1 Preparation of the soil containment box [Ref. CIT Drawing No. 4-28 (2/03)] and installation of the sensor.

A6.1.1 Use a standardized box capable of containing a fixed weight and volume of the representative soil type. The box shall wet and drain the soil through a perforated bottom. The box shall allow for the determination of the net weight of water required to bring the soil sample to field capacity. The volume of soil shall be sufficient to permit the sensor to function without being influenced by the box. The soil shall be oven dried and screened for ease of packing around the sensor. The soil shall be placed and tamped so as to result in the representative bulk density (range 1.2 to 1.4). Sensor reading and temperature measuring device output wiring shall be arranged so as not to interfere with the procedure for weighing the box. The weight of all components, except for the soil and water shall be known.

The box is designed to represent a section of turf grass root zone with a depth of 6-7 inches. The sensor will be located at the depth recommended by the manufacturer. It is recognized that the combined effects of surface drying and drainage below the root zone will result in a moisture gradient within the box. This is meant to represent the actual environment in which the sensor is asked to function.

A6.2a Test for the sensor's ability to provide a consistent calibration curve between drying cycles and individual sensors in a fine textured soil.

6.2.1a Assemble two boxes complete with moisture and temperature sensors including provision for electrical hookup to registering and/or recording devices. Predetermine the weight and volume of the soil moisture sensing device. Place the oven dried soil in the box and tamp to achieve the design bulk density. Include in this process the installation of the soil moisture sensor in the location recommended by the manufacturer. Obtain the weight of the box plus soil, and the volume of the soil and calculate the actual bulk density. Place the box in the environmental chamber set at 25°C. By a process of adding known amount of de-ionized (DI) water, fill the box until the soil is completely saturated. Allow the box to drain until all free drainage ceases. Measure the amount of drainage water and calculate the net amount of water stored in the box. Alternatively the box can be weighted before and after being saturated and drained to determine the net amount of water retained. In both methods the box should be covered to be sure the water loss is from drainage only. Read and record the soil temperature and sensor reading and weigh the box. This is the beginning of the test run and represents the water content at field capacity. Let the soil dry in the environmental chamber taking periodic readings of temperature, sensor output, and box weights. Initial test runs with a sandy loam in Fresno suggests that the drying process will take 15-18 days. In this case, two readings per day would be adequate. Plot the results from the two boxes; obtain a regression curve on each box.

Repeat the test by re-wetting the soils and taking readings as previously defined. Plot the results and develop the regression calibration curve.

A6.2b Test for the sensor's ability to provide a consistent calibration curve between drying runs and individual sensors in a medium textured soil.

A**6.2.1b** Repeat Clause 6.2.1a except:

- Use a medium textured soil

A6.2c Test for the sensor's ability to provide a consistent calibration curve between drying runs and individual sensors in a coarse textured soil.

A6.2.1c Repeat Clause 6.2.1a except:

- Use a coarse textured soil

A**6.3** Test for the sensor's ability to provide a constant calibration curve between individual sensors in a medium textured soil at 20°C and 30°C.

Note: Testing to Clause 6.2.1b gives comparable results at 25°C.

A**6.3.1a** Repeat Clause 6.2.1b except:

- Set the environment chamber at 20°C
- Conduct a single wetting run only

A**6.3.1b** Repeat Clause 6.2.1b except:

- Set the environmental chamber at 30°C
- Conduct a single wetting run only

A**6.4** Test for the sensor's ability to provide a consistent calibration curve between individual sensors when water of elevated salinity levels of 1.5 and 3.0 dS/m are used on a medium textured soil at 25°C

Note: Testing to Clause 6.2.1b gives comparable results with a water conductivity of 0 dS/m.

A**6.4.1a** Repeat Clause 6.2.1b except:

- Wet the soil with water with a conductivity of 1.5 dS/m
- Conduct a single wetting run only

A**6.4.1b** Repeat Clause 6.2.1b except:

- Wet the soil with water with a conductivity of 3.0 dS/m
- Conduct a single wetting run only

A7.0 Analysis of Results

A7.1 Summary analysis of the calibration for two sensors subjected to two wetting cycles with a medium textured soil a 25°C and wetted with water with a conductivity of 0.0 dS/m. Develop a regression and confidence limit analysis (95% and 99% levels).

A**7.2** Summary analysis of the calibration for all three soil types at 25°C and water with a conductivity of 0.0 d S/m. Develop a regression and confidence limit analysis. (95% and 99% levels).

A**7.3** Summary analysis of the calibration for the medium textured soil wetted with water with a conductivity of 0.0 dS/m at 20°C, 25°C, and 30°C. Develop a regression and confidence limit analysis. (95% and 99% levels).

A**7.4** Summary analysis of the calibration for the medium textured soil at 25°C when wetted with water with a conductivity of 0.0 dS/m, 1.5 dS/m, and 3.0 dS/m. Develop a regression and confidence limit analysis. (95% and 99% levels).

PROTOCOL B: **The Center for Irrigation Technology Draft Testing Protocol**

Turf and Landscape Irrigation Systems – Climatologically Based Controllers

FIRST DRAFT

B1.0 Scope

This protocol provides a procedure for characterizing the efficacy of irrigation system controllers that utilize climatological data or sensors as a basis for scheduling irrigations. The concept requires the use of accepted formulas for calculating crop evapotranspiration (ETc). Commercial versions of this type of controller include the following:

- Controllers that store historical ETc data characteristic of the site
- Controllers that utilize on-site sensor as a basis for calculating real time ETc
- Controllers that utilize a central weather station as a basis for ETc calculations and transmit the data to individual home owners by a wireless connection

The concept of climatologic control has an extensive history of scientific study and documentation. The objective of this protocol is to evaluate how well current commercial technology has integrated the scientific data into a practical system that meets the agronomic needs of the turf and landscape plants. This will be accomplished by creating a virtual yard subjected to a representative climate and to evaluate the ability of individual controllers to adequately and efficiently irrigate that yard. The individual zones within the yard will represent a range of climatic, soil and agronomic conditions. As a standard from which to judge the controller's performance, a detailed moisture balance calculation will be made for each zone. The total accumulated stress over time will be a measure of the adequacy. The accumulated surplus of applied water over time will be a measure of system efficiency. Further water applied beyond the soil's ability to absorb it will be characterized as run off, further degrading the application efficiency. The study is not meant to include a scientific critique of the many formulas by which crop water needs are calculated from weather data. The study will use CIMIS data from a weather station on the California State University campus in Fresno (#80).

B2.0 Normative References

California Irrigation Management Information System (CIMIS) (ww.cimis.water.ca.gov)

B3.0 Terms and Definitions

B3.1 Crop Coefficient (C)

Coefficients as determined for specific crops that relate ETo to ETc as follows:

ETo (C) = ETc

This provides a convenient method for calculating Etc when field data is not available.

B3.2 Crop Evapotranspiration (ETc)

Specific crop moisture requirements as determined by lysimeter studies or calculated using formulae.

B3.3 Evapotranspiration (ET)

Water transpired by vegetation plus that evaporated from the soil

B3.4 Field Capacity

The amount of water remaining in the soil after the soil has been saturated and allowed to drain away

B3.5 Landscape Coefficient (KL)

A functional equivalent of crop coefficient that integrates the effects of a species factor, microclimate factor, and density factor when calculating landscape water needs

B3.8 Permanent Wilting Point

The largest content of water in a soil at which plants will wilt and not recover when placed in a humidity chamber

B3.9 Reference Evapotranspiration (ETo)

Estimates of crop evapotranspiration as calculated using climatological information and accepted formulas. CIMIS values approximate loss from a large field of 4-7 in. tall, cool season grass that is not water stressed

B3.10 Zones

A portion of the system connected to a common water supply and intended to operate at the same time

B4.0 Functional Tests

B4.1 General

System controllers from individual companies will be installed on-site at (CIT) complete with required weather sensors and/or communication links. The controller will be wired to 5 zones simulated by using an electronic device that will automatically record the run time signal from the controller, to the individual zone "Control Valves".

B4.2 Sampling: A representative of the testing laboratory will select test specimen for each test at random from a sample of at least 10 units.

B4.3 Test for Adequacy and Efficiency: Communicate with the controller manufacturers the starting date of the test run and the source of the real time weather data (CIMIS weather station #80 on CSUF campus). Communicate with the controller manufacturer the definitions of the virtual yard as given in Table B1.

ccess the valve run time monitors to determine the run times per valve as specified by the manufacturers system. Use the run times, the specified application rate, and application efficiency to calculate the net application. Develop a moisture balance calculation assuming the calculation starts with a full root zone. Continue the calculation for a time period long enough to demonstrate the controller's ability to adequately meet a range of climatic conditions. Note: The general lack of summer rainfall in Fresno will be compensated for by manually adding periodic virtual rainfalls.

B4.4 Test Report

The moisture balance by zones for each manufacturer's controller will be developed. Total deficit and surplus for each zone will be calculated. The magnitude of the deficit will suggest an effect on the quality of the vegetation. The magnitude of the surplus will impact the overall operating efficiency.

Table B1: Description of Zones

Item No.	Description	Zone #1	Zone #2	Zone #3	Zone #4	Zone #5
1	Soil type (Texture)	Medium	Fine	Coarse	Medium	Fine
2	Slope, %	0-5	0-2	0-2	4-6	4-6
3	Exposure	Full Sun	50% Shade	Full Sun	50% Shade	Full Sun
4	Root Zone Storage, in. (1)	1.80	0.80	1.40	6.00	3.00
5	Vegetation	Fescue (Tall)	Bermuda	Ground Cover	Woody Shrubs	Trees & Ground Cover
6	Grass (Crop) Coefficient (C)	See Table 2	See Table 2	N/A	N/A	N/A
7	Landscape Coefficient (KL)	N/A	N/A	0.9	0.2	0.8
8	Desired Grass Quality Rating (2)	6.0	7.0 (3)	N/A	N/A	N/A
9	Irrigation System	Pop-Up Spray Heads	Pop-Up Spray Heads	Pop-Up Spray Heads	Pop-Up Spray Heads	Surface Drip Tape
10	Gross Application Rate, in./hr.	1.28	1.28	2.0	2.0	0.16
11	Estimated Application Efficiency, %	50	70	50	60	80
12	Area, FT^2	2,500	2,400	1,200	1,800	4,000

(1) Total moisture storage from field capacity to permanent wilting point for the vegetation noted with assumed typical rooting depths. (2) See Table B3, (3) Assume that the curve for tall fescue also applies to Bermuda.

Table B2: Grass (crop) Coefficients (C)

Month	Fescue	Bermuda
January	0.61	0.52
February	0.69	0.64
March	0.77	0.70
April	0.84	0.73
May	0.90	0.73
	0.93	0.71
July	0.93	0.69
August	0.89	0.67
September	0.83	0.64
October	0.75	0.60
November	0.67	0.57
December	0.59	0.53

Table B 3: Relationship between Grass Quality Rating and % ETc for Tall Fescue

% Etc	Quality Rating
30	2.0
40	3.6
50	5.0
60	6.1
70	7.0
80	7.6
90	7.9
100	8.0

Some Preliminary Results

The following four graphs show results obtained at our CIT laboratory for tests conducted on a moisture sensor operating on Time Domain Reflectometry (TDR) principles. Test conditions are summarized as follows:

Test # 1 - D.I. water (~ EC = 0 dS/m) conducted @ average temp.= 25.1^{0}C (**Figure 1**);
Test # 2- D.I. water (~ EC = 0 dS/m) conducted @ average temp.= 42.1^{0}C (**Figure 2**);
Test # 3- Application of salt solution (~ EC = 1.5 dS/m) conducted @ average temp.= 29.5^{0}C (**Figure 3**);
Test # 4- Application of 2nd dose of salt solution (i.e. an EC = 1.5 dS/m was added to the soil from test no.3) and experiment conducted @ average temp.= 30.1^{0}C (**Figure 4**).

Sensor Measurement vs Calculated Volumetric Water Content with 95% Confidence Limits for Test #1

Sandy Loam; D.I. water (EC ~ 0 dS/m); Avg. temp= 25.1°C.

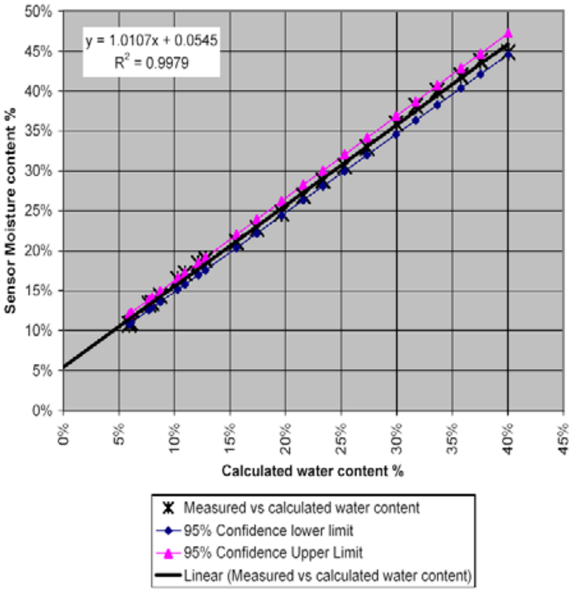


Figure 2: Sensor Measurement vs Calculated Volumetric Water Content for Test #2

Sandy Loam; D.I. water (EC ~ 0 dS/m); Avg. temp= 42.1°C.

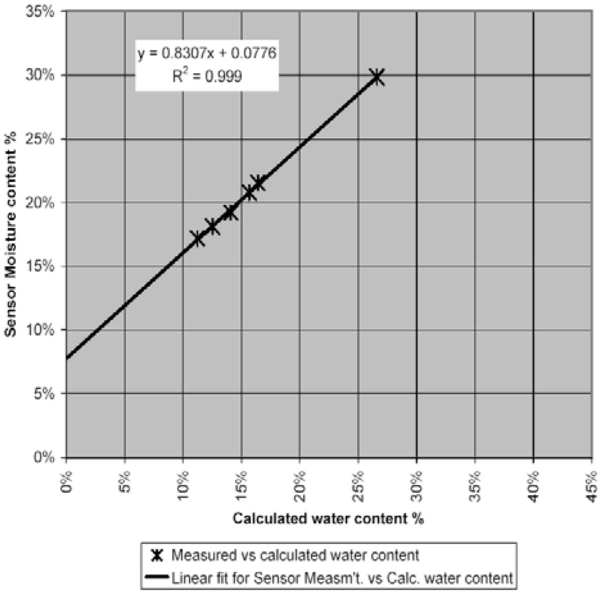
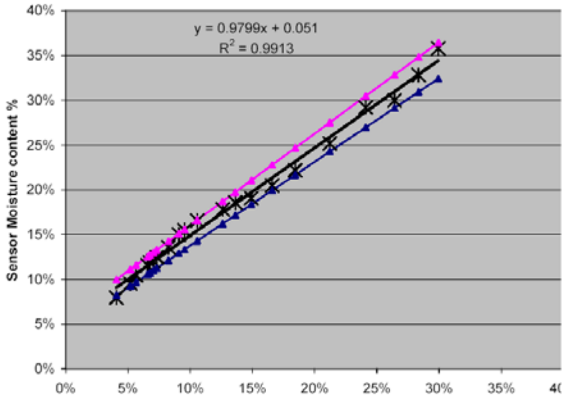


Figure 3: Sensor Measurement vs Calculated Volumetric Water Content for Test #3

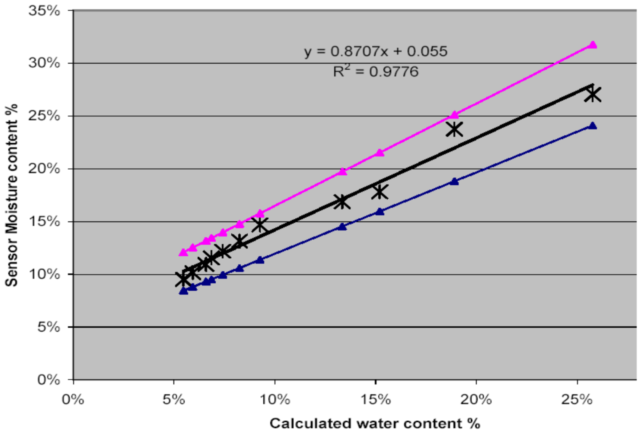
Sandy Loam; D.I. water (EC ~ 1.5 dS/m); Avg. temp= 29.5°C.



Sensor Measurement vs Calculated Volumetric Water Content- Test #4

Two applications of 1.5 dS/m.

Sandy Loam; Water (EC ~ 3.0 dS/m); Avg. temp= 30.1°C.



