EVALUATION OF THE AGRICULTURAL FIELD SCALE IRRIGATION REQUIREMENT SIMULATION (AFSIRS) IN PREDICTING GOLF COURSE IRRIGATION REQUIREMENTS WITH SITE-SPECIFIC DATA

By

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Golf courses are often the focus when it comes to water use. Various water-use models are used by Florida's five Water Management Districts, including the Agricultural Field Scale Irrigation Requirement Simulation (AFSIRS), to estimate irrigation requirements on golf courses. The St. Johns River, South Florida, and North Florida Water Management Districts use the AFSIRS model with available default data to predict irrigation requirements for all golf courses in their jurisdiction. Default values are used because of the limited research on golf course irrigation requirements. In this study, data were collected at five golf courses in the Central Florida area to use in the AFSIRS model for comparisons to irrigation requirements made using default data. Irrigation system distribution uniformity (DU_{LQ}), rooting depths, and weather data were collected from each golf course. Updated crop coefficients (Kc) for turfgrass were used in place of the default values. Average soil water content for a green built to USGA specifications

was used for golf courses with these types of greens, instead of the native soil average water content. A sensitivity analysis was used to determine which inputs had the greatest influence on the model outputs. When actual data were used, the predicted irrigation requirements increased between 15 and 46 cm (6 and 18 in) per year for the golf courses. Distribution uniformity had the greatest impact on predicted irrigation requirements. When only distribution uniformities were substituted for the default irrigation system efficiency, the irrigation requirement increased between 13 and 76 cm (5 and 30 in) per year. Because of a limited length of actual on-site weather data, and unusually high rainfall amounts during the year, it was difficult to use actual weather datasets in place of the 20-year historical datasets available to the model. Sensitivity analysis further indicated that DU_{LQ} inputs have the greatest influence on the predicted irrigation requirements made by the AFSIRS model. Changing a DU_{LQ} from 40 to 80% (a 100% increase) resulted in a 65% decrease in irrigation requirement. The sensitivity analysis also showed that daily maximum temperature and mean solar radiation had the largest impact on reference evapotranspiration rates (ET_o) calculated using the FAO 56 Penman-Monteith equation in the REF-ET program (computer program used to calculate ET_o from meteorological data). A 25% increase in the starting point for maximum temperature resulted in a 45% increase in ET_o, and a 50% increase of the starting point for mean solar radiation results in a 33% change in ET_o. Using actual data in place of default values in the AFSIRS model can result in site-specific estimates of irrigation requirements on golf courses. According to the AFSIRS model, and further illustrated through sensitivity analysis, DU_{LQ} and Kc values had the greatest impact on irrigation requirements. Therefore, these variables need to be measured with the most accuracy.

CHAPTER 1
INTRODUCTION

In recent years, golf has become popular in the United States. There were over 15,000 golf facilities in the country in 2000, and over 1,100 courses located in Florida (National Golf Foundation, 2004). Because of the number of golf courses in Florida, and their visibility, there is a public concern that the golf industry wastes water. Because of Florida's erratic distribution of rainfall and large extent of sandy soils, irrigation is necessary to maintain quality turfgrass.

Water use in Florida is controlled by five Water Management Districts. Each District is responsible for issuing consumptive use permits to large water users (including golf courses) located in their jurisdiction. These permits allocate the maximum amount of water a golf course should use per year. A golf course is required to report these water use amounts yearly; and if the allotment is exceeded, a financial penalty may be issued by the District.

The Water Management Districts use various mathematical models to determine crop irrigation requirements. The St. Johns River Water Management District (SJRWMD), South Florida Water Management District, and North Florida Water Management District use the Agricultural Field Scale Irrigation Requirement Simulation (AFSIRS) to estimate crop water needs, including turfgrass. The AFSIRS model was developed at the University of Florida, and is a numerical simulation model that estimates irrigation requirements for Florida crops, soils, irrigation systems, climate conditions, and irrigation management practices (Smajstrla, 1990). Historical (default) datasets are available to the model for crop (turfgrass) coefficient values, rooting depths, irrigation system efficiencies, soil water capacities, rainfall, and reference evapotranspiration rates. Because the SJRWMD uses the default data when determining irrigation requirements for golf courses, the allotment amounts are not site-specific to each golf course in their jurisdiction.

Because of limited research on golf course irrigation requirements, there were two objectives to this research. The first objective was to compare AFSIRS water requirement estimates made with default data to estimates made with actual data collected from golf courses. The second objective was to determine what model inputs have the greatest influence on outputs, in order to ascertain the variables that should be measured and monitored to the greatest extent.

CHAPTER 2
LITERATURE REVIEW

Golf Course Water Consumption

Total water use by Florida golf courses in 2000 was estimated at 650 billion liters (172 billion gal) (Haydu and Hodges, 2002). According to this survey, nearly 321 billion liters (85 billion gal) came from recycled water, 185 billion liters (49 billion gal) from surface water, 132 billion liters (35 billion gal) from on-site wells, and 5.7 billion liters (1.5 billion gal) from municipal sources. It was estimated that the average water use per golf course was 503 million liters (133 million gal) per year.

