Turfgrass Irrigation Requirements Simulation in Florida

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Abstract

A number of turfgrass (i.e. landscape) irrigation scheduling methods exist in Florida. Due to the variety of methods, there is often confusion as to which method balances water conservation with plant needs. As water supplies become more strained, irrigation management will become more important. In this paper the irrigation scheduling recommendations that are available were reviewed and irrigation water requirements were simulated for a 30 year period with a daily soil water balance to compare net irrigation requirement, drainage below the root zone, and the influence on effective rainfall. An optimized irrigation schedule was simulated based on refill of the soil profile when the soil water content reached allowable depletion. This schedule is representative of soil moisture sensor and ET controllers (Smart controllers) and reduced irrigation requirements 60% compared to a recommendation of 0.75 inches when turf wilts. Drainage was reduced accordingly. The optimum schedule should be verified in field studies and possibly used as a benchmark for Smart controller performance.

Introduction

Irrigation of urban landscapes is standard practice in new construction in many urbanizing areas of the U.S. In some locations this standard practice coupled with rapid growth in recent years has resulted in a strain on water supplies. In Florida, municipal groundwater accounts for 43% of total water use (Marella 2004) and more than half of this water is thought to be used for urban landscape irrigation. Many utilities estimate that half of all water supplied is used for irrigation; whereas, Haley et al. (2007) found that the fraction of total household supply used for irrigation can be as high as 74% under well-drained sandy soils that are common to many new housing development areas in Florida. Although agricultural water use exceeds municipal supply, agricultural water use has increased by 12.5 MGD from 1975 to 1995 while municipal demand has increased by 57.5 MGD over the same time period. This trend in water

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use will likely continue as more agricultural land is urbanized due to the influx of more than 1,000 people per day (USCB 2006). It has also been documented that residential irrigation results in a substantial amount of wasted water with homeowners in parts of the state applying two to three times plant water requirements (Haley et al. 2007). Competition between agricultural and municipal water users will likely become more acute in the future, thus there is a need to maximize irrigation efficiency.

Numerous landscape irrigation scheduling recommendations exist for Florida (Table 1). The variety of recommendations attempt to provide a compromise between recommendations that can easily be implemented statewide as opposed to accurate information to provide the correct amount of irrigation to meet plant water requirements. The resulting compromise is a simplification of a complex process that varies depending on soil type, plant type and distribution, weather patterns, and irrigation system design and installation. The simplest recommendations suggest watering 0.5" to 0.75" when turfgrass shows signs of stress (see Table 1 for references). Several publications utilize a soil water balance to give guidelines on the amount of turfgrass irrigation required on a monthly basis (Augustin 1983) and also time required on a typical irrigation time clock for two day per week irrigation frequencies (Dukes and Haman 2002) from the monthly soil water balance calculated by (Augustin 1983).

The simplistic recommendations ignore the fact that in-ground irrigation systems are installed with time clocks to facilitate the convenience of automatic irrigation. The disadvantage to time clock based irrigation schedules is that the time must be adjusted to account for plant water demand over the season and for different plant types across irrigation zones. This type of adjustment is not straightforward for the typical user. However, Dukes and Haman (2002) have attempted to provide a practical guide for residential irrigation scheduling considering irrigation equipment types with variable application rates

The objective of this paper is to compare the long term irrigation requirements of various recommended irrigation schedules using a daily soil water balance. This methodology assumes optimum irrigation resulting in no stress or only the onset of minimal stress prior to initiating irrigation.

Materials and Methods

A daily soil water balance was used to compare irrigation scheduling recommendations over a 30 year period of record. Inputs to the water balance were precipitation (P) and irrigation (I) while potential outputs consisted of crop evapotranspiration (ETc), drainage of water below the root zone (D), and surface runoff (RO). The general approach for the soil water balance determination was adapted from several references (e.g. Allen et al. 1998; Smajstrla 1990).

Soil hydraulic properties were used to set upper and lower boundaries for the determination of irrigation amount, drainage and effective rainfall. Soil physical properties were defined as follows:

$$AWHC = FC - FWP \quad [1]$$

$$AW = AWHC * RZ \quad [2]$$

$$PAW = AW * MAD \quad [3]$$

where AWHC is available water holding capacity, FC is soil field capacity or an estimate of how much water can be held in a soil after gravity drainage ceases, PWP is permanent wilting point and these three quantities have units of volume of water per volume of soil (in^3/in^3). AW is available water and RZ is the depth of the root zone that extracts the bulk of the water for plant needs and both have depth units (inches). Finally, PAW is the plant available water determined by the product of AW and the maximum allowable depletion (MAD) which is a function of plant type, soil type, and climate and is a dimensionless number between 0 and 1 resulting in depth units for PAW. The MAD for turfgrass was assumed to be 0.5 based on data from St. Augustinegrass irrigation experiments in Florida where over 50% wilt was observed at a MAD level of approximately 0.5 (unpublished data).

The soil type used for the analysis was assumed to be a sandy soil common to much of Florida where most soils are classified as sands (Irmak and Irmak 2005). The representative soil chosen for the simulations was an Arredondo fine sand. The particular soil series is not as important as the soil physical properties, which were FC = 0.10 in^3/in^3 and PWP = 0.03 in^3/in^3 (Carlisle et al. 1989) which gives available water holding capacity (AWHC) = 0.07 in^3/in^3 or 0.84 in/ft of soil.

The root zone of turfgrass is highly variable and is a function of climate, soil, watering frequency, turfgrass variety. Boman et al. (2002) studied root length density on several turfgrass varieties including St. Augustinegrass, bermudagrass, and zoysiagrass and found that across all varieties 80% to 99% of the root length density was in the top 30 cm of soil. The authors found that 81% of warm season turfgrass roots were in the top 18 cm of soil. Our work in Florida on St. Augustinegrass has shown that the majority of roots were in the top 6 inches across a variety of irrigation treatments on plots established for one year (unpublished data). Since most of the research indicates that 70% to 80% of warm season turfgrass roots typically occur in the top 6 inches of soil, we used an 8 inch root zone to ensure that the simulations would represent a well established stand of warm season turfgrass.

Daily turfgrass water use, ETc was calculated as follows:

$$ETc = ETo * Kc \qquad [4]$$

where Kc is the crop coefficient and ETo is reference ET calculated by the ASCE-EWRI Standardized Method (Allen et al. 2005). The Kc values used here were recommended for warm season turfgrass by Jia et al. (2007) as measured by the eddy covariance method for bahiagrass in North Florida. The Kc values ranged from 0.35 in January to 0.90 in May (Fig. 1).

Daily irrigation and soil water content were calculated according to the following equations:

If,

$$SWC_t < AW - PAW \qquad [5]$$

Then,

$$I_t = AW - SWC_t$$

Else,

$$I_t = 0$$

If,

$$SWC_{t-1} + P_{t-1} + I_{t-1} - ETc_{t-1} < AW \qquad [6]$$

Then,

$$SWC_t = P_{t-1} + I_{t-1} - ETc_{t-1}$$

Else,

$$SWC_t = AW$$

where SWC is soil water content, P is precipitation, I is irrigation, and ETc is crop evapotranspiration. All variables have units of depth (inches) and subscripts i and i-1 indicate the current day and previous day, respectively. Equation 5 establishes the lower boundary (AW-PAW) for allowable water storage in the root zone, while Equation 6 establishes an upper boundary for the SWC (AW).