Some of the Comments Received in Response to the First Draft of the Protocols

Item	Comment/Observations	Accept	Reject	Explanation
(#)				
1	If a sensor provides useable data in the lab tests how can we be sure it will function satisfactorily in the field	✓		Lab tests address the impact of soil moisture content, temperature, and water conductivity on sensor readings. This test is meant to verify the scientific logic of the sensor design. Those sensors with favorable results would be recommended for a second phase of testing where they would be used with a control system to produce satisfactory turf grass.
2	How do we evaluate the sensor based system's ability to deal with soil and microclimate variability?	✓		Both soil and microclimate variability must be dealt with by all currently available control concepts. Some variability will be built into the Phase 2 field study. Also factors not identified in the lab study will be addressed in the field study.
3	Sensors should be tested for tolerance to freezing conditions	✓		Added to standard as paragraph 6.3.1c
4	2.0 No gravimetric soil moisture content referenced	✓		To be added
5	3.0 include a definition of "Soil Water Potential"	✓		To be added
6	Table 1 concerned about two few replications	✓		Made a modest increase in replications (from 2 to 3 & 1 to 2)
7	6.0 question fundamental methodology of using containment box. Notes the moisture redistributing effect of roots in a natural environment.		✓	The box is meant to geometrically represent a section of turf root zone. Drying occurs through moisture loss at the surface and through drain holes in the bottom. To that end it represents the root zone in the field except for the presence of roots. The fact that the root zone does not dry out uniformly should not affect the results as long as the sensor is placed in the same relative position for all drying runs.
8	6.0 soil variability could affect results		✓	Soil sample is oven dried and screened and hand placed and tamped. It should be free of stones, roots, and other debris.

Item (#)	Comment/Observations	Accept	Reject	Explanation
9	6.0 it would be helpful to have a copy of the soil containment box	✓		Copy of drawing added to appendix
10	6.0 how is sensor depth of placement determined in the absence of roots?		✓	Soil depth in containment box is approximately 6½ in deep. Sensor is placed at a depth of 3 in. or as specified by the manufacturer. See also #28 & # 29. This is meant to simulate a well irrigated root zone
11	Recommend installing a plug of turf grass on the surface of the containment box		✓	This lab test is meant to be a short term screening test. Adding turf would create serious logistical questions involving time and lab space. Questions of performance under actual turf management demands will be addressed in a proposed Phase 2 study involving both sensors and controllers.
12	6.2.1a why use de-ionized water? Why not use a real world water like rainwater?		✓	We need to use water of a fixed and known conductivity as a base. Thus DI is used.
13	How do you deal with the question of a variety of units, (e.g. volumetric moisture content, metric potential, dielectric constant, TDR, etc.)?	✓		Manufacturers are free to put whatever label on the calibration reading that they want. The protocol is only interested in how the calibration readings correlate with soil mass (or volumetric) moisture content. Each sensor will be evaluated on its ability to accurately correlate with soil moisture content when subjected to variations in temperature, conductivity and soil type.
14	What type of least squared regression will be completed? Will it be based on a linear regression?			The program uses a curve fit routine that evaluates the data against a fit to 25 equation forms and 3 polynomials. Best fit results in the highest correlation coefficient (R^2).
15	Could a pressure plate apparatus also be included?		✓	Moisture retention curves will be run on the three soil types involved. Individual sensor's calibration curves will be checked against the moisture retention curves to verify that the range of the sensor's curve covers the stress values involved in managing turf and landscape.
16	TDR probes of significant length integrate moisture content over the length of the probe. This could be an advantage in actual field use.	✓		Other sized containment boxes may be required for sensors sampling large soil volumes. In the field studies planned for Phase 2 of the test program, the importance of sampling larger soil volumes can be evaluated.
17	Could add basic equations involved in the appendix	✓		Included in the definitions

Item (#)	Comment/Observations	Accept	Reject	Explanation
18	Some soil moisture sensors do not have data recording features but operate to interrupt irrigation at predetermined set points.	✓		The protocol needs to be modified to include this type of sensor. In this case the evaluation will be made to determine repeatability of the set points over the range of the test conditions covered in the protocol. A discussion will be held with the manufacturer to determine if set point actuations can be sensed and recorded electronically. It would be desirable to sense all 16 set points with a single wetting run.
19	How will the protocol handle sensors that may have a different response curve for different soil types, water conductivity values, or temperature?	✓		The protocol will determine the repeatability of the sensors calibration for each of the variables involved (soil type, temperature, and water conductivity). The manufacturer will have to explain how this is useful in a water management scheme using a sensor with a matrix of calibration curves. They may also have to deal with transient conditions such as a fertilizer round.
20	Life tests are required to determine the stability of the sensors calibration overtime	✓		This will be suggested for inclusion in the Phase 2 study where sensors with controllers are responsible for the quality of turf in test plots
21	Soil moisture sensor must be easily adjustable to levels of watering that the user decided are adequate.			The protocol will describe the operational characteristics of the sensor with associated controller to allow for familiarization with the concept. The fundamental purpose of the Phase 1 protocol is to determine if the sensor is based on soil physics principals as demonstrated by providing a repeatable calibration curve when subjected to variable field conditions.
22	Reiterate the need for stability over time without the need for re-calibration.	✓		Time related issues to be included in Phase 2 of study with turf plots irrigated for say 3-5 years.

Item (#)	Comment/Observations	Accept	Reject	Explanation
23	Suggest making a distinction between absolute and relative soil moisture sensor.	✓		We understand the distinction between absolute and relative soil moisture sensors to be as follows: **Absolute Soil Moisture Sensor** This sensor is sensitive to soil moisture changes only and not affected by soil type, water conductivity, or temperature. Using moisture retention curves, the sensor can then be used to set limits on root zone tension at values known to provide quality turf with efficient water use. **Relative Soil Moisture Sensor** This sensor is sensitive to soil moisture changes and other factors including for example soil texture, water conductivity and temperature. This sensor must be calibrated "in situ" by an iterative process of adjusting water applications and making observations on turf quality. Related factors such as water conductivity changes during fertilization could change threshold stress and require a change of threshold setting values by the operator. The prime objective of the protocol is to characterize the sensors repeatability under known controlled conditions.
24	6.1.1 "Representative Bulk Densities (range 1.2 to 1.4)". What is the significance of the bulk density range?			Bulk density must be known and controlled to be representative of typical field conditions. Soil water content measurements are expressed on a mass water content basis (wcm) and some are expressed on a volume water content basis (wcv). The relationship between the two measurements involves bulk density (bd) as per the following equation: wvc = wcm (bd)
25	6.1.1 It would be interesting to record the depth of sensor placement.	✓		Documentation added to the protocol

Irvine Ranch Water District's application of signal paging to ET controllers for medium size commercial landscapes

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Introduction

Over the last 5 years, the Irvine Ranch Water District has joined with the irrigation industry, wholesale water suppliers, environmental groups and other government agencies to develop proper water management through weather based controllers. The results of IRWD's weather based irrigation management studies point to an impressive effective on irrigation water management. While past District efforts have focused on market forces to modify irrigation practices, the ET controller studies switched focus to providing the tools for water management.

In the Residential Run-off Reduction (R3) study, the District replaced 112 residential irrigation controllers with a weather based controller that used a combination of local (at the controller) programming and weekly schedule adjustments based on the change in evapotranspiration (ET). A remote operator adjusted the schedule by sending a paging signal. The controller's design allowed the irrigation to adjust for rain, heat, cloud cover and high wind conditions without requiring a landscaper's physical presence at the controller.

While the focus of the R3 study was conservation and run-off reduction in a residential setting, which included parks, streetscapes and condo associations. These landscapes are typically viewed as commercial sites or medium sized landscapes (MSL). A MSL for this article is 0.14 acres to 2 acres of actual landscape. The study team has concluded that MSL provides for the most effective water conservation and the team believes that most of the run-off reduction can be attributed to controllers in the 17 meters

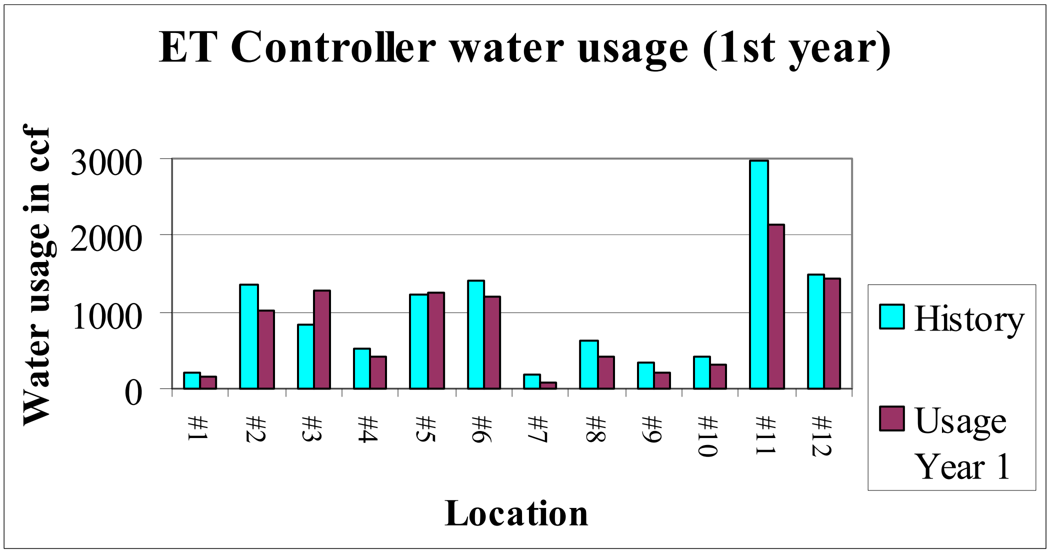
1st year of Water Savings

The R3 study consisted of 12 city streetscapes, 1 city park, 2 condo landscapes and 3 landscapes in a Home Owner Association (HOA). After the success of these larger landscapes, the District expanded the concept of using this type of controller to other MSL sites. IRWD installed ET controllers at manufacturing plants, offices building, and warehouses.

From a water district perspective, the critical question is water conservation. The chart, shown below, lists the historical usage of the individual meter associated with the City of Irvine landscapes along the street or in the street median and the city sites were well managed. This is reflected by comparison between the *Historical average* column to the *ET Year 1* and the *ET Year 2* columns. The ET is calculated by the IRWD weather station for 100% cool season turfgrass. Thus, the ET column contains the maximum water requirements for each site.

A discernable pattern occurs, the City landscape lead operators maintain the water usage with in 20% of the ideal water usage for 10 of the 12 sites. This is a tribute to the City of Irvine but only 4 of the 12 were below the ET usage. Prior to the installation of the paging ET controller, the City demonstrated a clear effort to manage the water and was fairly successful in the efforts. The 12 landscapes were just 3% over the expected water consumption for 100% turfgrass. The controllers were in installed at the 12 sites in the belief that weekly adjustments would result in more effective water usage. The lead operators could reprogram every city valve on a weekly basis but this would be costly.

The controllers were installed in the City landscapes. The results during the first year were impressive. 10 of the 12 landscapes were below the ET and 8 of the 12 used 85% of the measured ET or less. The total water usage on the sites was 14.5% less than the ET measured and 17.5% less than the historical average of the combined 12 sites. Equally important is the water usage after the first year.



Installation effort per year

During the 1st year, the controller required a higher degree of effort to install and maintain. The controller operated on a series of sequential calculations. This is the common method used through out the irrigation industry. The equations include the maximum runtime for sprinkler without run-off; the water holding capability of the soil to determine the number of irrigation days needs per week; to calculate the precipitation rate; calcualte a precise total runtime on any given irrigation day. This method of water management is a half-century old and applied by all educated irrigators through out the world. However, in the landscape industry, the level of education varies from college education to field worker that set controllers based on observation of other field worker with no background in landscape irrigation science.

In order for the controller to function, the controller is programmed with a series of factors that are specific to each valve. This includes the type of plant material, the slope factor, soil type and the sunlight exposure. However, the two most important factors are the precipitation rate and the root depth.

The root depth can vary from one area of the landscape to another. The operator could increase the number of irrigation days per week to adjust the root depth valve to accommodate the shortest plant root depth. This adjustment changes the schedule to assist the landscapers with brown spots caused by inefficient irrigation systems. Yet, the increase in the number of irrigation days does not increase the total volume of water applied during a day. The soil holding capacity calculations, which were performed by the controller, reduced the volume of water applied each day. Thus the total volume of watered applied during the week remained the same.

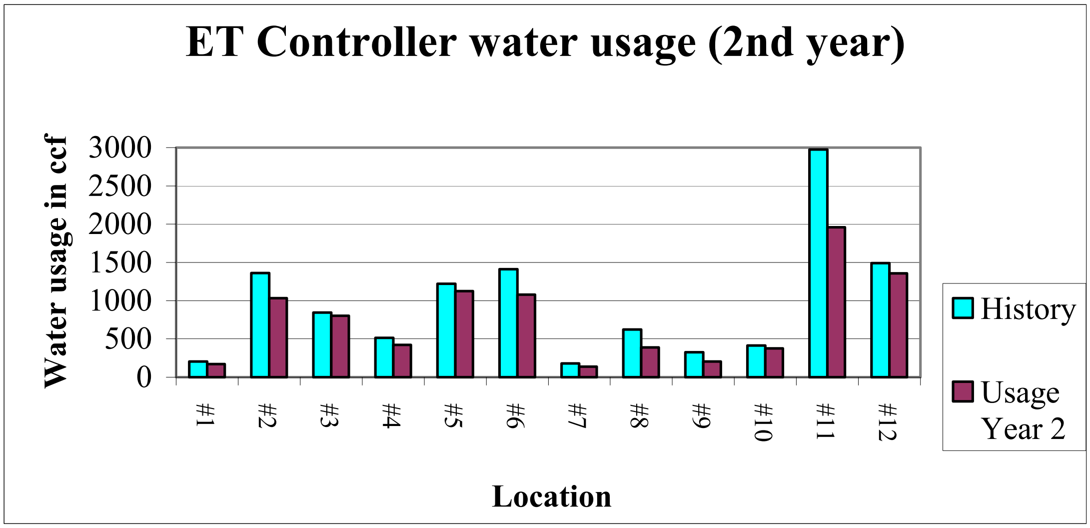
The second factor used to adjust the controller was the precipitation rate. The initial measurement of the precipitation rate was accomplished by an area/flow measurement. This provides the general range of the precipitation rate but the landscape has to be monitored. The monitoring allows the factors to be adjusted to improve the irrigation performance and deliver a proper irrigation volume to all parts of the individual landscape areas. This monitoring was time intensive during the installation period and continued for most of the first year to correct for the first generation controller used by the study. The landscapes were inspected on a weekly basis and the meters of each landscape were read to spot any hardware problems. This routine was significantly reduced after the first year.

At the end of the first year, two patterns emerged. The ET controller could be more successful with monitoring of the MSL than with the single family. Second, the consistently highly maintained landscapes of the City of Irvine do not completely reflect the water saving potential of the interactive weather based controllers. Therefore, IRWD installed additional ET controllers on other MSL landscapes. At the time of this report, 8 commercial location have completed a single year of continuous operation.

2nd year for City sites and the 1st year for commercial sites

The second year result was an improvement on the first year's accomplishment. All 12 sites were under the ET value for turfgrass. This is not surprising since all of the sites have a mixed use of warm season turfgrass and either trees or shrubs. 11 of the 12 sites had water usage below 75% of the ET value as measured by the IRWD weather station.

Additionally, during the second year of operations, the study group reduced the number of site visits. Both the City and IRWD noticed marked improvement in the performance of the controllers. The precipitation rate and root depth factors were fine tuned to the equations established by the controller's programming. The schedules adjusted according the ET signal with very little manipulation. When problems did occur in the landscapes, the majority of problems could be traced to physical problems with the hardware of the irrigation system and not with the irrigation schedule. The 2nd year demonstrated improved labor cost, greater efficiency and increased water savings.



Total water usage for a year in ccf

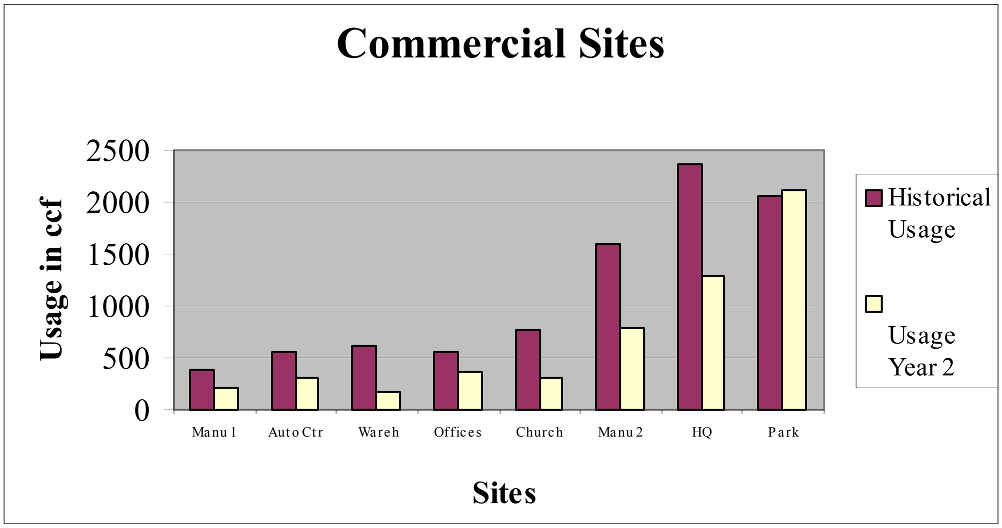
	Historical Average	ET Year 1	Usage Year 1	ET Year 2	Usage Year 2
Site #1	207	221	164	233	171
Site #2	1364	1484	1005	1561	1030
Site #3	845	1014	1269	1074	802
Site #4	512	559	407	590	424
Site #5	1219	1413	1244	1545	1122
Site #6	1414	1139	1201	1209	1080
Site #7	180	361	82	355	138
Site #8	624	557	414	590	387
Site #9	328	298	217	317	203
Site #10	413	588	316	624	376
Site #11	2976	2530	2139	2661	1958
Site #12	1492	1738	1437	1843	1357

Commercial Sites

Because the success of the controllers in city landscapes was greater than expected, the study team believed that 1 acre or less commercial property would benefit from this method of water management. Since the city site were regularly monitored by the city lead operators who had water management knowledge and irrigation education, the effect on sites that often are tended to by landscape crew without any irrigation experience or education should produce similar results.

