EVALUATION OF EVAPOTRANSPIRATION-BASED AND SOIL-MOISTURE-BASED IRRIGATION CONTROL IN TURF

Garry L. Grabow¹, Arjun Vasanth¹, Dan Bowman², Rodney L. Huffman¹, and Grady L. Miller²

¹Department of Biological and Agricultural Engineering
²Department of Crop Science
North Carolina State University

Published version at:
http://cedb.asce.org/cgi/WWWdisplay.cgi?165363

ABSTRACT

A study was initiated in Fall 2006 in Raleigh, North Carolina to compare two types of commercially available irrigation control technologies, one based on estimates of evapotranspiration (ET) and the other based on feedback from soil moisture sensors. Water applied and turf quality from one ET-based system and two sensor-based systems were compared to a system using a standard time-based irrigation schedule. The effect of irrigation frequency was also a part of the study. Estimates of turf ET were obtained from the Penman-Monteith equation using on-site weather data, and also from an atmometer. Results from the twenty week evaluation in 2007 showed that on average the “add-on” soil-moisture-based system evaluated applied the least amount of water while the ET-based system evaluated applied the most water. Weekly irrigation frequencies used the least amount of water, followed by bi-weekly and daily frequencies in increasing amounts when averaged across all technologies. Minimally acceptable turf quality was maintained by all technologies and frequencies through most of the study, but turf quality declined substantially the last month of the study for the add-on system and standard timer-based system. The “on-demand” sensor-based system resulted in the best combination of water efficiency and turf quality.

INTRODUCTION

Turfgrass is a major part of the urban and sub-urban landscape in the state of North Carolina, with acreage equal to 44% of the state’s harvested crop acreage (NCDA 2001). North Carolina residences using irrigation systems increased 29.4% between 1994 and 1999 (NCDA, 2001). With drought a recurring problem, several municipalities in North Carolina have imposed water-use restrictions on turf and landscape irrigation. Municipalities are also considering promotion of “smart” irrigation technologies to increase outdoor water efficiency.

Variability and irregularity in rainfall make irrigation scheduling difficult in North Carolina and an efficient irrigation schedule (applying the right amount of water at the right time) is essential in meeting the dual goals of water conservation and acceptable turf quality. Under-irrigation and over-irrigation can negatively affect turfgrass quality (Cardenas-Lailhacar et al., 2005) and over-irrigation results in waste of water and leaching of nutrients. With increasing competition for water resources, controllers that use feedback technologies show promise for improved water management.
So-called “smart” irrigation technologies can be separated into two categories - those that use a feedback sensor to monitor the amount of water in the root zone, and those that use weather data and a soil-water budget to adjust irrigation amounts.

Systems that are based upon soil-water feedback incorporate buried sensors that are wired in series with and electrically actuated solenoid valve. The sensor acts as a switch opening the circuit between the controller and the valve when the soil-water content is high preventing irrigation, and closing the circuit when watering is needed.

Another type of system used in turfgrass irrigation control is based on controllers that use weather information to estimate ET and adjust irrigation using a soil-water budget. An ET controller can make adjustments to the watering schedule based on weather conditions without requiring human interaction. ET controllers receive information from local or on-site weather stations and adjust watering durations to replace ET.

This paper presents an overview of the experimental site and design and results from the first season of a three-year study.

**Site Description and Experimental Design**

This study was initiated in fall 2007 at the North Carolina State University Lake Wheeler Turf Field Laboratory, Raleigh, North Carolina. The soil is classified as a Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludults)

The experiment site was established to ‘Confederate’ tall fescue (Festuca arundinacea Schreb) using sod. Forty 13-ft x 13-ft (3.96-m x 3.96-m) plots were irrigated independently by four quarter circle pop-up spray head sprinklers. Prior to sodding, the field site was leveled and the irrigation system installed. The irrigation system uses water from a nearby irrigation pond that is filtered with a 60 mesh filter and pressure regulated at 30 psi. Water meters measure flow to four plots each, and flow to each plot is controlled by a separate solenoid valve.

A weather station (Watchdog 700, Spectrum Technologies, Plainfield, Illinois) was installed at the site to record weather data and estimate reference evapotranspiration (ET₀) by the Penman-Monteith method. A separate tipping bucket rain gauge was logged by a CR10X logger (Campbell Scientific Inc., Logan, Utah), and a recording atmometer (ETgage Co., Loveland, Colo.) with a #30 canvas cover to simulate ET₀ was installed on site. The State Climate Office of North Carolina maintains a weather station about 0.8 miles (1.3 km) from the experimental site.