It is recognized that not all rainfall is stored in the root zone. It was assumed that all rainfall infiltrated the soil which is a reasonable assumption for well-irrigated sandy soils in Florida that have infiltration rates as high as 35 inches/hr on undisturbed sites and over 6 inches/hr on relatively compacted construction sites (Gregory et al. 2006). Equations 5-6, prevent irrigation from causing deep percolation (D); however, many rainfall events exceed the storage capacity of shallow rooted turfgrass resulting in drainage below the root zone. Effective rainfall (ER) was defined as rainfall stored in the root zone up to the AW limit. Any excess water from precipitation is assumed to runoff or result in drainage below the root zone and was calculated as the difference between the precipitation and effective rainfall. The following equations were used to calculate D and ER both with depth units:

If,

$$SWC_t + P_t + I_t - ETc_t > AW \quad [7]$$

Then,

$$D_t = SWC_t + I_t + P_t - ETc_t - AW$$

Else,

$$D_t = 0$$

$$ER = P - D \quad [8]$$

Finally, in the case that SWC or ER became negative due to the model calculations, these quantities were set to zero. For the optimum irrigation simulation (see OPT below), drainage only included that due to rainfall and not excess irrigation since there was no excess irrigation. For all other simulations, drainage included both excess rainfall and irrigation.

Weather data were gathered as part of the development of the Agricultural Field Scale Irrigation Requirements Simulation (AFSIRS) project (Smajstrla 1990) and were originally gathered from weather stations located throughout the state at the airports of major cities and are now available through NCDC (USDC 2007). Measured data included daily maximum and minimum temperature, maximum and minimum relative humidity, daily average wind speed at 10 m height, a cloudiness index (0 = clear and 10 = cloudy), and daily total precipitation. Daily average solar radiation values were estimated based on Hargreave’s equation as presented by

(Allen et al. 1998). It is important that all data are screened, but in particular that solar radiation data are accurate since this is the most sensitive input for the calculation of ETo under humid conditions (Irmak et al. 2006) during the summer months. All other weather data were screened according to procedures outlined by (Allen et al. 1998).

Irrigation Schedule Simulations

Five irrigation schedules based around the various recommendations in Florida (Table 1) were simulated by the daily SWB as follows with codes indicated in brackets:

1. [OPT] Optimal scheduling to refill the root zone when SWC was at or below the lower limit established by the MAD. This simulation emulated perfect control that could be established by careful manual scheduling or by real time soil moisture sensor or ET control. This methodology simulates optimum irrigation resulting in minimal plant stress prior to initiating irrigation.
2. [FIX] Irrigation of 0.75" when SWC was at the lower limit established by the MAD to simulate simplified irrigation recommendations.
3. [FIX-RS] Simulation #2 plus a rain sensor that would bypass irrigation if rainfall of at least 0.25" occurred the same day.
4. [HIST] Time-based irrigation schedule based on net irrigation requirement as given by Augustin (1983) and adjusted by (Dukes and Haman 2002) to provide an irrigation time assuming 2 d/wk irrigation frequency, Kc = 1. The weekly schedule for North Florida is given in Table 2.
5. [HIST-RS] Simulation #4 plus a rain sensor that would bypass irrigation if rainfall of at least 0.25" occurred.

Simulated irrigation schedules did not consider irrigation efficiency, thus calculated irrigation amounts are net irrigation requirements and total irrigation delivery would need to consider application and other efficiency terms.

Results and Discussion

Weather Data

A 30 year record (1961-1990) of weather data for Jacksonville, Florida was available from the AFSIRS modeling effort as mentioned previously. Weather characteristics of the 30 year data set are presented in Table 3. During the quality control screening procedures, it was found that the average wind speed frequently exceeded the threshold for concern of 5 mi/hr (Allen et al. 1998) as seen in Fig. 2. Through detailed investigation of the site including photos of the station, it was determined that the wind velocity was measured at 10 m height. Wind velocity data were adjusted to 2 m accordingly by standard methods (Allen et al. 1998). In addition, it was found that maximum relative humidity was slightly depressed and minimum relative humidity was slightly higher than would be expected for humid Florida conditions (Fig. 3). Solar radiation appeared reasonable and did not exceed the Rso envelope as recommended by Allen et al. (1998) and shown in Fig. 4. Measured dew point temperature was found to diverge substantially from the daily minimum temperature (Fig. 5). In a humid climate, these two temperatures should match on most days. The divergence of these two temperatures indicates arid characteristics from the weather data collection site (Allen 1996). The weather data were collected at airports which have substantial non-vegetative fetch and are prone to the heat island effect as a result. The weather data impacted the resulting calculated ETo to a great degree with an average annual total of 62.1 inches which is relatively high considering annual average rainfall across the 30 years was 51.1 inches.

The Simplified Aridity Adjustment (SAA) was used to correct the dew point temperature to reflect weather data collection under well-watered conditions (Allen 1996). This adjustment reduces maximum and minimum daily temperature as well as the daily dewpoint temperature based on the difference between minimum daily temperature and dew point temperature. The resulting annual average ETo was 50.7 inches and approximated values for ETo as given by Smajstrla (1990).

Irrigation Simulations

Rainfall and ETc varied dramatically over the 30 year period. Rainfall ranged from 31.2 inches in 1991 to 70.6 in 1973. The mean rainfall and ETc for the 30 year period were 51.1 inches/yr and 33.9 inches/yr, respectively (Tables 3 and 4). Net irrigation required varied for the OPT, FIX, FIX-RS, and HIST-RS schedules which simulated varying irrigation in response to rainfall events (Fig. 6). The HIST schedule did not respond to rainfall since the schedule is fixed irrigation run times two days a week (Dukes and Haman 2002) and this schedule did not simulate a rain sensor. Thus, the HIST schedule applied 21.6 inches of irrigation every year in the 30 year simulation. Adding a rain sensor with a ¼ inch threshold to both the FIX and HIST irrigation schedules did reduce average net irrigation requirements by 10.5% and 16.7%, respectively (Table 4). This savings is substantially lower than the savings reported by field research studies ranging from 17% to 34% for ⅛ to ½ inch thresholds compared to homeowner irrigation schedules similar to HIST (Cardenas-Lailhacar and Dukes In press; Cardenas-Lailhacar et al. In press). The addition of a rain sensor did not result in more savings due to the limited storage capacity of the root zone (0.56 inches completely dry) as a result of limited root depth and coarse textured soil. Also, in previous studies the 2005 year used for comparison had very frequent rainfall which could have differed from the "average" year represented in these simulations.