The installation utilized the same audit system as the city sites. The installation team surveyed the individual valve. This included a valve-by-valve measurement of the landscape area and the flow rate. The precipitation rate was the controlling factor for water savings and improving the general appearance of the landscape.

Prior to the installation of the ET controller, only 2 sites of the 8 total sites in the study used a volume of water that was less than the ET volume measured by the local weather station. After the installation of the ET controller, only 1 site exceeded the ET volume. Even this site showed a reduction from previous years water usage. Notice that the park water usage increased from the historical 3-year average to the 2nd year controller water usage. However, when the ET for the historical years are factored into the equation, the park actually saved water.



		Prior to Installation			After Installation				
Location	Acres	ET Historical	Historical Usage	Differential in ccf	ET Year 2	Usage Year 2	Differential in ccf	Net Change in ccf	Percent Change Usage
Manufacturer 1	0.17	297	392	94	288	218	-70	-164	-54%
Auto Center	0.22	274	561	288	258	307	49	-239	-82%
Warehouse	0.23	389	624	235	379	176	-203	-437	-109%
Offices	0.24	412	549	137	401	356	-45	-182	-40%
Church	0.34	578	764	186	574	309	-266	-452	-84%
Manufacturer 2	0.52	890	1597	707	831	794	-38	-744	-62%
Headquarters	1.55	2640	2373	-267	2117	1296	-822	-555	-30%
City Park	1.91	2607	2060	-547	3016	2117	-899	-352	-17%
Totals	5.18	8087	8919	832	7864	5572	-2293	-3125	-43%

Conclusion

The most important conclusion is that residential ET controllers, the City of Irvine ET controllers and the commercial ET controllers is that the weather based scheduling must include precipitation rate, internal calculation for run-off reduction and actual schedule adjustments from a signaled ET value or rain pause. The method of the signal is less important than the ability to change the irrigation schedule without the need for a person to be present at the site.

Second, the potential for water savings in the commercial setting and the corresponding run-off reduction is high. The single controller covers 0.17 to 1.91 acres as compared to a residential controller that manages the water for just 0.04 acres. The potential for saving water through water management is greatest for the large landscapes. The residential water users do not incur a high enough volume of water to justify the expense of a full-time water management operator.

Finally, the comparison of the first year after the installation to the second year after the installation indicates that the water savings continues. The second year may prove to increase the savings with less attention. Once the program is adjusted for the various anomalies in the irrigation system, the regular ET signal serves to maintain the water management without a need for manual overrides. This should result is cost saving to the customer for reduced water charges and reduced labor charges.

Climate-Based Irrigation Scheduling for Warm Season and Cool Season Turfgrasses

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ABSTRACT

Recent droughts and increasing demands for limited water supplies in the arid southwestern U.S. have caused many municipalities in the region to impose water restrictions that have reduced the volume available for urban irrigation. The potential adverse effects of these reduced water supplies on landscape quality, however, can be mitigated through careful irrigation management and selection of drought-tolerant species for planting. During 2002 and 2003, turfgrass crop coefficients (relationships between measured turf evapotranspiration [ET] and climate-based, Penman-Monteith reference ET [ETo]) formulated during a three-year study (1998 – 2000) at Farmington, New Mexico were used to schedule irrigations on established cool season and warm season turfgrasses. The ET estimates derived from the coefficients were designed to equal the minimum water required to maintain acceptable turfgrass quality. The crop coefficients (Kc) functioned well for turfgrass irrigation scheduling between early April and late October during 2002 and 2003 in Farmington. A correction ratio must be employed, however, if the Kc is used for scheduling irrigations at sites having significantly different growing season lengths than Farmington's.

INTRODUCTION

Booming population growth in the southwestern United States has placed an ever-increasing demand on available water supplies in the region. Due to below average precipitation in much of the area in recent years, many water storage reservoirs and groundwater aquifers used to help provide for this demand, are at their lowest levels since being filled. Consequently, municipalities such as Denver, Albuquerque, Santa Fe and Las Vegas, and many smaller communities, have imposed restrictions on the amount of water that can be used for irrigating landscapes. Potential adverse effects of reduced water availability on landscape quality, however, can be mitigated through wise irrigation scheduling and selection of drought-tolerant species for planting.

Irrigation scheduling techniques can be categorized as climate based or soil based but aspects from both categories should be used for high efficiency water management. In climate based turfgrass irrigation scheduling, an accurate estimate of the turf's water-use or evapotranspiration (ET) at various times during the growth cycle is required. These ET requirements, while primarily a function of climatic factors (air temperature, solar radiation, humidity, and wind), are also related to grass species or cultivar, growth stage or size of the plant, and cultural practices. By correlating measured ET to a reference ET (ETo) calculated from weather data, crop coefficients (ET/ETo or K_c) have been developed that can be used to derive a baseline estimate of actual crop ET on a daily basis if local weather parameters are available. Most states of the southwest maintain a network of automated weather stations that provides the data necessary to calculate ETo at various locations within each state. These weather data (along with ETo calculations) are downloaded periodically to a central computer and are usually made available to the public through the Internet. In many cases, K_c and irrigation scheduling recommendations for various agricultural crops and turfgrasses are also provided at the web sites. Unfortunately, a K_c provided for a particular turfgrass at a given site or region may not be suitable for a similar grass at a different site or region. This may be due not only to differences in the length of growing seasons between the two sites but also to differences in the method used to calculate ETo at the sites. To compensate for growing season variability between sites, the use of heat units as a time scale (in lieu of day of year, days after planting, etc.) has been suggested (Sammis et al., 1985; Slack et al., 1996). Heat units, expressed as cumulative growing degree-days, provide an indication of the phenological and physiological development of the crop and this development relates to ET. To compensate for K_c variability due to different ETo methods used between sites, it has been recommended by a panel of experts (ASCE, ASAE, and IA) that the FAO 56 Penman Monteith equation (Allen et al. 1998) be used as a standard. This would alleviate some of the confusion in comparing K_c and ET estimates between sites.

As previously mentioned, variability in K_c for a given grass can even occur between sites located within very similar climatic zones because of varietal (Shearman, 1986; Bowman and Macaulay, 1991), cultural (Feldhake et al., 1983; Richie et al., 2002), and microclimatical (Feldhake et al., 1983) differences between the sites. Nonetheless, regional K_c values can serve as valuable baseline indicators (or starting points) that can be fine-tuned for specific situations at a particular site.

Differences in ET requirements between cultivars of the same species appear to be minimal (Shearman, 1986; Bowman and Macaulay, 1991) or insignificant (Green et al. 1991; Ebdon et al., 1998; Atkins et al., 1991) compared to the differences in ET requirements between warm season (bermudagrass, buffalograss, blue grama, etc.) and cool season (Kentucky bluegrass, tall fescue, perennial ryegrass, etc.) turfgrasses (Kneebone and Pepper, 1982; Kim and Beard, 1988; Gibeault et al., 1989; Qian and Fry, 1997). In a California study (Meyer and Gibeault, 1987) for example, 36% less water was needed for acceptable quality of warm season grasses than cool season grasses. Seasonal K_c, referenced to a modified Penman ETo (Doorenbos and Pruitt, 1977), averaged 0.6 for the warm season grasses and 0.8 for the cool season grasses. In southern Nevada, Dean et al. (1996) showed that turf quality declined when irrigation/ETo ratios dropped below 0.65 and 0.8 in bermudagrass and tall fescue, respectively, when referenced to a modified combination Penman (Campbell Scientific) ETo. In a Kansas study, Qian et al. (1996) reported tall fescue ET to be 35% higher than bermudagrass ET during a two-year period.

Much of the research resulting in the formulation of K_c for turfgrass has been accomplished in desert environments (Kneebone and Pepper, 1982; Kopec et al., 1992; Devitt et al., 1992; Mancino, 1993; Brown et al., 2001) or in southern California (Meyer and Gibeault, 1987). Borrelli et al. (1981) published a summary of Blaney-Criddle K_c for those areas plus Wyoming and northern Colorado, while Hill (1998) suggested seasonal mean K_c for cool season turfgrass on golf courses in northern Utah. Aronson et al. (1987) formulated K_c for cool season turfgrass at a humid site in southern New England. Limited information related to the ET requirements (or K_c) for acceptable quality of warm and cool season grasses in the turf transitional zone of the U.S. is available.

The objectives of this research were to: 1) identify the ET requirements for acceptable quality of several warm season and cool season turfgrasses in the transitional zone; 2) formulate crop coefficients (using the suggested standard Penman Monteith ETo) that may be used to efficiently schedule irrigations on turfgrasses; and 3) validate the crop coefficients by using them to schedule irrigations on established turfgrass plots.

METHODS AND MATERIALS

Site Description

This study was conducted in northwest New Mexico at New Mexico State University's Agricultural Science Center at Farmington. The site is located at 36^{o} 41' N latitude by 108^{o} 18' W longitude at an elevation of 1720 m (5640 ft) above mean sea level. The average annual precipitation at the semi-arid site is 21 cm (8.2 in). The soil type is a Kinnear very fine sandy loam (Anderson, 1970) having a total water holding capacity of 6.9 cm (2.7 in) in the upper 45 cm (18 in) of the profile. Based on soil moisture measurements at permanent wilting however, only about 60% or 4.1 cm (1.6 in) of this water is presumed to be available. Although Kentucky bluegrass and tall fescue are the most common lawn grasses in residential areas, native, warm season grasses such as blue grama and buffalograss are being increasingly planted for turf. Cold tolerant bermudagrass and zoysia are two other warm season grasses that can be grown successfully in the region.

Plot Design

Two separate sprinkler-line source plots (Hanks et al., 1976) were used to provide irrigation treatments to six cultivars of warm-season grasses and seven cultivars of cool season grasses in 1998, 1999, and 2000 (Table 1). Each plot consisted of a single sprinkler line that applied a continuous, decreasing gradient of water to each grass on each side of the line with increasing distance [0 to 14 m (0 to 45 ft)] away from the line. Catch-cans, to collect applied water for measurement after each irrigation, were located at 2.3 m (7.5 ft) intervals away from the line. Neutron probe access tubes were installed to a depth of 1.5 m (5 ft) in four grasses in each plot at equal distances from the line as the catch cans. Soil moisture measurements were taken at these localities in depth increments of 15 cm (6 in) in the top 45 cm (18 in), and 30 cm (12 in) increments in profile depths below 45 cm about every 10 days during the active growing season using a neutron probe (Troxler model 4302). Turf ET per period was calculated using the water balance equation:

$$ET = I + P \pm \Delta SW - D$$

Where…

I = depth of irrigation (in)

P = depth of rainfall (in)

ΔSW = change in soil water, 0-135 cm

D = estimated drainage below 135 cm

Heat units, expressed as growing degree-days (GDD), were used as an indicator of grass phenological development during the growing seasons. Daily GDD were calculated using the following equations:

Cool Season Grass:

$$GDD = (T_{max} + T_{min})/2 - 4.4^{o}\,C \text{ (base)}$$

$$*(T_{max} \text{ cutoff} = 40.5\ ^{o}C,\ T_{min} \text{ cutoff} = 4.4^{o}\,C)$$

Warm Season Grass:

$$GDD = (T_{max} + T_{min})/2 - 15.5^{o}\,C \text{ (base)}$$

$$*(T_{max} \text{ cutoff} = \text{None},\ T_{min} \text{ cutoff} = 15.5^{o}\,C)$$

Where…

Tmax = daily maximum temperature (^oC)

Tmin = daily minimum temperature (^oC)

*Observed temperatures above Tmax cutoff were set to Tmax and temperatures below Tmin cutoff were set to Tmin prior to calculating the mean.

Climatological data (air temperature, relative humidity, solar radiation, wind speed, and precipitation) were recorded with an automated weather station (Campbell Scientific, Inc. Model CR10) located about 60 m (200 ft) east of the plots in an area planted to cool season grass. Penman Monteith reference ET (ETo) was calculated using an Excel spreadsheet (Snyder and Eching, 2002) available on line at: http://biomet.ucdavis.edu/evapotranspiration/PMdayXLS/PMday.htm.

Irrigations were applied two to three times per week at a depth required to maintain soil moisture at a level near field capacity in the top 45 cm (18 in) of the soil profile at subplots located 4.6 m (15 ft) from the line-source. Total irrigation applied during 1998 (from low to high irrigation treatment) ranged from 40 cm (15.8 in) to 91 cm (35.8 in) in the warm season plots and from 64 cm (25.1 in) to 110 cm (43.5 in) in the cool season plots. In 1999, treatments ranged from 22 to 52 cm (8.8 to 20.3 in) and from 36 to 75 cm (14.3 to 29.6 in) across the warm season and cool season plots, respectively. In 2000, irrigation ranges were 33 to 73 cm (13.1 to 28.6 in) in the warm season plots and 43.4 to 99 cm (17.1 to 39.0 in) in the cool season plots. During the active growing period of the warm season grasses (early May to early October), rainfall amounts were 9.4, 18.5, and 6.9 cm (3.7, 7.3, and 2.7 in) in 1998, 1999, and 2000, respectively. While the cool season grasses were actively growing (early April to late October), they received 17.5, 22.1, and 12.4 cm (6.9, 8.7, and 4.9 in) of precipitation in 1998, 1999, and 2000, respectively.

All grass plots were mowed weekly throughout the active growing seasons using a riding mower equipped with a rotary mowing deck and two mulching blades. All grasses, except the blue grama, were cut to a uniform height of 6.5 to 7.5 cm (2.5 to 3 in) at all irrigation levels. In mid-June of 1999, it appeared that low mowing was having an adverse effect on blue grama quality and mowing height was adjusted to 9 to 10 cm (3.5 to 4.0 in) for that grass only.

Balanced fertilizers were applied to the plots in small quantities per application five to seven times during each growing season. Total seasonal N, P (as P_2O_5), and K (as K_2O) averaged 22.7, 8.3, and 6.9 kg/1000 m^2 (4.7, 1.7, and 1.4 lbs/1000 ft^2) respectively, in the warm season grasses, and 24.4, 16.6, and 22.5 kg/1000 m^2 (5.0, 3.4, and 4.6 lbs/1000 ft^2) respectively, in the cool season grasses. Appropriate pest control techniques for weeds, insects and diseases were used throughout the three-year study period to maintain turfgrass quality.

Independent judges and/or research personnel evaluated the grass plots on several occasions during each growing season. Turf acceptance at each irrigation level was based on general turf appearance and quality considering factors such as color (greenness), density, uniformity, incidence of disease, and blade texture. The water requirement was defined as the ET measured at the location farthest away from the line-source where turf quality was judged to be acceptable. In most cases, this subplot occurred at a location equidistant from the line as the soil moisture and catch can measurements. In cases where the acceptable level was located in-between catch-cans, ET was interpolated.

Table 1. Cultivars and planting rates of warm and cool season turfgrass varieties included in the Farmington irrigation study.

Cultivars	Seed Planting Rate kg/1000 m^2 (lbs/1000 ft^2)
Warm Season Turf	
Bison Buffalograss	24.9 (5.1)
Tatanka Buffalograss	25.9 (5.3)
Texoka Buffalograss	26.4 (5.4)
Guymon Bermudagrass	13.7 (2.8)
N.M. Sahara Bermudagrass	7.3 (1.5)
Lovington Blue Gramagrass	11.2 (2.3)
Cool Season Turf	
Adelphi Bluegrass	18.1 (3.7)
Ascot Bluegrass	16.1 (3.3)
Coventry Bluegrass	18.6 (3.8)
Goldrush Bluegrass	17.6 (3.6)
Park Bluegrass	17.1 (3.5)
Seville Perennial Ryegrass	51.3 (10.5)
Shenandoah Tall Fescue	47.9 (9.8)

Planting dates:
Warm-season grasses: July 7-11, 1997
Cool-season grasses: September 9, 1997

RESULTS AND DISCUSSION

Total Seasonal ET

Total seasonal measured ET resulting in acceptable turfgrass appearance and quality over all three years averaged 64 cm (25 in) in the warm season grasses and 94 cm (37 in) in the cool season grasses. There were slight differences in the measured ET required to produce acceptable quality between grasses within each grass type (warm season and cool season). In the warm season grasses, the Bison and Texoka buffalograsses used about 7% less water than the Guymon bermudagrass (61 cm vs. 66 cm, respectively), while the blue grama ET was intermediate (64 cm). The Sahara bermudagrass suffered winterkill damage and would not be recommended for the Farmington area. In the cool season grasses, the Adelphi bluegrass used a few cm less water than the other grasses (89 cm vs. 91 cm) for acceptable quality while the perennial ryegrass required about 97 cm (38 in). Due to apparent heat stress however, the ryegrass was given low quality ratings at the highest irrigation levels in mid summer.