**Experimental Design and Monitoring**

Two factors, irrigation control technology and irrigation frequency, were examined in this study. The irrigation control treatments included a standard time-based controller, an ET controller system and two soil moisture sensor feedback systems.

Two soil-water sensor based systems were manufactured by the same company and used the same sensor for both technologies. One technology is designed as an “add-on” system that can be integrated with any standard irrigation control clock. A soil-water content setpoint is used to prevent irrigation when the soil-water content is above the

---

1 Mention of products does not imply endorsement by North Carolina State University
setpoint. The other soil-water based feedback system is designed as an “on-demand” system that uses two soil-water content setpoints, one to initiate irrigation and another to terminate irrigation. The “on-demand” system included a controller and software to collect sensor collected data and perform a number of other functions. The ET-based system was a ET-controller available in the region. A rain sensor was added to the ET controller and the standard time based controller. All treatments, except the “on-demand” system, were set to water daily, bi-weekly (2 times per week), or weekly (one day per week).

There were ten treatments combining control type and watering frequency (3 technologies x 3 frequencies + 1 on-demand technology), with four replicates of each arranged in a randomized complete block design. All the plots in the second block were individually monitored for soil-water content by TDT sensors of the same make used as the control sensors for the soil-water sensor based systems. The ten water meters were logged to record irrigation amounts. All systems except the ET controller were programmed to start between 0030 and 0600 hrs, to reduce potential water drift between plots and to decrease evaporation.

Turf quality was rated weekly using the standard turf quality index. This index is based upon a 1-9 scale with 9 representing the best possible turf quality. Turf quality was assessed once a week in the morning to minimize confounding of temperature-induced stress. Canopy temperatures were taken once a week late in the afternoon in sunny conditions to maximize the potential difference in canopy temperature between plots due to varying levels of turf stress. Twenty weeks of water use data were collected while fifteen weeks of turf quality and canopy temperature were recorded. The turf quality and canopy temperatures were recorded the last 15 weeks of the 2007 study period.

**Standard timer-based irrigation**

These treatments represent an average homeowner system set to apply water on a fixed schedule (weekly, bi-weekly, and daily) and irrigation duration to replace the historical irrigation requirement (adjusted monthly) of a cool season turf. The irrigation requirement factored in effective precipitation and the irrigation system uniformity. A rain switch was set with a different threshold for each frequency treatment: weekly – 0.75 in. (19 mm), bi-weekly – 0.50 in. (13 mm) and daily – 0.25 in (6 mm). The three different frequencies were programmed into separate programs in a standard irrigation controller.

**Soil moisture-based “add-on” system**

Soil-moisture feedback sensors were placed in block 2 plots of each irrigation frequency for the add-on system. These modules were connected to a standard irrigation controller with three independent programs similar to the time based controller. The controller was set to apply the same amount of water as the standard time-based system. The “add-on”system has a Time Domain Transmissivity (TDT) moisture sensor that measures the volumetric moisture percentage of the soil and prevents irrigation above a user-supplied soil-water content. The volumetric soil-water setpoint used in this study was 24%, equivalent to 75% of field capacity per manufacturer directions.
Soil moisture based on-demand system

The “on-demand” soil-water feedback controller system evaluated uses the same sensor as the “add-on” system; however it is designed to both initiate and terminate irrigation events by setting lower and upper setpoints respectively. The lower and upper setpoints were set at 21% and 30% volumetric moisture, respectively, with the lower setpoint (turn-on) corresponding to a depletion of 67% of the plant-available soil water, and the upper setpoint (turn-off) just below field capacity. Cycle and soak times of 10 minutes were programmed to allow for water infiltration and sensor detection.

Evapotranspiration-based system

The ET-based controller was evaluated at the same irrigation frequencies as the timer-based and “add-on” systems. The plots irrigated by the ET controller system received irrigation amounts based upon reference ET estimates downloaded daily from a weather service provider and a soil-water budget. User inputs that affect the soil-water budget include root depth, soil type, crop type, and sun exposure. In this study the rooting depth was set at 6 inches (152 mm) the soil type set for sandy loam, and the crop type set to cool season turf. A rain sensor set at a threshold of 0.50 in. (13 mm) was added to the controller to over-ride irrigation in case of substantial site rainfall.

Data Analysis

Weekly water use data for all plots were compiled from water meter data. The data were analyzed using a “mixed” effects statistical model with technology type, irrigation frequency and their interaction as fixed effects, and block (rep), week, and week x technology x frequency interaction as random effects. Mean values for weekly water use, turf quality, and canopy temperature was separated using least-squared means. Statistical inference was based upon an $\alpha=0.05$ significance level.