Generally, irrigation is required in North Florida in the spring months beginning in March and until the rainy season starts in June (Fig. 7). Depending on rainfall distribution, irrigation is likely required in the fall months of September through November and into December depending on when the first frost causes turfgrass dormancy. However, irrigation can be required most of the year including the rainy summer period due to short drought periods of one or two weeks. Effective rainfall contributed to 37% of the crop water demand in the OPT schedule, with the remaining 21.4 inches applied by irrigation (Table 4).

Both FIX and FIX-RS schedules resulted in substantial over-irrigation of 78.4% and 59.8%, respectively more than the OPT schedule (Table 4). Both of these schedules could be improved by basing the depth on site specific soil and root zone conditions. However, making this recommendation site specific is not practical due to lack of soil and rooting depth knowledge by users. Over-irrigation for both of these recommendations was evident for the entire year (Fig. 8). Adding a rain sensor or ceasing irrigation in response to 0.25 inches of rainfall contributed to irrigation savings May through September. In contrast, the HIST and HIST-RS schedules simulated under-irrigation until May where HIST then resulted in over-irrigation until November when both schedules under-irrigated. HIST-RS matched the OPT schedule quite well in June July and August but resulted in over-irrigation in September and October. The under irrigation early and late in the year and over-irrigation in the summer resulted in HIST average net irrigation requirement (21.6 inches) closely matching the OPT schedule (21.4 inches). However, the HIST-RS simulation was about 16% lower (18.0 inches) than the OPT schedule (Table 4). Both HIST schedules increased effective rainfall by 11.3% and 30.2% with the addition of a rain sensor. Differences between the HIST schedules and the OPT schedule are likely due to differences in the methodologies where OPT is a result of the daily soil water balance as described in this paper and the HIST schedules were generated from a different set of historical data

Figure 9 shows the trend of net irrigation requirement, deep percolation (drainage), and effective rainfall cumulatively across the year. Effective rainfall across the irrigation schedules ranged from 10.7 inches/yr to 16.2 inches/yr (Table 4). This limited variation was likely due to the limited root zone and small amount of water depletion prior to the onset of turfgrass stress (0.28 inches). The HIST-RS schedule had the highest effective rainfall at 16.2 inches/yr (Fig. 9) because of the under-irrigation for part of the year as described earlier. The lowest effective rainfall was observed for the FIX schedule with the highest amount of over-irrigation.

It can be seen in Fig. 9 that HIST matched the simulated net irrigation requirement fairly closely but as stated previously, HIST-RS resulted in under slight irrigation. Both FIX and FIX-RS schedules result in over-irrigation after March which continued to accumulate through the year. Thus, it is not surprising that both of these schedules resulted in the largest amount of drainage. As mentioned earlier, effective rainfall was not greatly different across treatments.

Summary and Future Work

This study showed that optimizing irrigation scheduling could reduce irrigation application relative to current irrigation recommendations as much as 60% (FIX-RS vs OPT). The OPT schedule is a good example of what might be achieved by new soil moisture-based or ET-based irrigation controllers. The irrigation recommendation of the HIST-RS schedule appears to be a reasonable schedule that balances water conservation with practicality. The OPT schedule should be attainable with ET-based and soil moisture sensor irrigation controllers and can be used as a performance comparison for these controllers.

The greatest uncertainty in the soil water balance approach for Florida conditions is the root zone depth where the majority of water is extracted as well as the maximum allowable depletion (MAD) level that can be tolerated by a particular plant type. This depth probably varies in time, especially in climates where there is winter dormancy as in North Florida. Net irrigation requirements can also be reduced by increasing the root depth of turfgrass or by increasing the soil water holding capacity through the addition of soil amendments.

Weather data from seven additional sites throughout Florida are available and will be used to simulate turfgrass irrigation water requirements in future work. Future simulations should also investigate variation in irrigation, drainage, and effective rainfall across a range of root depths that might be expected and a range of soil water holding capacities for a given location.

References

Allen, R. G., Walter, I. A., Elliot, R. L., Howell, T. A. (2005). *The ASCE Standardized Reference Evapotranspiration Equation,* American Society of Civil Engineers, Reston, VA.

Allen, R. G., Pereira, L. S., Raes, D., Smith, M. (1998). *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements,* Irrigation and Drainage Paper No. 56 Ed., United Nations Food and Agriculture Organization, Rome, Italy.

Allen, R. G. (1996). "Assessing Integrity of Weather Data for Reference Evapotranspiration Estimation." *Journal of Irrigation and Drainage Engineering,* 122(2), 97-106.

Augustin, B. J. (1983). *Water Requirements of Florida Turfgrasses,* University of Florida Cooperative Extension Service, Gainesville, FL.

Cardenas-Lailhacar, B., and Dukes, M. D. (In press). "Expanding Disk Rain Sensor Performance and Potential Irrigation Water Savings." *Journal of Irrigation and Drainage Engineering*.

Cardenas-Lailhacar, B., Dukes, M. D., Miller, G. L. (In press). "Sensor-Based Automation of Irrigation on Bermudagrass, during Wet Weather Conditions." *Journal of Irrigation and Drainage Engineering*.

Carlisle, V. W., Sodek, F.,III, Collins, M. E., Hammond, L. C., Harris, W. G. (1989). *Characterization Data for Selected Florida Soils,* Soil Science Research Report 89-1 Ed., Institute of Food and Agricultural Sciences, Soil Science Department, Gainesville, FL.

Dukes, M. D., and Haman, D. Z. (2002). *Operation of Residential Irrigation Controllers,* University of Florida Cooperative Extension Service, Gainesville, FL.

Garner, A., Stevely, J., Smith, H., Hoppe, M., Floyd, T., Hinchcliff, P. (2001). *A Guide to Environmentally Friendly Landscaping: Florida Yards and Neighborhoods Handbook,* University of Florida Cooperative Extension Service, Gainesville.

Gregory, J. H., Dukes, M. D., Jones, P. H., Miller, G. L. (2006). "Effect of Urban Soil Compaction on Infiltration Rate." *Journal of Soil and Water Conservation,* 61(3), 117-124.

Haley, M. B., Dukes, M. D., Miller, G. L. (2007). "Residential Irrigation Water use in Central Florida." *Journal of Irrigation and Drainage Engineering,* 133(5), 427-434.

Irmak, S., Payero, J. O., Martin, D. L., Irmak, A., Howell, T. A. (2006). "Sensitivity Analyses and Sensitivity Coefficients of Standardized Daily ASCE-Penman-Monteith Equation." *Journal of Irrigation and Drainage Engineering,* 132(6), 564-578.

Irmak, S., and Irmak, A. (2005). "Performance of Frequency Domain Reflectometer, Capacitance, and Psuedo-Transit Time-Based Soil Water Content Probes in Four Coarse-Textured Soils." *Applied Engineering in Agriculture,* 21(6), 999-1008.

Jia, X., Dukes, M. D., Jacobs, J. M. (2007). "Development of bahiagrass crop coefficient in a humid climate." *Proc., International Meeting of the American Society of Agricultural and Biological Engineers,* American Society of Agricultural and Biological Engineers, Minneapolis, MN, ASABE Paper No. 07-2151.