A study conducted in southern California by Meyer and Gibeault (1987) showed that warm season and cool season grasses required 134 cm and 209 cm, respectively, for acceptable quality. This more than twofold difference in seasonal water requirements between northern New Mexico and southern California demonstrates the importance of growing season length in turf ET estimation.

Consumptive-use (Daily ET Patterns)

Seasonal consumptive-use patterns at the minimum acceptable irrigation level varied only slightly between turf species but were quite different between the cool season and warm season grasses. The cool season grasses greened up in mid to late March and exhibited a faster rate of growth in the spring than the warm season varieties, which did not green up until late April or early May. Daily water use rates in the cool season grasses increased rapidly after green-up and peaked in June and early July at an average rate of 0.58 cm (0.23 in)/day (Fig. 1A). This peak rate is nearly identical to the mean measured ET rates of Kentucky bluegrass and tall fescue (0.57 and 0.58 cm, respectively) grown in lysimeters from June 8 to August 16, 1981 in northern Colorado by Feldhake et al. (1983).

Daily ET rates of the warm season grasses increased more slowly than the cool season grasses in spring and early summer and the average peak daily ET rate of 0.46 cm (0.18 in)/day was not reached until mid July (Fig. 1B). This peak value is very similar to those means reported by Feldhake et al. for bermudagrass (0.45 cm) and buffalograss (0.45 cm) in the Colorado study during the same seasonal time frame.

Greater peak daily ET rates for both warm season and cool season grasses than those measured at Farmington and Colorado have been reported in hotter climates. Kneebone and Pepper (1982), for example, measured rates as high as 0.64 cm (0.25 in)/day for warm season grasses and more than 0.85 cm (0.34 in)/day for cool season grasses in southern Arizona, while in Texas (Kim and Beard, 1988), ET rates averaged 0.56 cm (0.22 in)/day for bermuda, buffalo and blue grama grasses, and 0.71 cm (0.28 in)/day for tall fescue.

Crop Coefficients (ET/PET)

While the consumptive-use curves (Fig. 1) can be of value for scheduling irrigations in Farmington (or similar climatic area) during a typical season, as shown by the studies cited, due to climatic variability between seasons and sites, they may be of limited value during unusual weather patterns or at sites having significantly different climate than Farmington. To compensate for this variability, a seasonal K_c curve was formulated for each type of grass using the Penman Monteith (PM) ETo (Figs. 2 A and B). To further compensate for the effects of temperature on the initiation and duration of the active growing (green) period, and on plant growth and development during the season, K_c was plotted against cumulative growing degree-days (CGDD) rather than day of year.

The average K_c for cool season grass rose sharply from 0.3 to 0.9 between 300 and 1200 CGDD (Fig. 2A). This generally corresponded to the time period from late March to early June. From early June (1200 CGDD) to mid September (3000 CGDD), K_c averaged about 0.85. This mean is nearly identical to the average cool season K_c reported during a similar timeframe in Irvine, California by Meyer and Gibeault (1987) using the California Irrigation Management Information System (CIMIS) modified FAO 24 Penman ETo (Doorenbos and Pruitt, 1977). A comparison between a modified FAO 24 ETo (http://weather.nmsu.edu) and the PM ETo, using climate data from Farmington between 1998 and 2000, however, showed that PM ET_o = 0.785 x Penman FAO 24 ETo. If the modified Penman equations used by CIMIS and the NMCC (New Mexico Climate Center) are similar, Meyer and Gibeault's K_c would become 1.08 when referenced against the PM equation.

The K_c for warm season grasses (Fig. 2B) increased from about 0.15 to 0.75 within the CGDD range of 50 to 500 (about mid April to the end of June). Between 500 and 1200 CGDD (June 1 to early October) K_c averaged about 0.7. This is very similar to the mean K_c of 0.68 reported by Meyer and Gibeault (1987) between June and September for warm season grasses in California. Again however, their K_c, if referenced to the PM ETo, would be closer to 0.87. Brown et al. (2001) found that PM referenced K_c for bermudagrass in Arizona in the summer ranged from 0.78 in June and July to 0.83 in September. While the 0.78 K_c for July in Arizona agrees with the July K_c at Farmington, bermudagrass growth (and ET rate) slows considerably (relative to ETo) as temperatures begin to decline in late August and September and the K_c drops to about 0.65 at Farmington (Fig. 2B).

Validating the K_c

To validate the crop coefficients formulated in our study, they were used to schedule irrigations on established cool season and warm season turfgrasses using two solid-set sprinkler irrigation systems in 2002 and 2003. Additionally, in 2003, two new line source studies (warm and cool season grasses) were initiated and the formulated K_c were used to provide 100% of estimated ET to plots 4.6 m (2 catch cans) away from each line source. Irrigations were scheduled to replace estimated ET when 40% and 60% of available water in the top 45 cm (18 in) of the soil profile was depleted in the cool season and warm season grasses, respectively, minus precipitation. This equated to a maximum allowable depletion of 1.6 cm (0.64 in) in the cool season turf and 2.4 cm (0.96 in) in the warm season turf. Using this technique, irrigation system runtimes stayed relatively constant throughout the season while irrigation frequency varied. Irrigation efficiency was assumed to be 100%. A 45 cm (18 in) soil-sampling probe was used to periodically check soil moisture.

Between April 9 and October 25, 2002, the cool season grasses were irrigated with 83 cm (32.8 in) of water in 48 applications, while the warm season grasses were irrigated with 62 cm (24.5 in) in 42 irrigations. An additional 6.8 inches of precipitation that fell on the plots between April 1 and November 10 resulted in total water application depths during this period of 102 cm (40 in) and 79 cm (31 in) in the cool and warm season grasses, respectively. These totals were nearly equal to the seasonal ET estimates of 104 cm (41 in) and 76 cm (30 in) for the respective grasses using the formulated K_c.

Irrigation water was not available from October 25, 2001 to April 8, 2002 and the grass plots received only 1.58 inches of precipitation during this period. Consequently, the cool season grasses did not green up and begin using water until a deep irrigation (2.05 inches) was applied on April 9 to replenish soil moisture that had been depleted from the top two feet of the profile after October 25, 2001 when these grasses were still actively growing. Had sufficient soil water been available, the cool season grasses would have broke dormancy and began using water in March based on estimated ET. A deep initial irrigation was not required in the warm season grasses since they went dormant prior to October 25, 2001 and did not extract significant soil moisture during the winter.

In 2003, 4.5 cm (1.8 in) of precipitation in February and March recharged the soil moisture somewhat so that the cool season grasses began greening up during the third week in March. Cumulative irrigation then followed cumulative estimated ET closely through August in both the cool season and warm season grasses. Visual symptoms of water stress were not observed in any plots that received irrigation depths equal to estimated ET.

SUMMARY

The crop coefficients developed from the 1998 to 2001 study functioned well for turfgrass irrigation scheduling between early April and late October in Farmington, New Mexico. While this is sufficient for warm season grasses at this site, some adjustments may be required at the beginning and end of the crop coefficient if used to schedule irrigations on cool season turf during the winter. During this study, irrigation water was available between the first week in April and the third week in October. In the Farmington area, cool season grasses can begin to green up in late February to early March, and may not enter dormancy until late November if sufficient soil moisture is available. Measurements of ET taken during March and November in years when sufficient soil moisture was available for growth of cool season grass, however, indicate that total monthly ET is probably less than 5 cm (2 in) within each month.

Adjustments must be made to the K_c curves of both grasses before they can be used to schedule irrigations at sites having different growing season lengths than Farmington's. This can be done by applying a correction ratio to the curve based on differences in cumulative growing degree-days (CGDD) between sites. Possibly, CGGD expressed in relative terms (i.e. CGDD/total GDD for site) can also adjust for this difference. This would expand or compress the K_c curve to accommodate longer or shorter growing seasons, respectively.

Most of the previously published K_cs for turfgrass have been referenced to a Penman or modified Penman ETo. If the maximum or mean Kc of these studies are adjusted by the 0.785 ratio between the PM method and FAO-24 Penman method as suggested by this report, the maximum or mean K_c at Farmington are generally lower than those formulated elsewhere. This is probably due to the methods used to define measured ET. In most other studies, turf ET was measured from lysimeters that were heavily irrigated and the grasses were never stressed for water. In the line-source experiment at Farmington, the K_cs were derived from ET measurements taken at the lowest irrigation treatments that exhibited acceptable quality. This may have resulted in some water stress but it was not visually exhibited.

The crop-coefficients presented in this report are designed to serve as a guide only. While they are valuable in establishing a baseline for irrigation scheduling, they are not designed to replace actual field observations. Irrigation management strategies must always consider factors such as proper irrigation system design and maintenance, water application efficiencies, microclimatic influences, soil characteristics, cultural factors and other variables. There is no substitute for the wise use of a soil-sampling probe to monitor soil moisture at various locations in a landscape on a regular basis.

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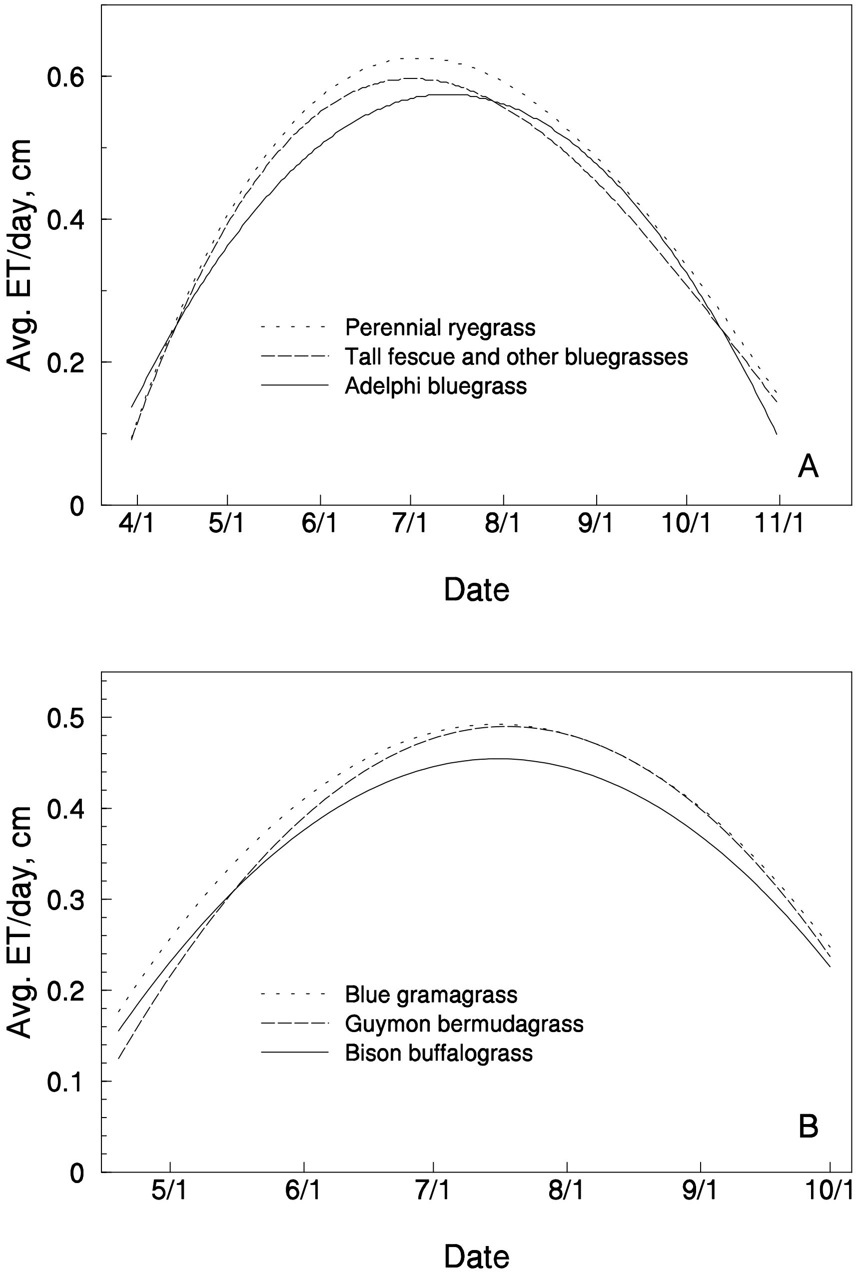

Fig. 1 (A & B). Average daily measured evapotranspiration (ET) of cool season (A) and warm season (B) turfgrasses at Farmington, NM over three years (1998, 1999, and 2000).

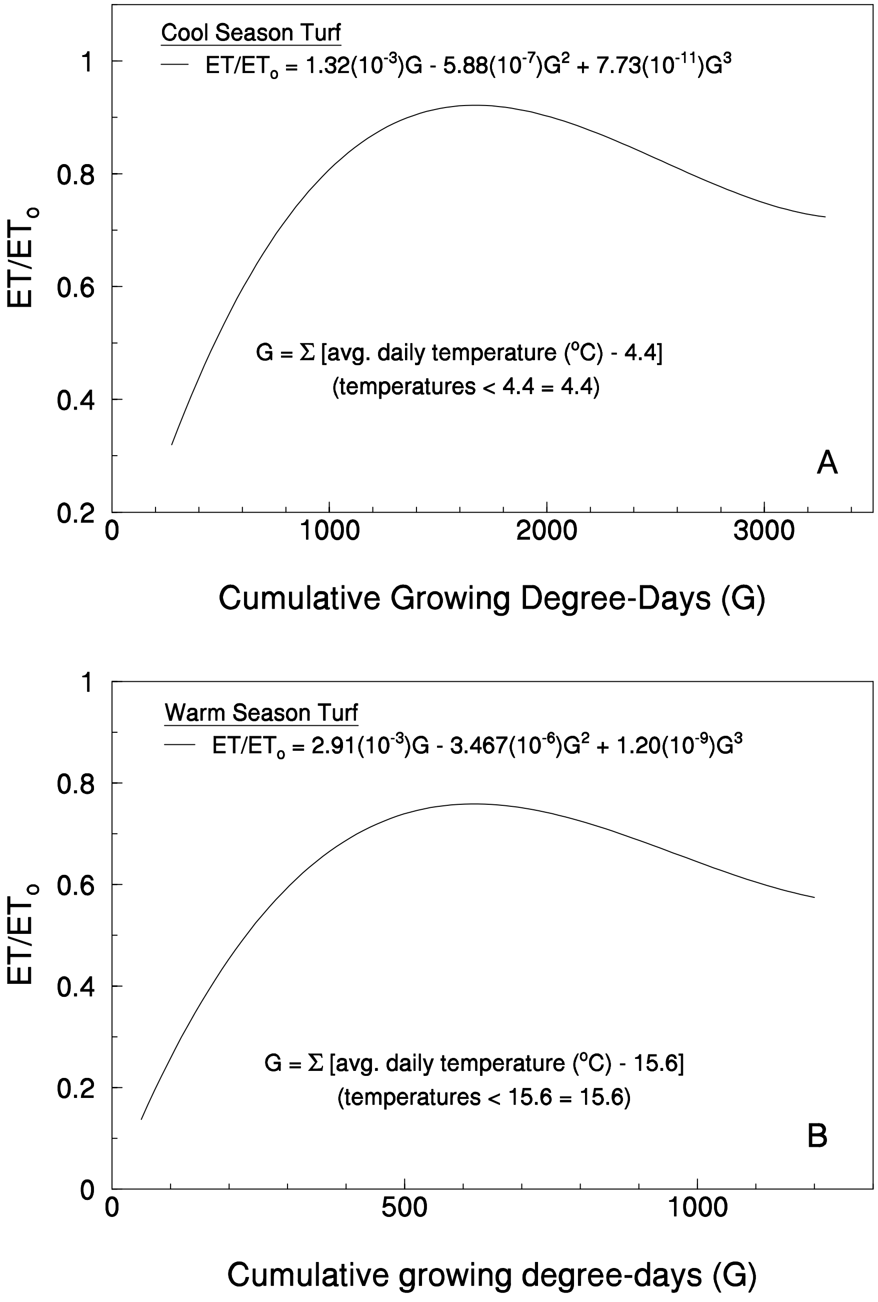

Fig. 2 (A & B). Crop coefficients for cool season (A) and warm season (B) turfgrasses at Farmington, NM. (ET = measured evapotranspiration, ET$_o$ = Penman-Monteith reference ET).