RESULTS AND DISCUSSION

The study period in 2007 (twenty week duration from April 22 to September 8) was slightly warmer and substantially drier than the long-term normal temperature and rainfall. The average temperature for a North Carolina State Climate Office agricultural weather station about 0.8 miles (1.3 km) from the study site was 0.5 degrees F (0.28 deg. C) warmer than the 30 year normal for May-Sep [4.5 degrees F (2.5 deg. C) warmer in August] and precipitation at the site was 10.86 in. (276 mm) versus the 16.71 in. (424 mm) normal for the same period.

Turf water demand was estimated to be 20.0 inches (508 mm) for the 20 week study period using the Penman-Monteith ET$_0$ estimates generated from the Watchdog weather station and using a crop coefficient of 0.8 to convert to turf water demand. Water demand estimated from atmometer data was 19.11 inches (485 mm) using the same crop coefficient. Pump failures occurred during the course of the study preventing scheduled irrigations for a total of six days. This impacted the weekly irrigation frequencies more severely, as the next available irrigation was delayed for seven days.
Standard time based irrigation system

Applied water for the three irrigation frequencies were: weekly – 16.88 inches (429 mm), bi-weekly – 16.92 inches (430 mm), and daily – 15.62 inches (397 mm). These values are nearly the same for the three frequencies as they were programmed to apply the same irrigation amounts weekly and only differed in the setting of rain sensor thresholds. The daily treatment skipped irrigation on 28 occasions (22 due to rain sensor override and 6 due to pump failures).

Add-on system

The add-on system used less water than the timer based system. This was due to the volumetric soil water content being above the setpoint on several occasions when irrigation was scheduled. Cumulative applied water was: weekly – 8.56 inches (217), bi-weekly – 12.81 inches (325 mm), and daily – 13.87 inches (352 mm). Figure 1 shows rainfall, irrigation and the soil-water content for the system set to irrigate bi-weekly. The lesser amount of applied water for the daily irrigation is mainly because of a higher proportion of skipped irrigation opportunities. The daily irrigation treatment skipped 34 potential irrigations. The soil-water level dropped and stayed below the setpoint the final four weeks of the study despite scheduled irrigations.

Figure 1. Soil-water content, rain, and irrigation for the add-on system set to irrigate bi-weekly. The horizontal dashed line represents the setpoint above which irrigations were disabled. Dots represent soil-water measured by the control sensor. This sensor was placed 1 ft (0.34 m) from the monitoring sensor.
On-demand system

This system applied 17.64 inches (448 mm) over the study duration. The system failed twice during the experimental study once on the 14th of May and again on the 13th of June, the second failure most due to a lightning strike near the site. While no water was applied until the units were replaced, the soil-water content had not reached the “turn on” level Figure 2 shows soil-water content, irrigation and rainfall during the study period. The soil-water content was keep above the “turn-on” level of 21% by volume for the entire period with few exceptions.

![Figure 2. Soil-water content, rain, and irrigation for the on-demand system set to allow irrigation daily. The horizontal dashed lines represent the upper and lower setpoints.](image)

ET controller system

The cumulative applied irrigation amounts over the twenty week study period were: weekly –16.27 inches (413 mm), bi-weekly – 24.54 inches (649 mm), and daily – 25.66 inches (652 mm). These amounts were substantially higher than most of the other treatments. The high values for the bi-weekly and daily frequencies were likely due to overestimation of $ET_0$ (30% higher that $ET_0$ estimated at the site) and may also have been because the system did not incorporate local rainfall into its water budget but rather relied on a “rain pause” invoked during regional rainfall. The weekly gross irrigation amount
was not as high as the bi-weekly or daily amounts because the controller probably limited the application to the amount that could be stored in the user-supplied controller-input 6 inch (152 mm) root zone. The cumulative irrigation application for all treatments and frequencies are given in table 2.

Table 1. Total applied (inches) applied between 22nd April and 8th September 2007

<table>
<thead>
<tr>
<th>Technology</th>
<th>frequency</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>weekly</td>
<td>bi-weekly</td>
<td>Daily</td>
<td></td>
</tr>
<tr>
<td>Timer(^1)</td>
<td>16.88</td>
<td>16.92</td>
<td>15.62</td>
<td></td>
</tr>
<tr>
<td>Add-on</td>
<td>8.56</td>
<td>12.81</td>
<td>13.87</td>
<td></td>
</tr>
<tr>
<td>ET(^3)</td>
<td>16.27</td>
<td>24.54</td>
<td>25.66</td>
<td></td>
</tr>
<tr>
<td>On demand system</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>On-demand</td>
<td></td>
<td></td>
<td></td>
<td>17.64</td>
</tr>
</tbody>
</table>

**Weekly water application**

Analysis of variance revealed that the technology effect and frequency effect on average weekly water use and their interaction were all significant.