Marella, R. L. (2004). *Water Withdrawals, use, Discharge, and Trends in Florida, 2000,* U.S. Geological Survey Scientific Investigations Report 2004-5151 Ed., USGS, Tallahassee, FL.

Smajstrla, A. G., Boman, B. J., Haman, D. Z., Izuno, F. T., Pitts, D. J., Zazueta, F. S. (1997). *Basic Irrigation Scheduling in Florida,* University of Florida Cooperative Extension Service, Gainesville, FL.

Smajstrla, A. G., and Zazueta, F. S. (1995). *Estimating Crop Irrigation Requirements for Irrigation System Design and Consumptive use Permitting,* University of Florida Cooperative Extension Service, Gainesville, FL.

Smajstrla, A. G. (1990). *Technical Manual Agricultural Field Scale Irrigation Requirements Simulation (AFSIRS) Model,* version 5.5 Ed., University of Florida, Agricultural and Biological Engineering Department, Gainesville, FL.

Trenholm, L. E., and Unruh, J. B. (2003). *Let Your Lawn Tell You when to Water,* University of Florida Cooperative Extension Service, Gainesville, FL.

Trenholm, L. E., Unruh, J. B., Cisar, J. L. (2001). *Watering Your Florida Lawn,* University of Florida Cooperative Extension Service, Gainesville, FL.

Trenholm, L. E., Cisar, J. L., Unruh, J. B. (1991). *St. Augustinegrass for Florida Lawns,* University of Florida Cooperative Extension Service, Gainesville, FL.

USCB. (2006). *National Population Estimates,* U.S. Census Bureau, Washington, D.C.

USDC. (2007). "National climate data center." <http://www.ncdc.noaa.gov/oa/ncdc.html> (October/12, 2007).

Zazueta, F. S., Miller, G. L., Zhang, W. (2000). *Reduced Irrigation of St. Augustinegrass Turfgrass in the Tampa Bay Area,* University of Florida Cooperative Extension Service, Gainesville, FL.

Zazueta, F. S., Brockaway, A., Landrum, L., McCarty, L. B. (1995). *Turf Irrigation for the Home,* University of Florida Cooperative Extension Service, Gainesville, FL.

Table 1. IFAS turfgrass and landscape irrigation recommendations published in EDIS (http://edis.ifas.ufl.edu).

Reference	Title	Irrigation Requirement or Scheduling Recommendation
(Augustin 1983)	Water requirements of Florida turfgrasses	Net irrigation requirement ranging from 19.02 to 34.58 inches per year.
(Trenholm et al. 1991)	St. Augustinegrass for Florida lawns	Irrigate 0.5 to 0.75 inches when lawn show signs of wilting. Vary watering frequency and not amount
(Smajstrla and Zazueta 1995)	Estimating crop irrigation requirements for irrigation system design and consumptive use permitting	Daily soil water balance with historical data to determine mean annual irrigation requirement.
(Zazueta et al. 1995)	Turf irrigation for the home	Gives general guidelines on water holding capacity for sandy Florida soils. Gives allowable depletion of 0.50 inches per foot not including irrigation efficiency. Guidelines are also given on days between irrigation events. Recommends tensiometers to automate irrigation scheduling.
(Smajstrla et al. 1997)	Basic irrigation scheduling in Florida	Describes water budget irrigation scheduling. Recommends tensiometer/soil moisture sensors to assist with scheduling.
(Zazueta et al. 2000)	Reduced irrigation of St. Augustinegrass in the Tampa Bay area	Described a study that evaluated turfgrass quality under deficit irrigation conditions where acceptable quality turfgrass was maintained with 60% of crop water requirement replacement. Recommends applying only the amount of water that can be stored in the root zone at each irrigation event and a general value of 0.75 to 1.0 inches is given for Florida soils. Gave irrigation intervals ranging from 2.7 to 11.6 days, 2.2 to 9.3 days, and 1.7 to 7.5 days for high, medium, and low water savings and a 6" root zone in Tampa Bay; 6.1 to 27.8 days, 5.2 to 21.6, and 4.4 to 20.2 days for a 12" root zone.

Table 1. Continued.

(Trenholm and Unruh 2003)	Let your lawn tell you when to water	Recommends irrigation when turf appears stressed by observing wilting. Encourage roots to grow deep by watering only when stressed and by mowing at highest recommended height. Apply 0.5 to 1 inches of water per application. General required watering frequencies are given for three geographic areas of the state.
(Garner et al. 2001)	A guide to environmentally friendly landscaping: Florida yards and neighborhoods handbook	Water early morning between 4 am and 7 am. Apply 0.5" to 0.75" when turfgrass shows signs of distress. Water less in cooler months.
(Trenholm et al. 2001)	Watering your Florida lawn	Over watering results in a less developed shorter root system. On average we receive over 60 inches of rain each year. Water when grass shows signs of wilting apply 0.75" of irrigation. Watering every 2-3 days is adequate in the summer and once every 10-14 days in the winter.
(Dukes and Haman 2002)	Operation of residential irrigation controllers	Controller run times given based on historical ET and rainfall data for three regions in the state. Assumptions include 60% efficiency and two d/wk irrigation. NIR data were taken from Augustin (1983).

Table 2. Recommended irrigation depths for landscape irrigation in North Florida based on (Augustin 1983).

	Weekly Irrigation (inches)	Monthly Irrigation (inches)
Jan	0.04	0.16
Feb	0.00	0.00
Mar	0.09	0.34
Apr	0.49	1.98
May	0.84	3.34
Jun	0.75	3.00
Jul	0.70	2.79
Aug	0.64	2.57
Sep	0.82	3.28
Oct	0.54	2.15
Nov	0.34	1.34
Dec	0.13	0.52
Total		21.5

Table 3. Weather parameters for 30 year period of record, Jacksonville, Florida.

Parameter		Mean	Maximum	Minimum
Daily T_{max}	(°F)	78.3	102.9	32.0
Daily T_{min}	(°F)	58.5	82.9	15.1
Daily RH_{max}	(%)	75.3	97.7	26.3
Daily RH_{min}	(%)	51.7	97	13
Daily Avg R_s	($MJ\ m^{-2}\ d^{-1}$)	16.5	30.8	3.4
Daily Avg U_2	(mph)	7.6	30.0	0.7
Rainfall	($in\ d^{-1}$)	0.14	7.82	0.00
	($in\ yr^{-1}$)	51.1	70.6	31.2
Uncorrected ETo	($in\ d^{-1}$)	0.17	0.42	0.02
	($in\ yr^{-1}$)	57.3	65.4	52.1
Corrected ETo	($in\ d^{-1}$)	0.14	0.28	0.02
	($in\ yr^{-1}$)	50.7	54.5	47.3

Table 4. Summary of water balance components for simulated irrigation schedules.