City of Tustin and Irvine Ranch Water District Study:
Wick irrigation to beautify, save water and meet the run-off regulations

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Introduction

Since 1996, the concept of wick irrigation has never fully developed as common method of irrigation. The initial tests of wick irrigation demonstrate a new means to apply water to turfgrass. The application of wick irrigation eliminated key problems associated with traditional irrigation methods. Primarily, traditional irrigation sprinklers have low efficiency and wastes water through runoff. Wick irrigation is has a higher efficiency because of its design. Wick is a series of low volume emitters. The spacing and the flow rate are calculated using the soil type, and the slope.

The major reason for the development of wick irrigation study was the unique nature of the Jamboree Median in the City of Tustin. The city was dedicated to maintaining the appearance of the median and preferred a turfgrass site. Yet, many factors work again sprinklers in this location. Street median require the full amount of Evapotranspiration (ET) for turfgrass. The median is in a corridor between the ocean area of Newport Beach and the desert area of Riverside. The corridors of this nature tend to experience high winds on a regular basis. Because of these conditions, transplanting other plants material may not solve the three main problems associated with the median.

The city recognized the need for a different approach to maintain. The first element is the landscape appearance of the City of Tustin. The traditional sprayheads have never produced a healthy turf area. Second, Tustin cooperates with IRWD in water conservation but this area had continuous problems with over usage to maintain even a sub par appearance. Finally, the new storm water permit changes both Tustin's and IRWD's emphasis on irrigation runoff. Excess watering as demonstrated in the Residential Runoff Reduction Study is directly related to runoff.

The study is a work in progress but the 5 months of operation suggests general conclusion are possible at this time. A further analysis is planned after the full year of operation of the wick irrigation system.

General Study design

The wick irrigation study consists of 5-metered areas. The first site is the wick irrigation. This site's irrigation consists entirely of wick emitters. The second site is a combination of rotors with wick emitters along the outside by street. The rotors are set in from the curb by 2 feet. The outside 2 feet are watered by the excess irrigation of the rotors and the wick emitters. The last three meters are control meters. There is a single valve, which is similar in size to the wick irrigation site.

In addition, the single valve control site and the 2 wick sites are sub-metered from 2 metered landscapes. These two meters have over a decade of the irrigation history. The meters are part of the IRWD landscape irrigation allocation system, which is based on IRWD's tiered rate structure. This will allow for a historical comparison for water conservation.

Appearance

While it can be argued that conservation and runoff reduction should be regarded as the advocate for changing irrigation systems, cities, businesses and residents demand a solution that focuses on their main irrigation concern. That concern is a healthy landscape. The authors and a representative from the city of Irvine evaluated the general appearance.

The ranking of the turf was performed on a bi-monthly basis. The ranking was done in three categories: Color, density and presence of weeds. The general appearance was discussed among the group and the consensus is listed in the chart below.

	16-Apr	14-May	16-Jul	17-Sep
Wick				
Color	5	4	5	4
Density	3	3	5	3.5
Weeds	3	2	4.5	3.5
Sprayhead- Wick				
Color	5	4	3	3
Density	3	3	2.5	2.5
Weeds	3	3	4	3.5
Control				
Color	5	3	2	2
Density	3	3	2	2.5
Weeds	3	3	4	3.5

The rankings show that the wick irrigation has out performed the traditional sprayheads in the same type of landscape in the side-by-side plots. The general evaluation is that the wick irrigation and the side strips that are augmented by wick irrigation have a very good overall appearance. The general appearance of the traditional sprayhead area is a fair overall appearance with noticeable dry spots. These dry spots are several feet in width, in many parts of the landscape and brown spots are visible even at a distance. While the wick has dry spots, there are few of them; none is greater that a foot in width, and the brown spot are not visible at a distance.

Runoff

The runoff is qualitative at this time. The study sites do not lend themselves to volume measurements. The observation is two parts. The first observation is a black resurfacing strip. The length of the three sites has been resurfaced with a stripe of 9 inches in width. The second observation is the actual operation of the wick, the wick combination and the traditional sprayheads.

The visual change in the black stripes or the surface of the road is only long term change. Members of the study team agree that there is a noticeable difference on the road surface. The water residue marks the road along the traditional system but not at the wick or the wick combination. However, the erosion of the black stripes is not noticeable. It should be cautioned that the winter rains may remove any noticeable different between sites.

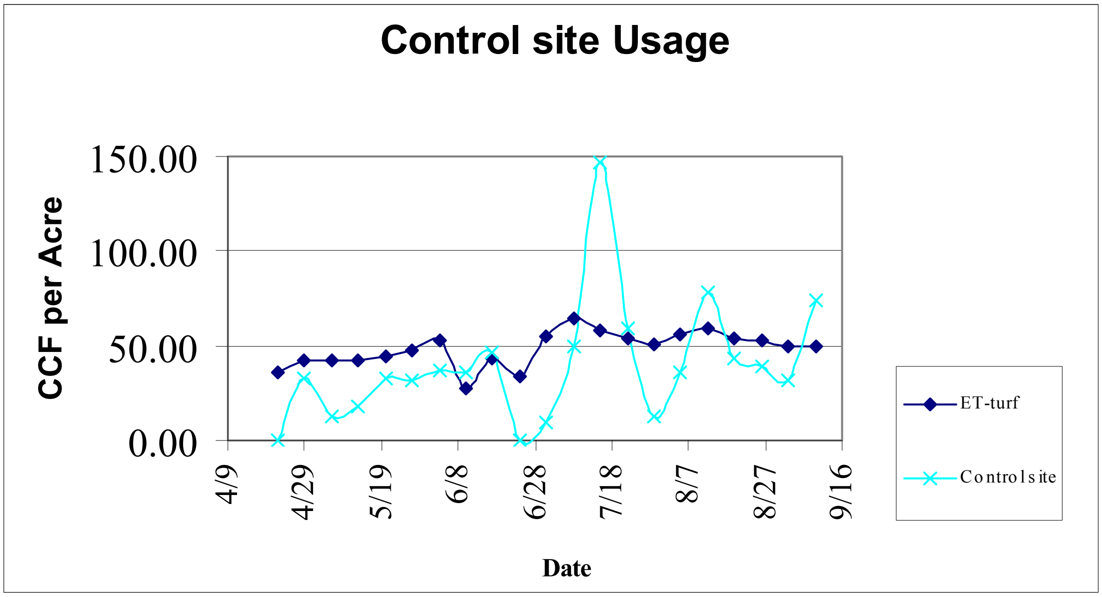
The direct operation of the irrigation at each site leads to a better understanding of the difference in runoff. The operation of the three different systems demonstrates the runoff reduction of potential. The traditional sprayheads were activated for 6 minutes. This was the setting on the controller prior to the study. After the sprayheads were active for 2 minutes, water began to runoff the site. At the end of the 6 minutes, water had sheeted across 1 full lane and a few streams ran from the median to the other side of the street.

The wick combination had limited runoff. The operation of the rotors was angled to so that the spray extended past the line of rotors. The heads' angle allowed the irrigation stream to touch the curb. This resulted in a small amount of water wetting the pavement. The largest wetted pavement covered an area of approximately 4 feet in length and 1 foot width from the curb. None of this water crossed the lanes from the median to the other side of the street.

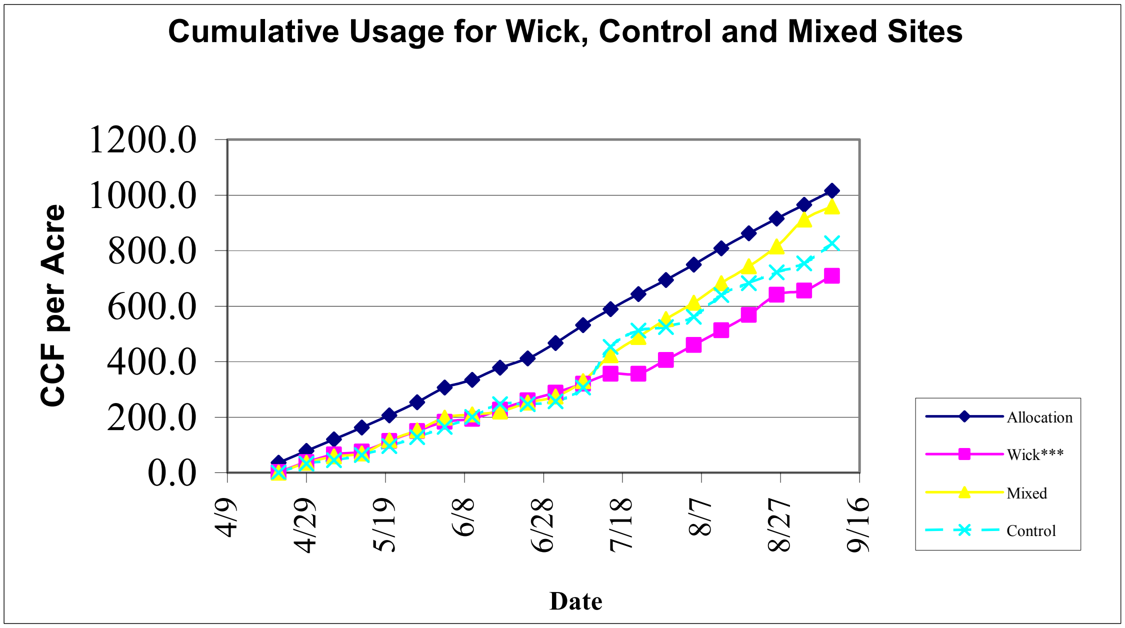
The study team operated the wick system for a full 40 minutes as a trial test of the system. The first two trials resulted in no runoff but after a rain, a third trial resulted in some water seeping out a few cracks in the curb. The largest observed wet spot was less than 1 foot wide and approximately 2 feet in length.

Conservation

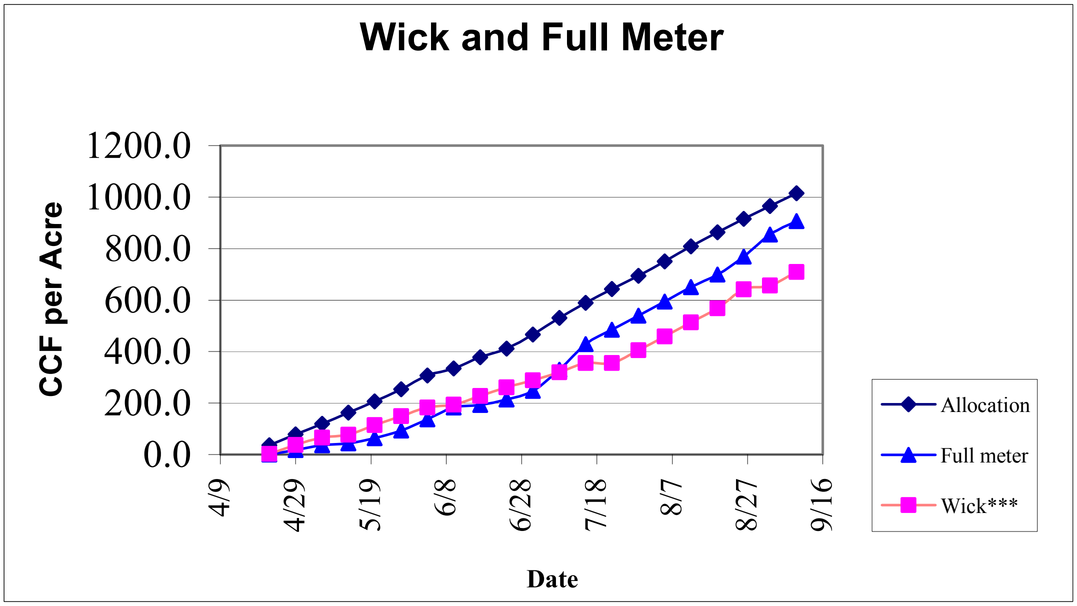
The actual value of the volume of water conserved is difficult to determine at the present time. Several factors have worked against the study. Malfunctioning controllers and a car accident which knocked down a controller added unforeseen problems. The result of the malfunctions was that the control site did not receive regular irrigation for several weeks. The graph (Control site usage) shows the erratic usage during that period.



After a full year, the statistical noise caused by the accident will be less significant. The following graph (Cumulative Usage for Wick, Control and Mixed sites) shows that cumulative usage of the three sites: the wick site, the mixed site (wick irrigation strips and rotors) and the control site. These three sites are side-by-side landscapes of similar size, weather and plant material to compare water saving. The water usage should be the same but the wick irrigation used less water.



An alternative comparison of water usage is the utilization of the Full meter. The wick site is a sub-meter to the Full meter. The remainder of the Full meter's landscape surrounds the wick site. When the Full meter usage and wick site usage are adjusted to the usage to a per acre basis, the usage should be the same. The graph (Wick and Full Meter) below shows that the wick irrigation used less water. Evaluation of the volume of water saved should be calculated after the completion of one full year of operation.



Conclusion

Wick irrigation can beautify the landscape and maintain the landscape as well as if not better than traditional sprayheads. Wick irrigation works well in turfgrass in summer and in an area where high winds limit the effectiveness of other systems. While wick may not replace all applications for sprinklers, wick irrigation can play a significant role in future developments of landscape irrigation.

Second, wick can reduce or eliminate run-off. This appears to be true for both the full wick irrigation system and the mixed system of wick irrigation and rotors. Runoff reduction is becoming an increasingly important environmental issue.

Finally, the study will continue for the full year before calculating the conservation savings. However considering the problems encountered, it can be further suggested that a second year of data may enhance the understanding of wick and the conservation potential. Especially since the data suggests water saving despite the controller problems, a second year of data might prove larger savings.

1 Hung, Joe Y.T., Joe Byles, Eudell Vis, Ramesh Kumar (1996) Wick Irrigation for Lawn, Irrigation Association International Exposition and Technical Conference, San Antonio Texas.
2 Joe Y.T. Hung, Eudell Vis (1997) Wick Irrigation For Turfgrass Field, ASAE Annual International Meeting, Minneapolis, Minnesota.
3 Joe Y.T. Hung, Arturo Mandoza (1996)

Irrigation Association - Water Management Committee

The IA has developed these Best Management Practices for turf and landscape irrigation (T&L BMPs) for use in a wide range of activities from policy making to the implementation of efficient irrigation practices. This document has identified the relevant stakeholders and their linkages, relationships and common values. The primary stakeholders include water purveyors, system owners, irrigation designers and consultants, contractors and maintenance personnel. Additional stakeholders include state, federal, public agencies and related landscape industries and associations. Each stakeholder group has specific needs and operates with different resources. This document provides the required hierarchies of information that are comprehensive, and specific while allowing for local interpretation.

The landscape and irrigation industry must demonstrate the ability to irrigate efficiently. The landscape industry is the most visible user of water in an urban setting. Landscape water use during the growing season defines the "peak load" that the water delivery infrastructure must accommodate. The failure to demonstrate efficient irrigation could set the stage for serious consequences to the landscape industry. A drought or perceived water shortage could provide all the impetus necessary for onerous mandates determining when and how much to irrigate as well as the type of plants a landscape can have. The ability to irrigate efficiently will help the landscape industry control its destiny.

The broad and comprehensive nature of the T&L BMPs is what differentiates it from previous "efficiency" initiatives. It provides tools to create active partnerships between the water purveyor, property owner and the green industry. It elevates the scope of efficient irrigation to encompass the development of appropriate water allowances for a site (and by extension a municipality or region), in the hope of improving decision making with respect to regional water demand. Specific benefits include:

- By enjoining the water purveyor and the Green Industry in water allowance planning and development of local strategies for implementation, both the Green Industry and the water purveyor are accountable for reduced water use in a way that is not detrimental to the landscapes.

- Reduced peak demand mitigates the need for infrastructure improvements, a cost benefit to the water purveyor.

- May reduce energy cost of pumping water at times of high energy demand and peak load water requirements.

- Reduces the need for onerous mandates regarding irrigation and as a consequence allows greater flexibility in the preservation of existing landscapes, with increased community support for the water purveyor as a result.

Irrigation Association - Water Management Committee

The T&L BMPs is distributed as a two-document set:

- Turf and Landscape Irrigation Best Management Practices
- Landscape Irrigation Scheduling and Water Management

The Turf and Landscape Irrigation Best Management Practices document includes:

- Definition of a *Turf and Landscape Irrigation Best Management Practice*
- Five Best Management Practices that address the quality, design, installation, maintenance, and management of irrigation systems
- Definition of a *Practice Guideline*
- Five Practice Guidelines (PG) that address ways to implement respective Best
- Management Practices. Each PG is meant to be a guide to facilitate the development of local specifications
- Appendices that include a system design package and benefits of advanced irrigation control
- Glossary of terms used in the BMPs and Practice Guidelines

The second document, Landscape Irrigation Scheduling and Water Management, provides science-based ways to implement efficient irrigation while reducing water use and protecting water quality. The material includes:

- Landscape irrigation theory
- Scheduling theory and examples
- Landscape water management theory and examples
- Quality ratings for irrigation systems
- Landscape water allowance theory and examples
- Deficit irrigation theory and examples
- Expanded glossary of terms used in turf and landscape irrigation

The tools provided herein are meant to ensure the installation and management of efficient irrigation systems. This in turn enhances the value of landscapes while making responsible use of a precious and finite resource. The metrics defined raise the bar for turf and landscape irrigation systems, while pinpointing specific opportunities for greater efficiency. The T&L BMPs and related Practice Guidelines provide the basis for sensible, informed decision making regarding regional water use and response to drought.