*Comparison between technologies*: The means of the technologies were different when compared across frequencies. The add-on system applied the least water while the ET system applied the most water.

*Comparison between frequencies*: Similar analysis of different frequencies across technologies showed that the weekly treatments were significantly different from both the bi-weekly and daily frequency treatments. On average the weekly schedules used the least amount of water followed by bi-weekly frequency and then the daily treatment.

*Technology by Frequency Comparisons*: The add-on system at a weekly frequency applied the least amount of water, followed by the bi-weekly and daily add-on treatments. The weekly ET treatment was not statistically different than the add-on daily treatment or any of the timer-based treatments. The ET controller at bi-weekly and daily frequencies applied the most water.

**Turf Quality**

The on-demand system had the best turf quality followed by the ET controller, the timer-based system and the add-on system when averaged across frequencies. The daily and bi-weekly frequencies had better turf quality than the weekly frequency across technologies. Minimum acceptable turf quality (5) was met by all the plots, however, while the plots had healthy turf for most of the experimental period, quality declined dramatically in some of the treatments in the last month of the study when the daily ET values were high and no appreciable rainfall occurred. In addition there were six days when irrigation did not occur due to pump failures. Some plots suffered from the effects of substantial soil cuts that occurred when the two terraces were built and leveled. This
seemed to affect both fertility and soil physical properties (infiltration rate and water holding capacity).

Turf quality ratings over the last few weeks were biased high due to inexperience with the rating system, and turf quality of some of the plots at the end of the study were not at an acceptable level. The plots that looked the worst also had the highest canopy temperatures. To investigate the cumulative effect over time on turf quality of the technologies, time was introduced as a fixed effect in the mixed model to see if there was an interaction effect between time and technology. A statistically significant interaction effect would indicate that turf quality changed differently over time than another technology. The interaction term was not significant, but this was likely due to the subjective assignment of the turf quality index rating (too high) the last few weeks.

Canopy Temperature

There were significant differences in average weekly canopy temperature between treatments. ET treatments had the lowest temperatures and the add-on treatments had the highest temperatures. The temperatures were inversely correlated to applied water. There were no differences in average canopy temperatures between frequencies across technologies.

Canopy temperatures were also used to explain the decline in turf quality with some technologies that were not found using the turf quality index ratings. When turf is stressed, the latent heat of vaporization declines and sensible heat increases so elevated turf temperatures indicate reduced turf quality. Canopy temperatures for the last four weeks of the add-on system for all three frequencies was statistically higher than both the ET and on-demand systems, yet that difference was not statistically significant for the first eleven weeks. Afternoon canopy temperatures for the add-on system with a bi-weekly irrigation frequency was nearly 7 deg. F (3.9 deg. C) higher on average than the on-demand system over the final four weeks. This corroborated the reduced turf quality observed at the end of the study for the add-on system. The timer system had elevated temperatures relative to the ET and on-demand systems for the last four weeks, but the difference in temperatures was not statistically different.

**CONCLUSIONS**

- The water on demand system was the most effective system applying less water than the ET controller while maintaining excellent turf quality. This system is expensive but maybe ideal for commercial landscaping applications. It applied only 1-2 inches (25-50 mm) more than the timer-based treatments but had much better turf quality at the end of the study.

- The add-on systems can reduce water use, but if the timer is not programmed to apply enough water, turf quality can suffer as it operates on prohibiting irrigation rather than initiating irrigation. These systems may be more effectively used by setting the controller to daily apply an amount equal to a management allowable depletion, e.g. 25% of field capacity with a setpoint of 75% of field capacity, and letting the system override scheduled irrigation events until that condition is met. In this study, the daily frequency was set to apply a maximum of only 0.15 inches
or 8% of field capacity to satisfy a long-term daily irrigation requirement. Since the last month of the season was warmer and drier than normal, the system as programmed “fell behind”.

- The ET controller followed trends in weather, but applied more water than required. The use of more representative weather stations or adjustment of the controller would be beneficial for water conservation. Quality of turf irrigated by this system was excellent.
- Turf quality was reduced at weekly irrigation frequencies across all technologies compared to bi-weekly and daily frequencies.
- “Smart” irrigation technologies hold promise for efficient irrigation by conserving water while maintaining acceptable turf quality.

REFERENCES