							Compared to OPT Schedule		
Irrigation Schedule	ETc (in)	Rainfall (in)	Irrigation (in)	Effective Rainfall (in)	Drainage (in)	Balance (%)	Irrigation (%)	Effective Rainfall (%)	Drainage (%)
OPT	33.9	51.1	21.4	12.5	38.7	0.0	0.0	0.0	0.0
FIX	33.9	51.1	38.2	10.7	55.5	0.0	78.4	-14.0	43.4
FIX-RS	33.9	51.1	34.2	13.0	51.5	0.0	59.8	4.7	33.1
HIST	33.9	51.1	21.6	13.9	41.4	3.6	0.9	11.3	7.2
HIST-RS	33.9	51.1	18.0	16.2	37.8	3.8	-16.2	30.2	-2.1

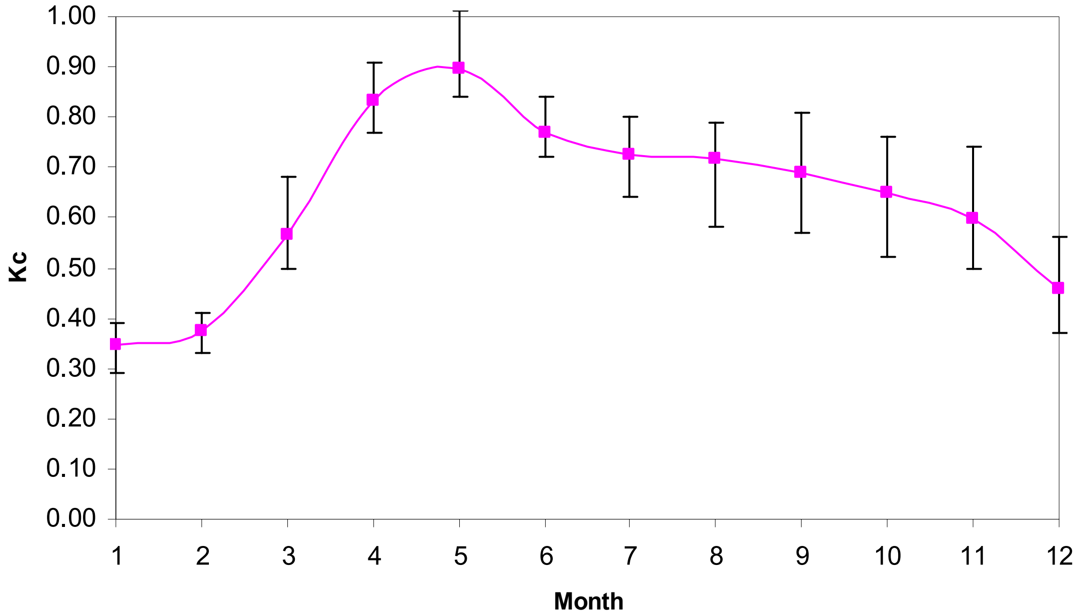

Fig. 1. Crop coefficient (Kc) values use in the simulation as reported by Jia et al. (2007). Error bars indicate minimum and maximum values observed during the multi-year study to determine warm season turfgrass Kc values.

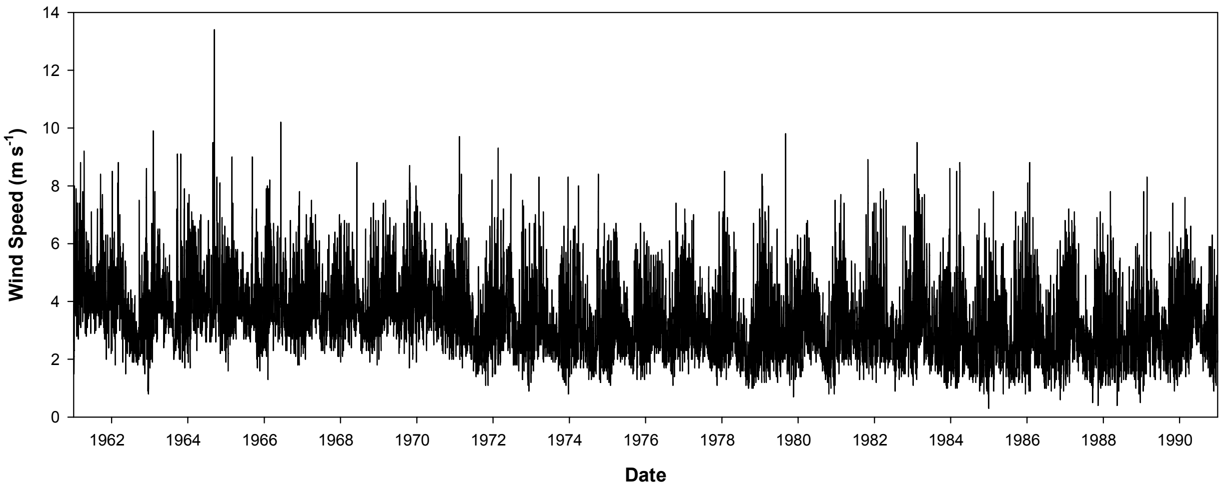

Fig. 2. Average daily wind speed 1961-1990 for Jacksonville, Florida. Note that 1 m s^{-1} = 2.24 mi/hr.