John Ossa
Chairman, Water Management Committee of The Irrigation Association

LANDSCAPE SIZING IN SANTA ANA HEIGHTS – A MODEL TO EFFICIENTLY SIZE LANDSCAPE AREA FOR ANY COMMUNITY

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Irvine Ranch Water District is a recognized leader in water use efficiency. One of the key elements is its unique rate structure, adopted in 1991. A tiered rate billing system based on a water budget allocation was established to encourage conservation and discourage substandard irrigation systems. The rate structure is based upon providing customers with the water they need at the lowest rates in Orange County ($0.75 per CCF). Inefficient use is penalized with higher rates, ranging from $1.50 to $6.00 per CCF. Since the introduction of this rate structure, water consumption has dropped significantly, while the health of the landscape has improved.

By 1997, inclining rates and outreach education programs had accounted for a reduction of 29.8 inches of water per year.[1] From 1994 to 1997 a visual assessment study of the turf at 16 different sites was conducted comparing turf appearance prior to 1991. The study showed that despite the reduction in allocation due to the introduction of the new rate structure, turf quality either improved or remained unchanged. Sites that were initially poor prior to the introduction of the new rate structure improved the most.[2] Since 1991, water use has dropped from an average of 4.4 acre foot per acre to 2.2 acre foot per acre. In the year 2000, the number of acres that were developed in IRWD's service area doubled, yet water use only increased by 3% over water use in 1992.

IRWD'S SINGLE-FAMILY RESIDENTIAL RATE STRUCTURE

Tier	Rate Per CCF	Use (As a Percent of Allocation)
Low Volume Discount	$0.59	0-40%
Conservation Base Rate	$0.75	41-100%
Inefficient	$1.50	101-150%
Excessive	$3.00	151-200%
Wasteful	$6.00	201% +

Effective July 1, 2003
1 CCF = 748 gallons

RESIDENTIAL USE

IRWD's residential use has dropped from 0.32 AF/yr/customer in 1989-90 to 0.28 AF/yr/customer in 2002-03. This is a 12.5% decrease in residential use per customer. The residential water use per customer for Los Alisos (an area annexed to IRWD, but not yet on IRWD's water-budget rate structure) was 0.35 AF/yr/customer in 2002-3. This is 25% higher than the IRWD use per customer.

WATER BUDGET ALLOCATION

Upon introducing this new billing system to its customers, Irvine Ranch Water District was keenly aware of its responsibility in making sure their customers would be confident in and accept the new system. It was important that their customers understood that the new rate system was structured to encourage conservation and efficient irrigation, and not simply to limit allocation for the sole purpose of collecting revenue by penalizing customers. The key to doing this was by developing valid, scientifically based numbers for calculating customer allocations.

Looking at the following equation, all of the figures are readily available, even landscape size. The majority of IRWD's service area is made up of planned communities. This unique situation makes it relatively simple to come up with landscape area. IRWD uses a standard default of 1350 sq. ft of irrigated landscape for calculating single-family residential allocations.

$$\textbf{Single Family Allocation} = \frac{\text{Kc x ET x LA(acres)}}{\text{Eff.}} + \text{Indoor Use (4 people per home/ 3 CCF/person per month (billing period))}$$

CCF = 100 cubic feet = 748 gallons

Kc

The relative amount of water needed to irrigate the landscape. When determining the crop coefficient for Irvine Ranch Water District customers it is assumed that all of the irrigatable area is covered with cool-season turf.

Et (reference ET)

The amount of water that evaporates into the air and the amount of water that is transpired through the vegetation. Evapotranspiration numbers are computed daily from all three of Irvine Ranch Water District's weather stations. Adjusted daily. Multiply by 36.3 to convert to CCF.

Indoor Use

Each customer (single family residence) is automatically allocated 3 CCF, per person per month for 4 people or, a total of 12 CCF (12 x 748 gallons = 8976 gallons) per month.

LA

Landscape area in acres. IRWD has established 1,350 sq.ft. as the universal landscape area default for single family residences. The allocation assumes that 100% of the landscape is cool-season turf grass. Irvine Ranch Water District will provide a variance to any property owner that shows that their situation requires a larger allocation of water for their property. Divide sq.ft. by 43,560 to convert to acres.

Eff.

Efficiency. This is the efficiency of the irrigation system. Irvine Ranch Water District assumes 80%.

APPLICABILITY TO OTHER AREAS

Since the water-budget based rate structure is working so well, other districts have become interested in the same type of system in order to encourage water use efficiency. However, most of the communities within IRWD's service area have been built in the last twenty-five years. Since almost every single-family residence is located within a planned community, IRWD's method for establishing landscape allocation is not necessarily transferable to other cities or water districts.

In 1997, Irvine Ranch Water District acquired the community of Santa Ana Heights. Santa Ana Heights is very different than the rest of IRWD's service area and is mostly made up of single-family residences built in the 1950's. It is not a "cookie cutter" community like Irvine. Parcel sizes range from 4,000 square feet to 140,000 square feet, with most falling in a range between 7,000 to 10,000 square feet. Santa Ana Heights is not a community where Irvine Ranch Water District can simply base its water allocation on a default of 1,350 square feet of irrigated area per household. IRWD needed to develop an alternative methodology for calculating irrigated area that would give Santa Ana Heights customers an equitable allocation based upon site.

INSURING CUSTOMER CONFIDENCE IN ALLOCATION DETERMINATION

Landscape area is the only variable in the allocation formula that cannot be universally determined based on Irvine Ranch Water District's original method. The Kc, ET, and Indoor Use numbers that are used are selected to allocate the most amount of water in the most extreme conditions, (100% cool season turf grass), while always providing enough water for four people whether four people reside in the home or not. In addition, any customer can apply for a variance to address specific circumstances. So if a universal methodology to establish allocation levels for different communities is to be established, landscape area measuring must be studied.

MEASURING LANDSCAPE AREA

There are a number of ways to determine landscape area.

- Actual physical measurement using a measuring wheel.
- Using ArcView or a similar program to measure aerial photographs of parcels.
- Using aerial photographs and infrared imagery to measure parcels.

These are just a few methods for measuring landscape areas within lots. Each one has its advantages and disadvantages. When choosing a method of measurement, the level of pinpoint accuracy has to be weighed against the cost of obtaining the data to develop allocation levels. If the cost to obtain area measurements equals or exceeds the cost in water that is saved, the method is impractical.

MEASURING METHOD

For this study, we chose to use ArcView along with the aerial photographs of the Santa Ana Heights community. Lot size data was obtained from the county assessor and confirmed using ArcView. The cost for the photography and setup in ArcView was around $24,000. Resolution was approximately 6" per pixel. ArcView allowed us to trace polygons around the hardscape of each property and subtract the hardscape area from the total lot size to calculate the irrigatable area, or landscape area. It takes about one minute to measure the total lot size and the hardscape. Using this method of measurement, the only question in accuracy is in identifying landscape or hardscape that is hidden underneath any sort of canopy.

Sample aerial image of Santa Ana Heights

THE IMPORTANCE OF ACCURACY AND MEASURING

The accuracy of measuring using ArcView was found to be within 10% of manual measurements and about 10% compared with infrared measurements. The following example shows the difference in allocation with roughly a 10% (500 sq.ft.) difference in landscape area:

$$\text{Alloc.} = \frac{\text{Kc x ET x LA(acres)}}{\text{Eff.}} + \text{Indoor Use}$$

Assume:
Kc - .907 average for month
Et - 4.2 total for month (multiply by 36.3 to convert to CCF)
LA - Convert 4,500 sqr.ft to acres = 4500/43560 = **.1033 acres**
5,000 sqr.ft to acres = 5000/43560 = **.1148 acres**
Eff. – 80%
Indoor Use – 4 people x 3 CCF per person

For 4,500 sq.ft. of landscape

$$\text{Alloc.} = \frac{.907 \text{ x } (4.2 \text{ x } 36.3) \text{ x } .1033}{.8} + (4 \text{ x } 3) = \mathbf{29.86\ CCF}$$

For 5,000 sq.ft. of landscape

$$\text{Alloc.} = \frac{.907 \text{ x } (4.2 \text{ x } 36.3) \text{ x } .1148}{.8} + (4\text{x } 3) = \mathbf{31.84\ CCF}$$

The difference is **1.98 CCF**. Again, when determining allocations the level of conservation must be weighed against the cost of pinpoint accuracy and the confidence of the customers. Manually measuring each property and then measuring the hardscape within that property may be more accurate, however manual measurements are extremely impractical for a whole district and are still subject to error.

The following is a summary of our measurements. We categorized the lots by sizes, taking samples in 1,000 square foot increments, starting at the smallest lots of 4,000 sqr.ft. up to 12,000 sqr.ft., at which point we increased the square footage of the categories. Out of a total population of 1,380 for all categories, our sample size was 437.

Lot Sizes (Sq. Ft)	Total Pop.	Sample Size	Median Lot Size	Median Landscape Size	Median Landscape %	Max. Landscape Size with 1 Std.Dev.	Max. Landscape Size with 2 Std.Dev.
4,000 - 5,000	59	40	4332	1358	31%	1,866	2,301
5,000 - 6,000	59	50	5750	2225	39%	2,793	3,314
6,000 - 7,000	160	50	6267	3015	48%	3,614	4,161
7,000 - 8,000	414	50	7368	3735	51%	4,276	4,850
8,000 - 9,000	346	50	8686	4433	51%	5,315	6,149
9,000 - 10,000	103	50	9506	5080	53%	5,862	6,674
10,000 - 11,000	56	50	10473	5532	53%	6,566	7,582
11,000 - 12,000	37	30	11597	6384	55%	7,888	9,413
12,000 - 16,000	44	30	13819	7607	55%	9,082	10,637
16,000 - 80,000	95	30	19800	12531	60%	25,448	36,039
80,000 - 140,000	7	7	114715	85229	74%	99,012	113,280

SIZING LANDSCAPE

The ultimate goal is to develop a cost-effective methodology for sizing landscape areas for any district that is accurate in determining water allocations for single-family residences. The key factors are as follows:

- Insure customer confidence in allocation determination
  - Include landscape areas that fall within 1 standard deviation of mean, not median lot size.
- Develop allocation that truly promotes efficient irrigation practices
  - Include landscape areas that fall within 1 standard deviation of mean, not 2 standard deviations from mean.
- Develop a method that can be used universally in any community for a nominal cost
  - Method cannot require individual measurements, only lot sizes required. Any district can obtain lot sizes using Track Map data.

Landscape area is a percentage of the total parcel or lot area. If a ratio can be established showing landscape area to total lot size, allocation can be based upon this ratio.

The objective of this study was to develop a ratio that can be used in any community that is broken down by lot size, for instance every 1000 square feet. Using the ratio, the district would only need total lot size to calculate landscape percentages. If this method does not work for a certain district, the district could take samples of lots in each total square footage category, 4,000, 5,000 etc., and measure the samples to get their own ratio. However, the following will demonstrate that the ratios in this study should apply everywhere, when landscape areas that fall within 1 standard deviation are included.

ALLOCATION AND 1 STANDARD DEVIATION

The following table shows the calculated water allocations for Santa Ana Heights for the months of August '02 and September '02. These examples represent a good sample of the total population for all categories. Columns A and F show actual water use, whereas Columns B and G show allocation based on the median landscape area for the total lot category; 6,000 – 7,000 square feet and 7,000 – 8,000 square feet. Columns D and I show the allocation based on the median landscape area for the same lot category with landscape size increasing to include landscape areas 1 standard deviation from the mean. In this case, 95.5% of the properties will be provided with enough water without a need to request a variance. When looking at Columns E and J, it is clear that some customers have used less water than they would be allocated, but at the same time some customers have used more than what they would be allocated. These over-allocation customers would either need a variance, or be penalized and encouraged to investigate the efficiency of their irrigation system. The difference in allocation from Columns B and G versus Columns D and I is quite small, roughly 2 to 3 CCF, however, the number of variances, and the number of customer complaints drops significantly, since the number of landscape areas that are included at the standard rate level increases from 68.8% to 95.5%.

If the allocation is based on the landscape area to include lots within 2 standard deviations, 99.7% would be included and the emphasis on conservation would be less significant. If the allocation is based on the average landscape area, 68.8% of the customers would not need a variance. That leaves 31.2% of customers that will possibly be requesting variances. This would not build confidence in the rate structure.

Basing the allocation on the size of lots where the landscape area falls within 1 standard deviation of the average landscape area size encourages conservation, and provides the customer with a level of confidence in the water-budget based rate structure.

ALLOCATION (CCF) BASED ON MEDIAN LANDSCAPE AREAS AND LANDSCAPE AREAS THAT FALL WITHIN 1 STANDARD DEVIATION OF MEAN

6,000 - 7,000 SQUARE FOOT LOTS		A	B	C	D	E	F	G	H	I	J
Account Street Name	Total Area	AUG02 Used	Alloc.based on Median Size 6-7,000 sqr.ft.	Over Allocation (Difference) CCF	Alloc.based on 1 Std.Dev.	Over Allocation (Difference) CCF	SEP02 Used	Alloc.based on Median Size 6-7,000 sqr.ft.	Over Allocation (Difference) CCF	Alloc.based on 1 Std.Dev.	Over Allocation (Difference) CCF
E. Wilson	6600	54	24.61	29.39	27.12	26.88	31	22.41	8.59	24.48	6.52
Norse	6900	16	24.61	-8.61	27.12	-11.12	18	22.41	-4.41	24.48	-6.48
Brentwood	6125	29	24.61	4.39	27.12	1.88	32	22.41	9.59	24.48	7.52
24th Place	6873	20	24.61	-4.61	27.12	-7.12	21	22.41	-1.41	24.48	-3.48
Brentwood	6284	18	24.61	-6.61	27.12	-9.12	38	22.41	15.59	24.48	13.52
Orange	6558	21	24.61	-3.61	27.12	-6.12	25	22.41	2.59	24.48	0.52
E. Wilson	6268	26	24.61	1.39	27.12	-1.12	33	22.41	10.59	24.48	8.52
E. Wilson	6930	23	24.61	-1.61	27.12	-4.12	35	22.41	12.59	24.48	10.52

Median landscape area for lots that are 6,000 - 7,000 sqr.ft is - 3,015 sqr.ft.
Landscape area within 1 standard deviation for lots that are 6,000 - 7,000 sqr.ft is - 3,614sqr.ft.

7,000 - 8,000 SQUARE FOOT LOTS		A	B	C	D	E	F	G	H	I	J
Account Street Name	Total Area	AUG02 Used	Alloc.based on Median Size 7-8,000 sqr.ft.	Over Allocation (Difference) CCF	Alloc.based on 1 Std.Dev.	Over Allocation (Difference) CCF	SEP02 Used	Alloc.based on Median Size 7-8,000 sqr.ft.	Over Allocation (Difference) CCF	Alloc.based on 1 Std.Dev.	Over Allocation (Difference) CCF
Bay Farm	7200	38	27.62	10.38	29.89	8.11	44	24.90	19.10	26.77	17.23
Orchid Hill	7291	36	27.62	8.38	29.89	6.11	28	24.90	3.10	26.77	1.23
Orchid Hill	7199	24	27.62	-3.62	29.89	-5.89	57	24.90	32.10	26.77	30.23
Norse	7300	30	27.62	2.38	29.89	0.11	38	24.90	13.10	26.77	11.23
Santa Isabel	7487	15	27.62	-12.62	29.89	-14.89	18	24.90	-6.90	26.77	-8.77
24th Place	7557	41	27.62	13.38	29.89	11.11	35	24.90	10.10	26.77	8.23
E.Wilson	7835	42	27.62	14.38	29.89	12.11	46	24.90	21.10	26.77	19.23
Westminster	7794	12	27.62	-15.62	29.89	-17.89	13	24.90	-11.90	26.77	-13.77

Median landscape area for lots that are 7,000 - 8,000 sqr.ft is - 3,735 sqr.ft.
Landscape area within 1 standard deviation for lots that are 7,000 - 8,000 sqr.ft is - 4,276sqr.ft.

CONCLUSION

The reason for setting allocation limits is to encourage conservation and efficient irrigation practices. It is important to have an accurate and fair method for developing allocation levels in order to implement a billing rate system that the public will be confident in. Irvine Ranch Water District has been able to accomplish this and the methodologies being developed in this study will make it easier for other communities to adopt a similar rate structure model. The other half of the equation is how each single-family residence can meet these allocations. As water management becomes increasingly more important to communities, these communities will be looking for better ways to set allocation levels. As more communities adopt these methods, proper irrigation system design, effective irrigation products and effective maintenance and water management will become more important to the water user.