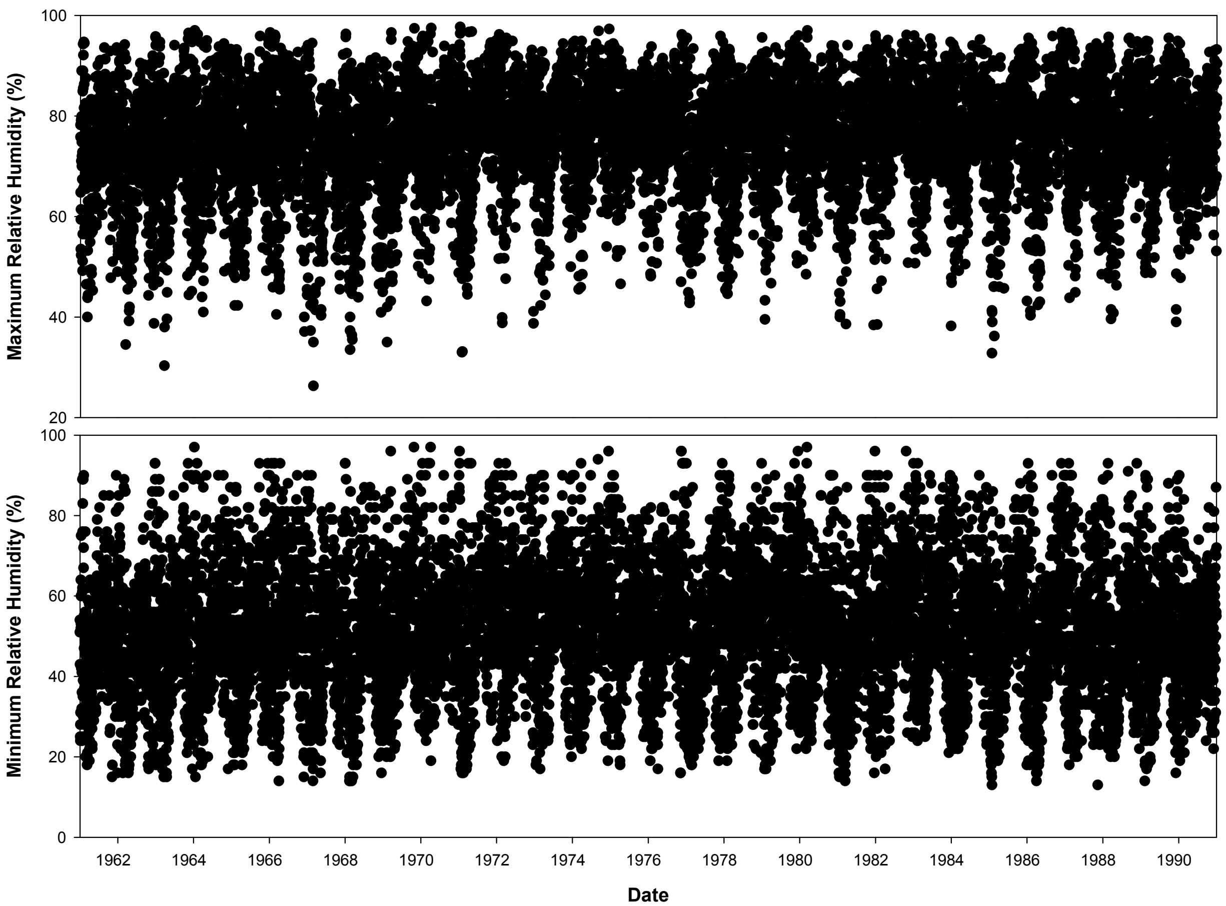

Fig. 3. Maximum and minimum relative humidity 1961-1990 for Jacksonville, Florida.

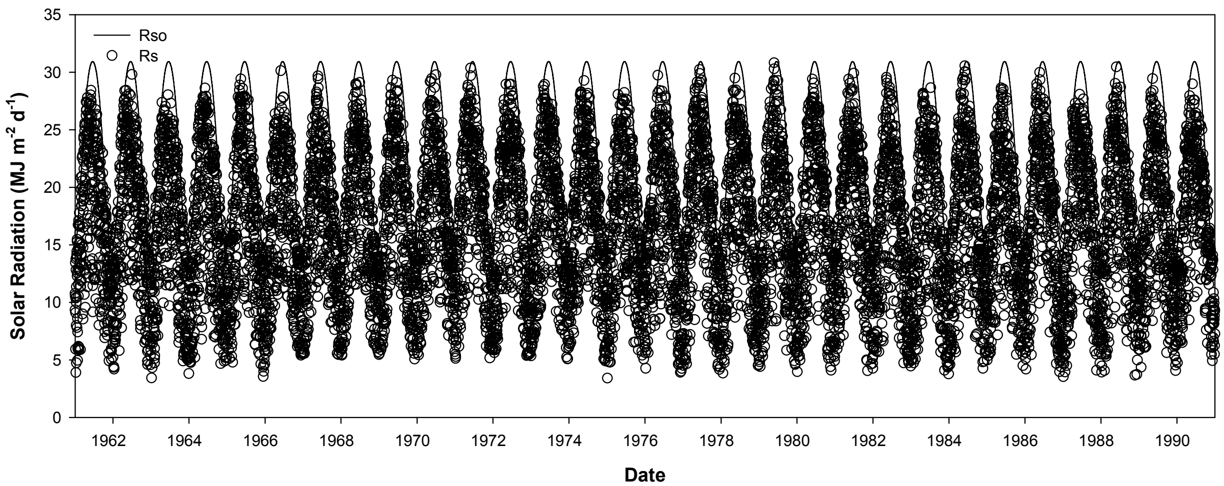

Fig. 4. Average daily solar radiation (Rs) and clear sky solar radiation (Rso) 1961-1990 for Jacksonville, Florida.

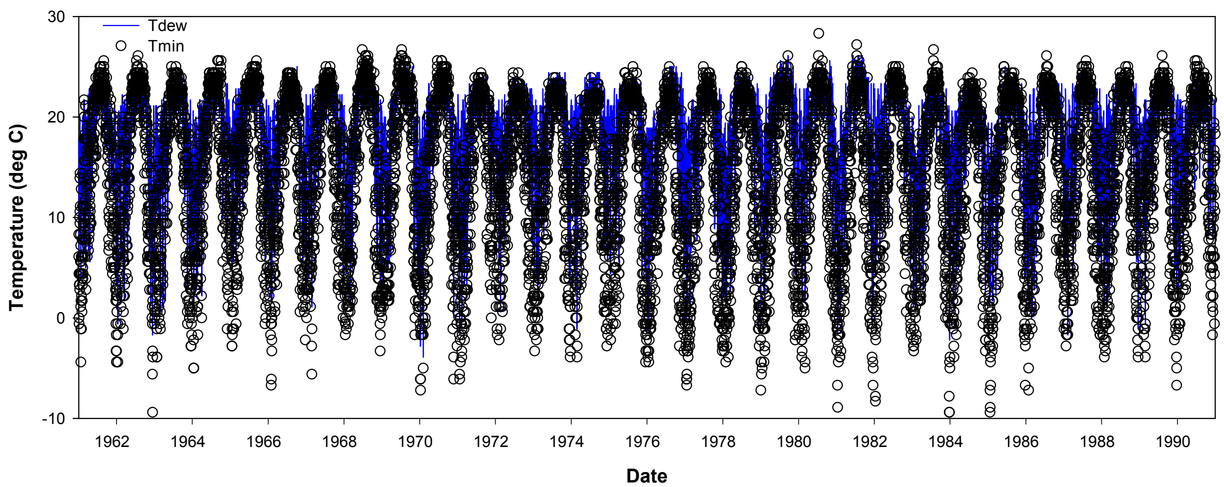

Fig. 5. Dew point and minimum temperature 1961-1990 for Jacksonville, Florida.

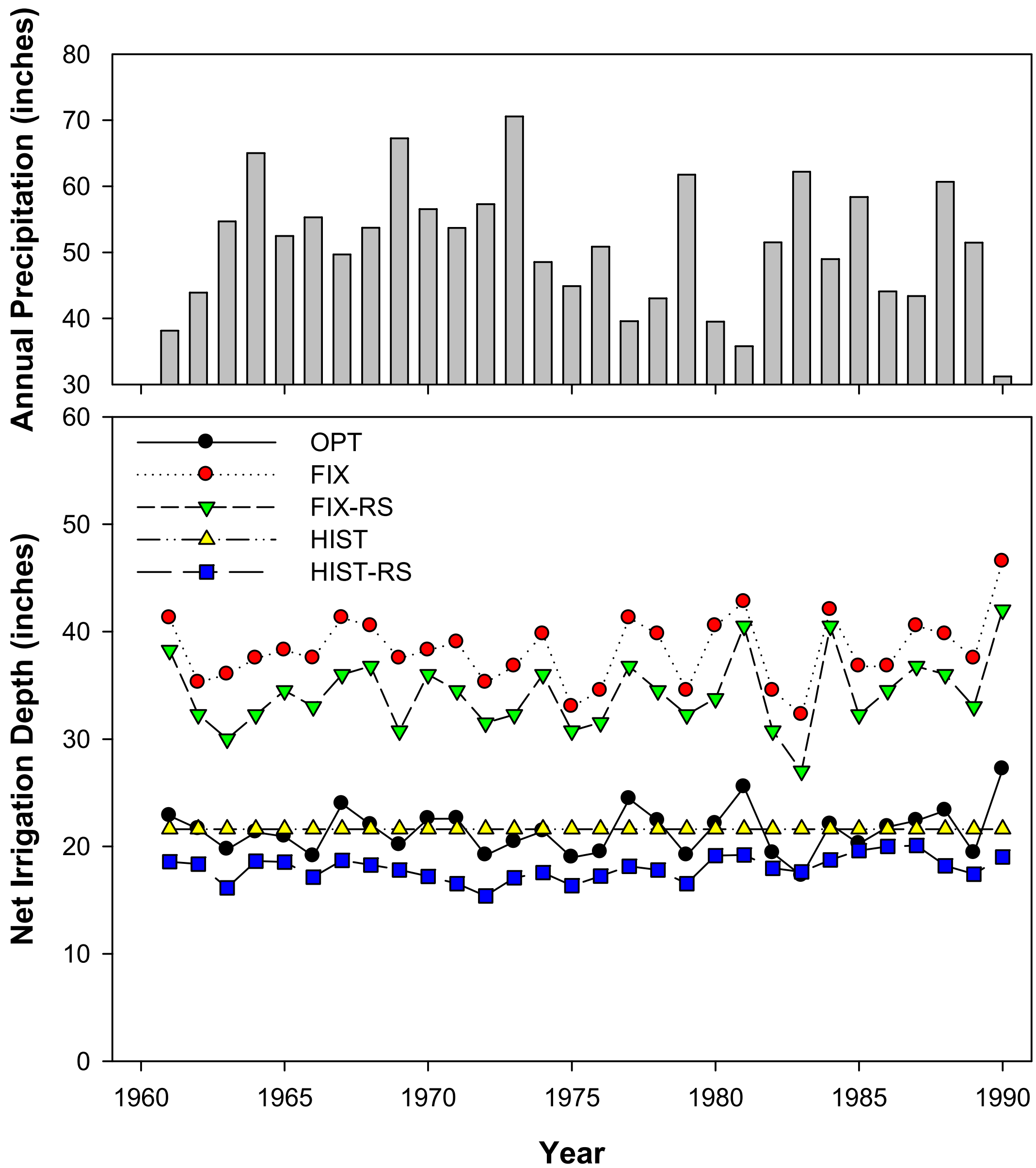

Fig. 6. Annual variability in net irrigation simulated across various irrigation schedule simulations.

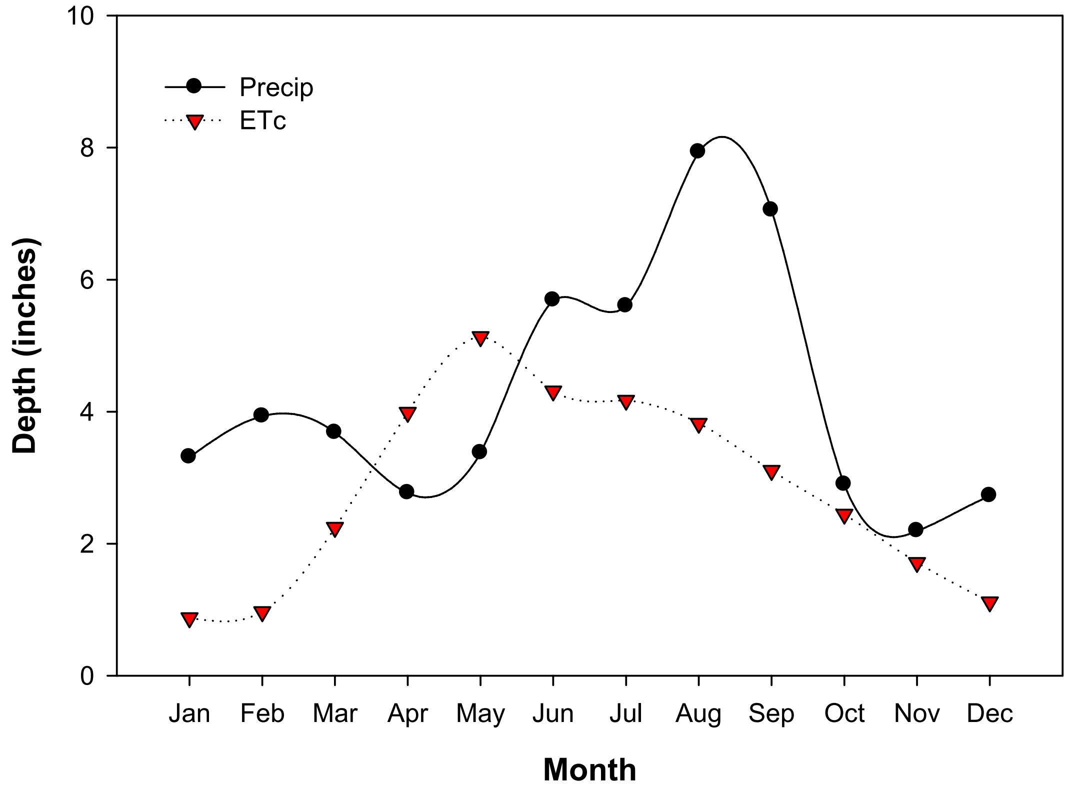

Fig. 7. Monthly average long-term precipitation and turfgrass ETc for Jacksonville, Florida.