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Thomas W. Chestnut
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350 South Grand Ave., Los Angeles, CA 90054-0153

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Spray Irrigation and Urban Run-Off: The Looming Crisis in Landscape Irrigation

Abstract: Cities in the US are under pressure from the Federal government and citizen groups to reduce pollution of the nation's waterways through the National Pollutant Discharge Elimination System (NPDES), an element of the Clean Water Act. Cities that violate this mandate face fines of $10,000 per day, or more. 40% to 60% of this pollution results from dry-weather surface run-off, and in urban areas, a significant portion of this run-off is a result of excessive irrigation and/or poorly designed or maintained irrigation systems.

The City of Santa Monica in California has identified spray irrigation of residential landscapes as a primary contributor to this problem and is moving ahead with a program to limit its use. This paper describes the City's program and its importance for irrigation professionals.

BACKGROUND:

The Clean Water Act promulgated in Washington, D.C., in 1972 started a ball rolling which is coming to rest against sprayheads in San Monica, California in 2003. Here's the story:

The National Pollutant Discharge Elimination System (NPDES), an element of the Clean Water Act, limits the amount of pollutants in the nation's waterways. One of those waterways is Santa Monica Bay which forms one of the borders of the City of Santa Monica. Tourist dollars generated by water-related activities in Santa Monica Bay and on its beaches form the basis for a large percentage of Santa Monica's revenue.

In the early 1990's, when research determined that up to 60% of the pollutants in the Bay was the result of urban runoff, Santa Monica's first effort to deal with the runoff was to build the Santa Monica Urban Runoff Recycling Facility (SMURRF).

The SMURRF, built in 2000, is the first facility of its kind in the nation and perhaps the world! This state-of-the-art facility treats dry weather runoff water that formerly went directly into Santa Monica Bay through storm drains.

An average of 325,000 gallons per day of urban runoff is treated by the SMURRF. The runoff water is diverted from the City's two main storm drains and treated to remove pollutants such as trash, sediment, oil, grease, and pathogens. The treatment process includes:

Coarse and fine screening to remove trash and debris
Dissolved Air Flotation (DAF) to remove oil and grease
Degritting systems to remove sand and grit
Micro-filtration to remove turbidity
Ultra-violet (UV) radiation to kill pathogens

Once treated, the water is used for landscape irrigation and dual-plumbed systems (buildings plumbed to accept recycled water for the flushing of toilets). The treated water meets all of California's Title 22 requirements. Landscape irrigation customers include highway landscaping, the City's parks and cemetery and several school grounds. Dual-plumbed customers include the City of Santa Monica's Public Safety Facility and the Water Garden commercial development.

In 2001 another occurrence upped the ante. Seven of the City's eleven wells, the source of 85% of its drinking water, were found to be contaminated with MTBE and had to be shut down. Overnight, Santa Monica went from importing 15% of its water, to importing 95%, and the average price of the water went from $111 to $450 per acre foot.

So it wasn't long until the City began an intensified program to reduce waste of this expensive, imported water. One element of that program is enforcement of a landscape water waste ordinance* that has been on the books since the 1992 drought, but not recently enforced. Among other things, the ordinance prohibits watering between the hours of 10:00 a.m. and 4:00 p.m., hosing down of hardscapes, irrigation runoff into streets and gutters, fountains without recycling and unrepaired leaks.

The newly established enforcement program includes regular patrols by City Code Enforcement Officers. An unanticipated, but not surprising, result of the patrols was the documentation of the extent of the contribution by residential parkway and front-yard sprinklers to the dry-weather runoff flow.

In the first five months of patrols, we issued 500 citations. Approximately three-quarters of these involved irrigation runoff violations. Less than ten of these runoff situations involved drip, bubbler or rotor systems. What's left? You got it! . . . sprayheads.

THE PROGRAM:

So, for purposes of both water conservation and runoff reduction, the City has embarked on a relatively simple program designed to limit the use of sprayheads and / or change them into something more environmentally responsible.

The program does not ban the use of any specific equipment *per se* nor does it ban any form of plant material such as turf. The program is performance-based and simply requires that there be no overspray or runoff. Not limited or reduced runoff. Not no-runoff-except-when-the-wind-is-blowing. Zero runoff; any and all the time.

As part of the program, the City tests and demonstrates technologies and landscape designs that further the Zero Runoff goal. Technology examples that show promise include the MP Rotator and several subsurface watering techniques. Landscape design examples include turf areas surrounded by buffer strips of permeable paving and planting designs that can be efficiently watered by drip and bubbler systems.

The City's Environmental Programs Division also pays for the appropriate conversion of selected City-owned shrub plantings from spray systems to drip irrigation.

This program is put into action for existing landscapes through public outreach efforts and the effect of the citations which result from the enforcement patrols. The fine for violating the water-waste ordinance is $250 for the first occurrence and escalates for additional occurrences.

For new construction, final inspections include a test of the irrigation system which must result in zero runoff.**

THE FUTURE

Santa Monica is a very small, but innovative and influential city. While its specific programs are not going to result in vast water savings for Southern California, history shows they will result in other larger regions following Santa Monica's lead. Hopefully, the sprayhead industry will rise to this challenge.

Visit us at http://www.santa-monica.org/environment/policy/water/ for an update.

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* See Attachment 1

** Pending City Council approval.

Attachment 1 – City of Santa Monica Water Waste Ordinance (7.16.020)

- No watering of lawns or landscapes between the hours of 10:00 a.m. and 4:00 p.m. on any day.
- No hosing down of sidewalks, driveways, patios, alleys, parking areas or other “hardscapes.”
- No runoff is permitted from lawns and landscapes into streets, alleys, or gutters at any time.
- Water must not be used to fill or maintain levels in decorative fountains, ponds, lakes or displays unless a recycling system is used.
- Swimming pools must not be filled or emptied unless it is a first filling of a new pool, or necessary leak repair work is being performed.
- Water leaks from exterior or interior plumbing must be repaired immediately.
- Water must not be allowed to flow without reasonable use.
- No washing of vehicles of any kind except with a hand-held bucket or a hose equipped with a shut-off nozzle.
- Restaurants must serve water only upon request and post signage indicating this restriction.

TITLE: Cross Cultural Sustainability: Managing our "liquid assets"

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PURPOSE: A Technical Presentation for 24th Annual International Irrigation Show, November 18-20, 2003, San Diego, CA.

ABSTRACT: Water conservation is an international issue. According to a report by the United Nations Commission on Sustainable Development, world water use has grown at more than twice the rate of the population increase during the past century. International collaborations between landscape architects and irrigation consultants optimize the application of sustainability best practices.

INTRODUCTION

Proactive members of the irrigation industry are beginning to recognize that they need to rethink or revise the methods by which water is used in their irrigation designs. Their thinking is being stretched throughout a site's water resource map from the water source(s) to the root zone. Water resource awareness has begun to require involvement in issues far beyond the individual site including river catchments, aquifer replenishment, and drainage, especially in urban areas. Increased density of the population and unreliable water sources conspire to bring attention to ways to mitigate the impact of contaminated water run-off and alternative sources for irrigation in cities. Sustainability awareness has become an active issue through forces as critical as the increasing cost and decreasing availability of water sources for irrigation world wide and external criteria such as LEED[1] building criteria. Place-specific, problem-specific solutions using collaborative processes involving landowners, developers, municipalities, water suppliers, architects, landscape architects, civil engineers, contractors and irrigation engineers from around the world need to be developed and implemented to meet the increased demand for irrigation by a growing world population.

The latest statistics report a projected worldwide population of over 9 billion by 2050.[2] With already intense strains on water resources to meet current needs for food and potable water, the call for innovation is tremendous. Two-thirds of the world's fresh water withdrawn for human use goes toward irrigation.[3] Therefore, the ways in which the irrigation industry manages water has a huge impact on how well it is conserved worldwide. Many Best Management Practices have been adopted by the industry to conserve water. Quality design is promoted to ensure efficient pump operation and high distribution uniformity. Instead of flooding crops, point-source drip irrigation systems are installed. Weather stations incorporated into a system measure daily rainfall and evapotranspiration (ET) rates. However, the limits of these methods are that they still exhaust a finite water supply. Are there ways to irrigate without drawing down water resources, albeit slowly?

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[1] The U.S. Green Building Council's Leadership in Energy and Environmental Design Green Building Rating System: http://www.usgbc.org

[2] Sustainable Development International: www.sustdev.org/industry.news/042000/0062.shtml

[3] Scientific American: www.sciam.com Feb 2001 article "Growing More Food with Less Water"

This presentation aims to highlight several cross-cultural examples of irrigation and drainage techniques that can be categorized as “sustainable”. Thus, a definition of sustainable design is necessary. The concept of sustainable design holds that technologies must maintain environmental integrity, contribute to the quality of the water, and reduce the impact of human use.[4] So the goal becomes to reuse water, not deplete it. Already in several parts of the world, projects have been designed to reflect the principles of sustainable drainage. We will address these issues through our work in England and the United States using a variety of sites to illustrate the issues outlined above.

WORLD CLIMATE CHANGE

The world’s climate is changing, and combined with rises in sea level and an average temperature increase of 3°C [37.4°F] by the year 2100, the current trend points towards a 10% increase in annual rainfall in the UK by 2080.[5] Although annual rainfall is increasing, it is the change in rainfall patterns that are of most concern. 80% of all rainfall in the UK is now received in autumn and winter, resulting in regular annual flooding of low-lying areas. The drier and hotter summer months result in a higher seasonal demand for water, which relies on the extraction of groundwater for potable water. The increase of built development on river catchments is also having an effect on the volume and quality of surface water runoff reaching groundwater aquifers. On top of this, the British continental shelf is sinking in the south, and rising in the north, with the result that London is under constant threat of both tidal and storm water surges.

Figure 1: The increased capacity to remove rainwater from our streets and towns compounds flooding problems and removes the potential for groundwater recharge. Image Atelier Dreiseitl

THE EMERGENCE OF A SUSTAINABLE APPROACH

AGENDA 21

At the Rio Earth Summit in 1992, Governments of the world were encouraged to ‘Think globally and act locally’ to preserve the world’s resources for future generations. One of the agreements signed at The Rio Conference was Agenda 21, an agenda to take us into the 21st Century. It is a 40-chapter document that examines the interconnectedness of social, economic and environmental issues and addresses the problems of today while considering the needs of the future. Agenda 21 outlines objectives and actions that can be taken at local, national and international levels and provides a comprehensive blueprint for nations throughout the world who are starting to make the transition to sustainability. Chapter 28 of the Agenda 21 document calls on local authorities to work with their local communities to achieve a local action plan, a ‘Local Agenda 21.’ One of the key objectives of Local Agenda 21 was the prudent use of natural resources and the preservation of the environment for enjoyment by future generations. Fresh water has long been recognized as one of the world’s most precious resources, and one that is in steady decline through the effects of climate change and through man’s destruction of natural ecosystems. In the context of sustainable development, water has been recognized as an important and renewable resource that needs to be carefully managed if we are to meet the needs of the next generation. According to worldwide conservation bodies, water is a good indication of how far we have come in attaining some level of sustainable living.[6]

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[4] National Parks Service, Denver Service Center www.nps.gov/dsc “Guiding Principles of Sustainable Design” Chapter 1

[5] Source: DEFRA, *Impacts of Climate Change, Implications for DETR, 14.12.01*

[6] Fottrell Q ‘On the Waterfront’ *Landscape Design* September 1995 p10

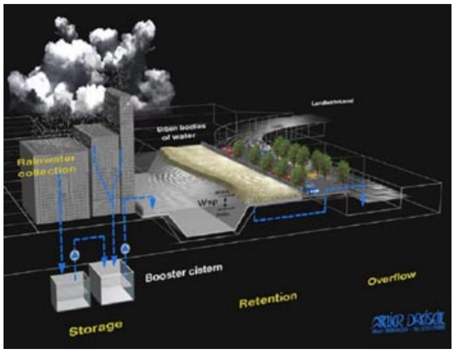
SUSTAINABLE URBAN DRAINAGE SYSTEMS

Figure 2: Increasing urbanisation of river catchments force stormawater runoff into ever constricted chanels. Image Atelier Dreiseitl

From as early as the 1970's, studies in Europe began to assess the effects of urban development on river catchments. The increased efficiency at which engineered drainage systems remove water from our cities and channel it into already overloaded river corridors has resulted in severe downstream flooding, especially in low lying countries. In the Netherlands, which receives some of the major rivers in Europe including the Rhine and the Meuse, the Dutch must contend not only with the changing characteristics of their own land, but those of France, Germany and Switzerland. The response to this increase in floodwater has been to construct raised riverbanks, canals, dikes and channels and the Rhine alone has had 70 kilometres [43.5 miles] of meanders and bends straightened out.[7] This means that the rivers flow fuller and faster into the Netherlands, thus compounding the problem.

Sustainable urban drainage systems or SUDS were developed as an alternative to the engineered drainage response to flooding. SUDS sought to balance the effects of increased runoff from hard surfaces by slowing down the rate at which water is channelled into river catchments, and to allow time for rainwater to infiltrate back into the ground to recharge subterranean aquifers. Typically the solution was to increase on site attenuation and filtration of rainwater runoff in order to balance out the peak flows and reduce the incidence of silt and pollution migration into stream systems. Although initially concerned with the quality and quantity of discharge from urban developments, SUDS have become widely adopted as best practice for developments regardless of their location. The creation of open ditches, attenuation ponds and storm water wetlands not only improves the quality of water systems downstream, but also improves the quality of the environment within a site whether it is urban or rural. We have recently used sustainable drainage systems on colliery regeneration schemes to trap and filter and attenuate runoff containing potentially damaging levels of nitrates and phosphates before it is discharged into sensitive wetlands and adjoining watercourses.

TOTAL CATCHMENT PLANNING



The term "total catchment planning" came about through an understanding that the prevention of flooding, the preservation of the environment and protection of water quality were dependent on the responsible management of development within entire river systems. Total catchment planning depends on government policy to provide guidance and control over the way in which development is allowed to proceed, and the standards of design and implementation that are required. An overall stewardship of the landscape in which government agencies, developers, designers and the community are involved in the decision making process has led to a remarkable change in environmental standards and development approach.

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[7] Vidal J; 'So Who's to Blame Then' *The Guardian* 3 February 1995 p4

In cities such as Berlin, which sits on a high water table and deep deposits of glacial sand, a mandate was passed which prevented new developments from discharging rainfall into the sewage system. Instead new developments had to attenuate rainfall on site until it could be discharged on site either through soil infiltration or through evapotranspiration. This prompted a huge increase in the number of roof gardens being built in the city as a means of attenuating rainfall on the rooftops of buildings and as a primary point of off site discharge through evapotranspiration. The Debis building on Pottsdamer Platz is a superb example of water management on confined urban sites. The entire site is built over transport and service infrastructure, so there is no possibility for soil infiltration. Rainwater that falls on the site is collected and stored in large underground cisterns and used to supply irrigation systems for the roof gardens and toilet flushing. Grey water from washbasins and cleaning is stored in a large attenuation pond where it is passed through a reed bed filtration system before being discharged into the adjoining Land-wehrkanal[8]. The scheme is the brainchild of Atelier Dreisetl in Germany who has also designed drainage systems for large housing schemes that not only have a decorative and aesthetic character, but also have little or no impact on surrounding watercourses. In their most ambitious scheme, they are developing the drainage concept for a new town in Austria that will co-exist with an existing wetland. Rather than sweeping water away into underground systems, a new generation of designers is integrating drainage design into the site character in order to enhance the quality of the water catchment.

Figure 3: Rainwater and grey water recycling, Potsdamer Platz Berlin. Images Atelier Dreiseitl

A NEW APPROACH

EMERGING EU LEGISLATION

Legislation has always played a large role in the development of sustainable development policies. In December 2000 the Water Framework Directive was introduced to all EU member states. The WFD requires all inland and coastal waters to reach ‘good status’ by 2015. It will establish a river basin district structure within which demanding environmental objectives will be set, including ecological targets for surface waters. The first objective of the WFD states that ‘Water is not a commercial product like any other but, rather, a heritage which must be protected, defended and treated as such.’ The directive identifies water as a community resource that transcends the boundaries of nations and must be protected on a total catchment basis that may extend outside of the territories of the EU.

Figure 4: Grass swale in housing estate, Hannover Germany. Image Atelier Dreiseitl

This is the first piece of legislation to recognise the principles of Total Catchment Planning and to implement policies for the protection of watercourses, which not only flow through but also originate or terminate outside of the jurisdiction of member states. One of the most powerful objectives is the power granted to member states under the directive to prosecute polluters in order to provide funding for the environmental regeneration of surface waters. This lays down a responsibility for developers to not only prevent pollution from occurring, but to prevent existing pollution from escaping into river catchments.

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[8] Waterscapes – Planning, Building and Designing with water. H Dreiseitl, 2001, Birkhauser

ZERO HYDROLOGICAL IMPACT DESIGN

A sustainable design approach which involves a much more holistic appraisal of the site has been developed within our practice ahead of a growing trend towards total catchment planning. We call our approach Zero Hydrological Impact (ZHI) design. In assessing the brief for a site we will assess the site characteristics, including the physical, geotechnical, cultural, and economical assets, and explore ways in which the brief for the site can be achieved while maximising the ecological amenity value that the landscape contributes the surrounding community. This means that the site must integrate with its surroundings, without any adverse effect on visual appearance, land use, water quality, wildlife habitat or cultural value of surrounding sites. In all cases it is preferable to involve the local community, use local materials, and employ local industry to develop a scheme that has a local identity. The issues that we are dealing with however have received international interest.