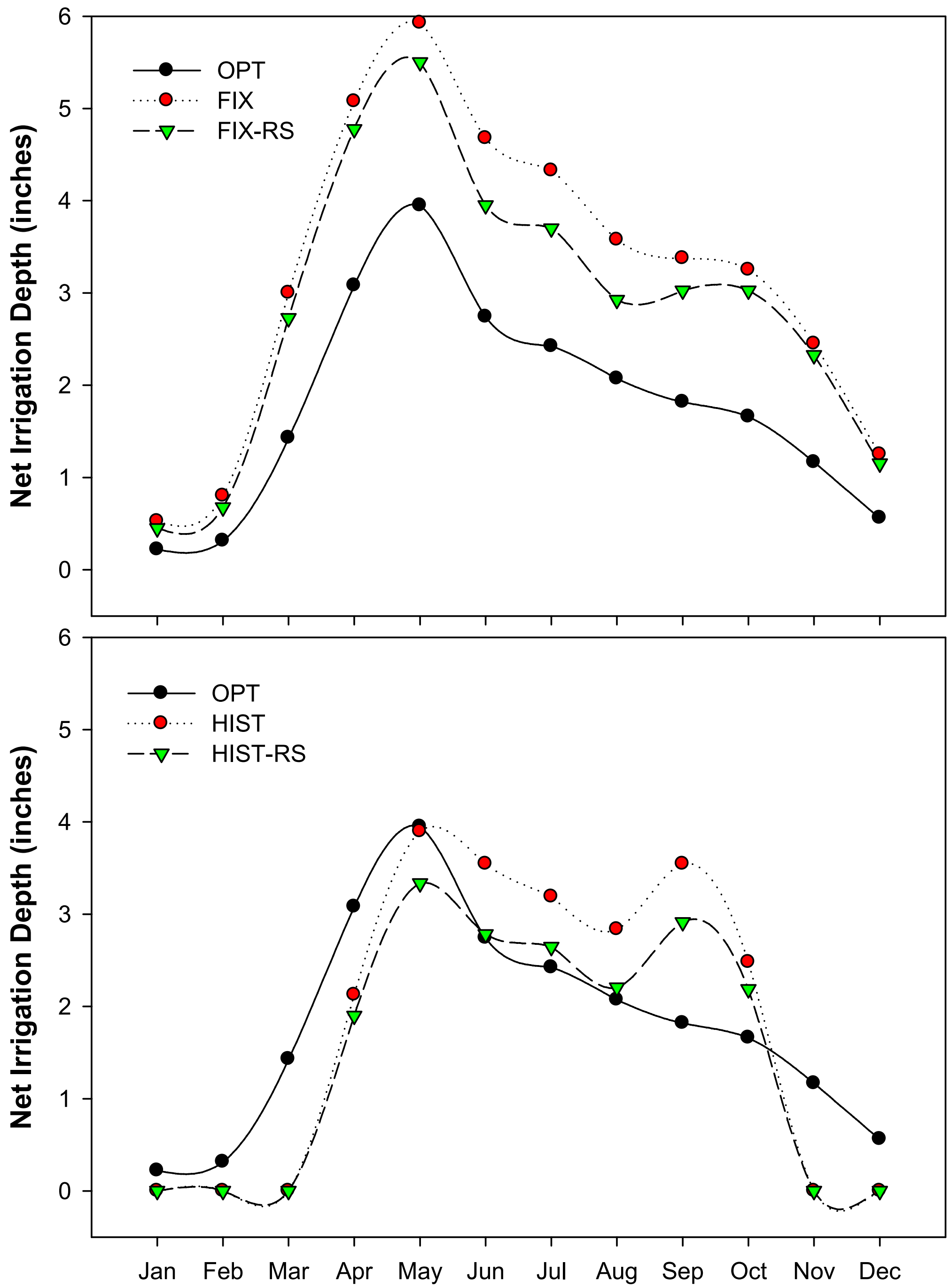

Fig. 8. Monthly average net irrigation requirements across various irrigation schedules simulated.

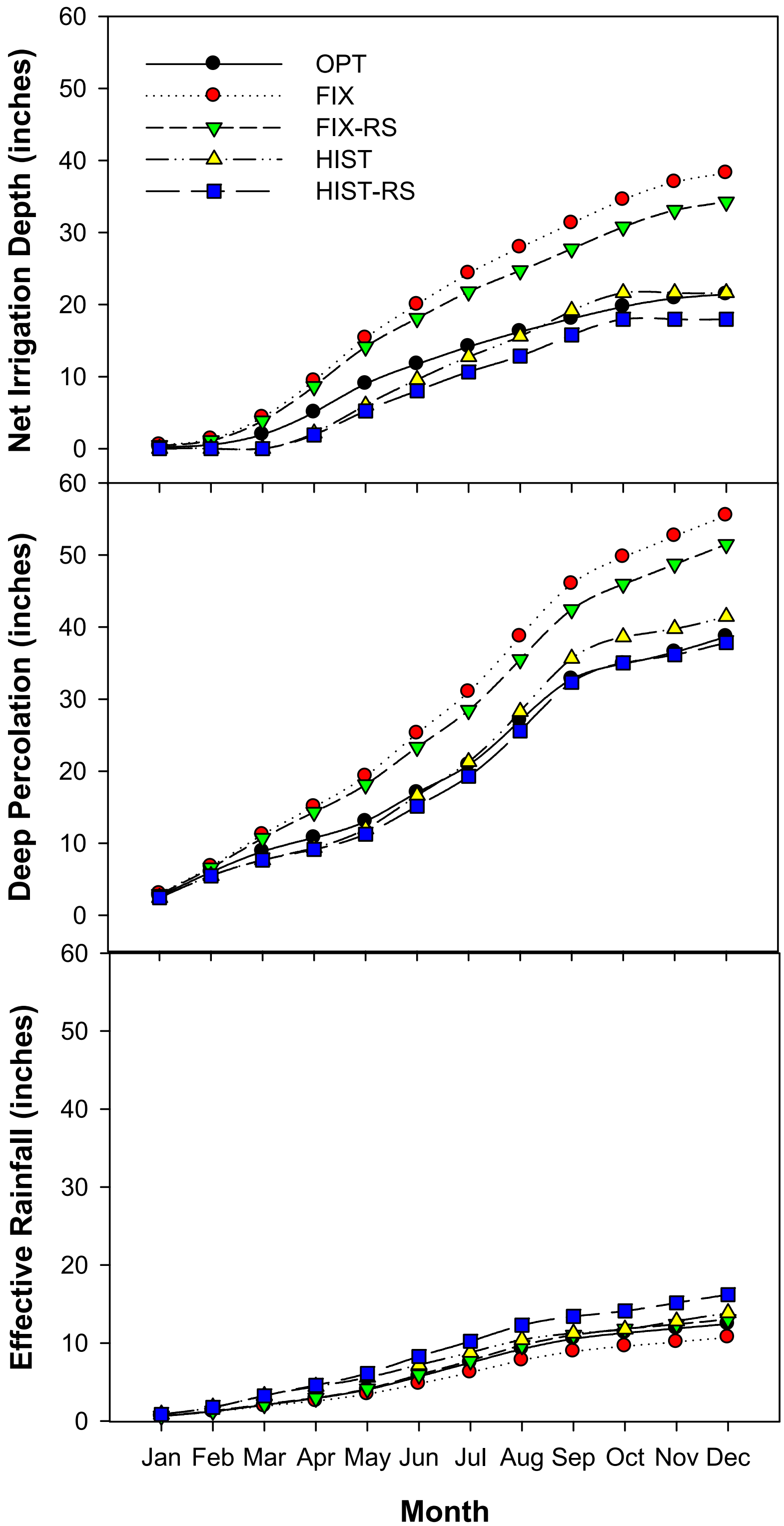

Fig. 9. Monthly average of cumulative net irrigation, deep percolation below the turfgrass root zone and effective rainfall simulated across various irrigation schedules.