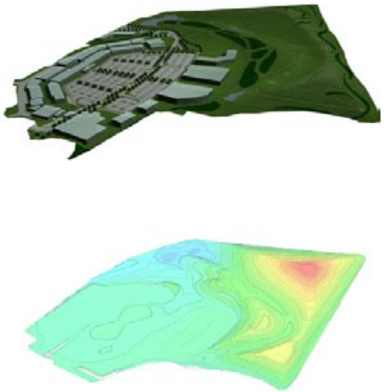
Figure 5: Terrain Modelling Dalton Park

A recent scheme in County Durham, near Newcastle, involved the moving of over 600,000m^3 [784,770yd^3] of colliery shale to create the footprint for a retail outlet centre in an economically deprived community. A culvert that carried a stream beneath the site was subject to collapse and therefore could not be further surcharged with site spoil. The removal of the site spoil was not viable from an economic and logistical point of view, and while the material was inert, it was unable to sustain vegetation. Using digital terrain modelling software we were able to determine cut and fill quantities for the site that gave us gradients of less than 1:3, as well as being able to determine the watershed characteristics of the new landform. We were able to determine where slope stabilisation would be required, and the direction and velocity of site runoff. By commissioning a soil scientist we were able to determine the likelihood of pollution migration from the colliery shale, and to identify locally available soil ameliorants (dried sewage sludge) that would enable us to establish a variety of vegetation habitats on the site. This meant that we were able to use waste products to sustain vegetation on the site rather than stripping another site of its topsoil in order to remediate this one.


Figure 6: Dalton Park Ephemeral stream and Balancing Pond

During the site excavations deposits of sand and clay were found on site, and carefully stockpiled. The clay was later used to line the stream and lake areas, while the sand was used to create growing media for the wetland planting zones where the sewage sludge was not permitted to be used. Over seven different habitat zones were created from material that was once considered waste, and two balancing ponds, a filtration pond, three wetland filter zones, an ephemeral streambed and numerous silt trapping plant colonies were created. The resulting landscape of sculpted earth, woodlands, wetlands, lakes and meadows is now a park which forms an educational facility for local school children and to visitors alike.

ZHI design assesses the potential for existing or new pollutants to become mobile on site and the level of filtration and attenuation required on site to prevent escape. It also ensures that increases in hard surfaces are balanced by on site attenuation to ensure that discharge from the site remains consistent with the coefficient of a greenfield site.

Figure 6: Skew Birdge Rushden Masterplan

Sometimes our work involves planning for developments within river floodplains. Although buildings are often protected from flood damage by being constructed on raised plateaus or piers, the river is often not protected from oil or pollutants associated with car parking in areas below the flood level. We have recently devised strategies that ensure that the first flush of runoff from sites subject to flooding is directed into water storage cisterns below ground. Although silt traps are effective in removing suspended solids from rainwater runoff, once breached by floods, petrol and oil interceptors often release their captive pollutants into the watercourse. By collecting site runoff in underground cisterns, pollutants can be slowly released through storm water wetlands for treatment when floodwaters have abated. Petrol and oil can be stored in sealed compartments that shut off when floodwaters rise, to be pumped out from their underground storage at intervals. This proposal has enable developments such as Skew Bridge in Rushden to gain planning permission even when they exist close to sensitive landscapes such as a neighbouring SSSI.

INTEGRATED WATER MANAGEMENT

Recent schemes have called for closer work with other disciplines on the integration of design skills. The Lower Lea Valley in London is the birthplace of post industrialism. This was the place where industry first learned that it no longer needed to locate next to primary resources, but that raw materials could be transported to where power and labour were most abundant. Today the area is a declining industrial zone in the midst of two expanding London boroughs. The 660-hectare [1,630.9 acre] site has been designated for urban regeneration and the location of the 2012 Olympics if London’s bid is successful. On the agenda for the team were the issues of transportation, infrastructure, spatial quality, flood protection, sustainable drainage, ecology, environmental impact, and pollution. In a bold attempt to reunite the tidal rivers of the Lea Valley with their landscapes, some of the flood defence walls would be taken down and replaced with Flood Buffer Zones.

Within these zones there would be sub zones:

1. Tidal expansion zone.
   These would be areas immediately adjacent to tidal rivers that offered a potential for vegetation that grows in salt marshes to colonise the embankments of the river that had been obliterated by flood defence barriers.
2. Flood alleviation zone.
   These would areas above the mean high tide mark that rose to a height of projected surge tide levels which would allow the swollen river to expand into the surrounding landscape and absorb the shock wave of storm water surges meeting tidal surges during peak flooding events.
3. Storm water wetland.
   Located behind the flood protection bunds these areas would attenuate both storm water and grey water from the urban development. They would have a sufficient expansion capacity to retain storm water for a period of several days in order to retain runoff from development zones until tidal floods recede and water can be release through flow control valves into the flood alleviation zone.
4. Filter zone.
   Effectively large grass swales, this zone would act as pre-filter to the storm water wetlands, and as metropolitan open land for recreation and linear corridors connecting communities.

Flood Buffer Zones are not intended as a replacement to engineered protection for flooding in lowland river catchments, but as a shock absorber to the collision of tidal and fluvial systems. They can also act a as transition zone between tidal and urban drainage systems, allowing space for filtration and discharge of runoff from hard surfaces into sensitive ecological systems such as salt water marshes. The creation of these spaces in derelict industrial land in the Lower Lea Valley would offer the chance to re-establish rich and diverse plant and wildlife communities with an intrinsic value to the urban communities which will grow up around them. Their creation would involve inter-disciplinary work between drainage engineers, sewage engineers, ecologists, soil consultants, landscape architects and irrigation engineers.

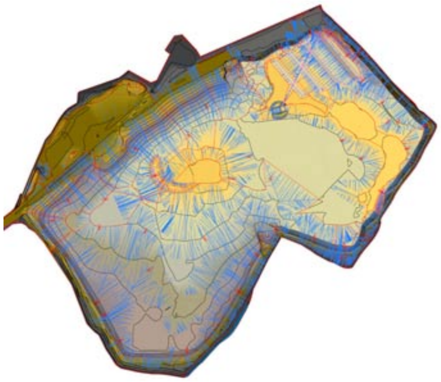

Figure 7: Hydrological Mapping of Betteshanger Colliery near Dover in Kent. Image Lovejoy.

It is ironic that the Lower Lea Valley should be the location of Joseph Bazalgettes famous interceptory sewer system, the device which sealed the fate of so many of London’s streams, and turned them into underground systems to remove the stench of raw sewage that once plagued the city. Although we still rely on modern sewage removal and treatment systems we have come to understand the importance of space and time. Water needs space to move if we are to live with it, and time to restore itself when it is used to carry away the pollutants that we subject it to. History has taught us that if we take any shortcuts in our treatment of water, the problem is only compounded elsewhere.

IMPLICATIONS FOR THE IRRIGATION INDUSTRY

In order to realise our greatest potential we, as irrigation engineering consultants need to reconsider our position as end users of water. With our engineering knowledge of hydrological principles, water storage, pumping systems, soil-water-plant relationships and climate, we are truly becoming Water Resource Consultants. By being involved as early as possible in the design stage of projects, we can provide “water utilization maps” for potable and non-potable systems using a combination of on and off site water resources, distributed processing for pollutants, grey water re-use and other dual use systems, catchment planning and remote sensors and control systems to optimise irrigation water use.

Combining principles of sustainability with our technical background in irrigation engineering and a corporate perspective as water managers, we have applied these principles with clients as diverse as the Sonoran Desert in Arizona and the front range of the Rockies. In arid climates, we design systems that make the best use of water in order to green the desert.

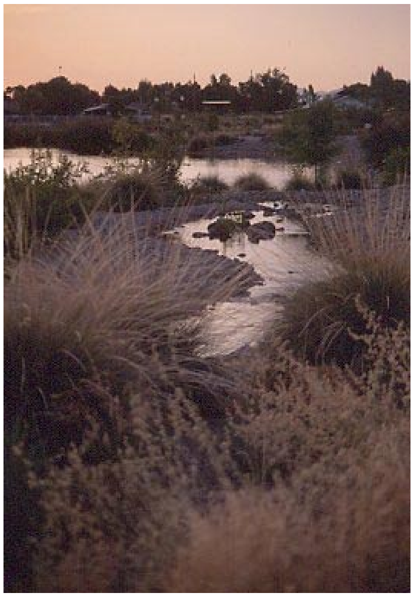

Figure 8: The Riparian Preserve. *Hines*

The Town of Gilbert, Arizona wanted to dispose of excess treated wastewater effluent in high production/low demand periods during winter as groundwater recharge, while providing sustainable wildlife habitat, public recreation, and educational venues year round. They brought together a team of landscape architects and engineers including irrigation engineers to solve the combined needs of the 48.6-hectare [120 acre] site. The resulting Riparian Preserve provides representation of the 17 lower elevation riparian and upland plant communities found in Arizona. Water sources as diverse as in situ shallow aquifer wells, raw water from the Central Arizona Project and a variable source up to 15.1 million litres [four million gallons] of effluent water per day have been combined to serve a fishing lake and 28.3-hectares [70 acres] of aquifer recharge in seven basins. Both the landscape features and mechanical systems on the site are interpreted so the public can see how the water is being recycled, where it is being used, and how the application of high efficiency irrigation equipment is minimizing water waste.

Irrigation engineering took into account the rich diversity of plant ecosystems represented. From lawn to marsh, and desert to lake, each vegetation system required a specific and controlled amount of water. Additionally, the irrigation system was designed to handle seasonal fluctuations in available water. Regulations concerning the sources or water were a factor in the design process as well. Computer generated hydraulic modelling of mainline piping aided in the selection of optimum pipe sizes. A raw water pumping station was designed and aeration and water circulation systems were necessary in order to maintain a high degree of water quality for the plant and animal habitat. A central control system was designed and specified to assist in optimizing system operational efficiency and to maintain the health of over 18,000 native trees and shrubs within the park. In addition to the state-of-the-art control system, high efficiency spray sprinkler equipment was specified in order to maximize overall system efficiency.

Figure 9: Interlocken – Golf Course. *Hines*

We also develop systems and components that can deal with the variable nature of treated waste water effluent and raw (surface/untreated) water to minimize the use of potable water for irrigation and water features. By working with clients and affiliated disciplines as strategic partners, we master plan projects such as Interlocken in Broomfield, Colorado. This 404.7-hectare [1,000 acre] advanced technology commercial office and mixed use development in the Front Range of the Rocky Mountains included a 121.4-hectare [300 acre], 27 hole executive golf course, community parks, athletic fields, landscaped roadways and numerous tenant sites. Sustainability goals for this project included the utilization of runoff water for propagation of wetland and natural areas and development of dual-use water systems for potable and non-potable water distribution.

Irrigation engineering at Interlocken needed to take into consideration significant changes of elevation on the site and the extreme weather conditions of it’s location along the eastern slope of the Rockies. Engineering tasks included computer hydraulic modelling of the complete irrigation water delivery system including pipe sizing from 150mm [6in] to 600mm [24in] in diameter, analysis of system pressures at selected locations with varying demands to optimize the piping network, design and installation of a 1,700m^{3}h [7,500gpm] central pump station operation with multiple booster pump stations and on-site water storage facilities. Each sprinkler hydro zone from arterial roadways, golf course, athletic fields, community parks, open space and wildlife habitats required individual assessment to consider terrain slope, aspect, soil type and infiltration rate, plant material type, sprinkler precipitation rate and distribution uniformity. Because of the variable terrain on site, sprinkler check valves were specified at each head to prevent low head drain down. And, pressure regulation was designed into the system to control water droplet size at the sprinkler nozzle to minimize evaporation, reduce “wind drift” of spray and optimize distribution uniformity on the wind-prone, mile-high site. A separate, potable water system for the golf greens was required to leach out salts present in the sewage effluent water source. Finally, a complex central control system including multiple weather station locations to track and respond to daily/real-time evapotranspiration data was designed and installed.

Figure 10: Interlocken – Walkway. *Hines*

In urban schemes we can do all of the above and encourage schemes that involve roof gardens to lower the core temperature of buildings, improve the environment for tenants and optimise evapotranspiration. In one urban “brown-field” scheme, we are recommending the utilization of both roof gardens and the re-use of grey-water from high-rise mixed commercial/residential buildings. In this setting rainfall is unpredictable, the city uses surface drainage to carry run-off away from the civic centre, and flooding frequently occurs during heavy rains. Sources of water for the centralized potable water source are being challenged by high rates of suburban growth and the city sits in a desert environment where temperatures soar to over 46.1°C [115°F] in the summer. Capturing and re-using grey-water would allow for a reduction of up to sixty percent of the potable water use for the site and roof gardens could lower the heat map of the site by as much as 15°C [5°F] saving on electrical costs for air conditioning as well.

Our challenge to the industry is to develop partnerships with clients who are developing schemes with sustainability as a prerequisite. As irrigation engineers we have broadened our perspective to include best practices from other continents to provide a cross-cultural approach to our problem solutions. We encourage others in the industry to join us as we find new ways to manage our limited but most precious “liquid asset.”

NOTES ON AUTHORS

Sharon C. Hines is a graduate civil engineer and Senior Engineering Designer for Hines Irrigation Consultants, Inc. currently assigned to their UK subsidiary located in Oxford, England. Sharon has distinguished herself in the engineering skills necessary to excel in this design environment. She has served as a Consulting Engineering Intern, Engineering Research Assistant, and Field Surveying Technician developing skills necessary in design solution development. Sharon's irrigation design experience encompasses project work in the Rock Mountain Region, the Desert South West, California, Wyoming and Afghanistan.

Peter Wilder Cert. Hort. BA(Hons) Dip LA MLI. Peter is an experienced conceptual and technical designer and an Associate with Derek Lovejoy Partnership in London, England. He has worked on large-scale projects from urban and brownfield regeneration through to roof gardens and private estates in throughout Europe. His current work focuses on the development of sustainable design principles for large scale regeneration, and his work has been published in *RIBA Journal*, the official monthly magazine of the Royal Institute of British Architects, and, *AJ Focus*, the product guide for designers published by The Architects' Journal in the UK.

NOTES ON THE COMPANIES THAT SUPPORTED THIS PRESENTATION

HINES™
Irrigation Consultants, Inc.

Hines Irrigation Consultants, Inc. is a Colorado based company with offices in Fort Collins, Denver and through its subsidiary, Hines Irrigation Consultants, Ltd. in Oxford, England. Hines provides design, construction observation, maintenance, and management services to clients internationally, focusing on projects requiring a high level of sensitivity to water source modelling and sustainability. The engineering and design staff create computer generated hydraulic modelling, full dual-use water delivery systems, distributed water processing systems, water features, pump-station design, irrigation system design and specification and central control system design and management. www.hinesirrigation.com

LOVEJOY

Derek Lovejoy Partnership, plc, is one of the largest international land planning and design practices based in the UK. The practice has three offices in London, Edinburgh and Birmingham employing a dedicated staff of planners, landscape architects, and urban designers. The practice invests substantially and consistently in IT ensuring they remain at the forefront of the application of computer technology for the generation, analysis and presentation of information. DLP's philosophy is based on enabling sustainable and environmentally responsible development. They have found that their 'land planning' approach which brings a profound understanding of landscape and planning issues and particularly the interaction between open space and built form can enable innovative even ground-breaking thinking. www.dlp-plc.co.uk

SELECTED INTERNET RESOURCES

UK

http://www.defra.gov.uk
UK Department for environment, food and rural affairs
http://www.silsoe.cranfield.ac.uk/iwe/irrigres.htm
Cranfield University site for water resources – UK
http://www.bbc.co.uk/weather/features/climate_change4.shtml
BBC news report on climate change in UK
http://www.tyndall.ac.uk
The Tyndall Centre focuses on climate change.

US

http://www.rmi.org
Excellent resource for research on sustainability in US
http://www.climatehotmap.org/impacts/water.html
US impact of global warming
http://www.ogp.noaa.gov/library/rtnw91.htm
General discussion of climate and change
http://www.sustainabledesignguide.umn.edu/MSDG/water_pi.html
Design guides developed in Minnesota…see water section especially
http://www.sustainable.doe.gov/efficiency/weinfo.shtml
Wide variety of information for "Smart Communities Network"
http://www.globalchange.org/impactal/96nov1d.htm
Good internationalisation of water issue into the US

OTHER/INTERNATIONAL

http://www.csiro.au
This organization in Australia is focused on conservation.
http://europa.eu.int/comm/research/water-initiative
Excellent resource for EU perspective
http://www.worldbank.org/wbi/sdwater/irrigation.html
Brief list of issues facing developing countries… irrigation initiatives
http://www.tec.org/tec/tec/terms2.html
Excellent resource/dictionary of water terms

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