Golf courses receive water allotments from water management districts based on total irrigated acreage; but courses consist of areas managed with varying levels of inputs, and areas that often require different amounts of water. Greens (areas prepared for putting) usually receive the most maintenance, followed by the tees (areas prepared for playing the first shot of each hole); fairways (turfed areas between tees and greens); and rough (turfed area surrounding the greens, tees, and fairways) (Beard, 2002). The amount of water these areas require depends on the type of grass, rooting depth, soil type, maintenance level, amount of inputs, and the desired effect.

A traditional golf course has 4 par 3-holes, 4 par 5-holes, and 10 par 4-holes, which occupy approximately 54 hectares (133 acres) (McCarty et al., 2001). Tees take up 0.16 to 1.2 hectares (0.4 to 3 acres) of a golf course (McCarty et al., 2001). Par 4 and par 5 tees typically occupy 9.3 to 18.6 m^2 (100 to 200 ft^2), and par 3 tees range from 18.6 to 33.2 m^2 (200 to 357 ft^2) per thousand rounds of golf annually (Beard, 1985). Greens typically range from 465 to 697 m^2 (5,000 to 7,500 ft^2) in size, and occupy 0.85 to 1.33 hectares (2.1 to 3.3 acres) on a typical 18-hole golf course (Beard, 2002).

Fairways comprise 12 to 24 hectares (30 to 60 acres) on a golf course (Beard, 1985). The average size of a fairway (the turfed area between the tee and green) is approximately 1.2 hectares (3 acres), which is dependent on the playing length of the hole and the width of the fairway. The usual fairway width on a golf course is approximately 32 meters (35 yards) (Beard, 2002). Depending on the total acreage and design of the course, the rough can range from 26 to 49 hectares (65 to 120 acres) for a golf course (Beard, 2002).

Approximately 26% of the total acreage of a golf course is considered fairways and 55% is rough. Therefore, most water use on a golf course occurs in irrigating fairways and rough, and increasing and decreasing the total area of these zones can have a great impact on the amount of water use on a golf course.

In the past, golf courses were built using only the existing soil at the construction site. Greens were built by pushing up the soil, in order to promote runoff of water (Beard, 1982). Fairways and roughs are still generally built using available soil on site, but to construct some surface features, soil may be excavated. Therefore, fairways or rough may be established using subsoil, which usually has different soil characteristics than surface soil layers. Because the subsoil may have a different water-holding capacity than the surface soil, water requirements can differ in areas where subsoil was used.

Although some golf courses still have push-up greens, most newly constructed or renovated greens have been built to United States Golf Association (USGA) green specifications. The profile of a USGA green consists of 30 to 36 cm (12 to 14 in) of rootzone medium (fine textured) above a 5 to 10 cm (2 to 4 in) coarse sand layer (choker layer) covering a 10 cm (4 in) layer of gravel (Higgins and McCarty, 2001). Drainage tile is installed underneath the gravel layer, in a herringbone design. This design allows for the entire rootzone to reach field capacity before water drains through the gravel layer and into the drainage tile. Field capacity is the percentage of water that remains in the soil after having been saturated and after free drainage has practically ceased (Brady and Weil, 1999). The field capacity of a USGA greens mix should be in the range of 0.16 to 0.33 m^3 m^{-3} (Beard, 2002).

Consumptive Use Permitting

Florida has five Water Management Districts that regulate water control and use. The Districts' main responsibilities include management of water and related land resources; proper use of surface and groundwater resources; regulation of dams, impoundments, reservoirs, and other structures to alter surface water movement; combating damage from floods, soil erosion, and excessive drainage; developing water management plans; maintenance of navigable rivers and harbors, participation in flood control programs; and maintaining water management and use facilities (Olexa et al., 1998). Each District is run by a governing board consisting of nine members. The members serve 4-year terms, and are appointed by the governor and confirmed by the state. Generally, an executive director is responsible for the operation of the District, including the implementation of policies and rules (Olexa et al., 1998).

Florida's Water Management Districts issue several types of water use permits, the most common being consumptive use permits (CUPs). A CUP authorizes how much water should be withdrawn from surface and ground water supplies for reasonable and beneficial uses such as public supply (drinking water), agricultural and landscape irrigation, industry, and power generation (SJRWMD, 2004). The water withdraw situations that require a CUP are: a well that measures 15.2 mm (6 in) or more in diameter, the annual average is more than 378,500 liters (100,000 gal) of water use per day, or there is the capacity to pump 3.78 million liters (1 million gal) or more of water per day (SJRWMD, 2004).

The St. Johns River Water Management District (SJRWMD) began issuing consumptive use permits (CUPs) in 1983. The District covers parts of Central Florida and the Northeast portion of the state. Since 1991, all permitted users have been required to report their water use by using a meter or by an alternative method approved by the District. In the year 2000, 504 CUPs were issued by the District (SJRWMD, 2004).

To receive a CUP, an applicant must submit an application form, along with a fee, a listing of adjacent property owners, and a water conservation plan which provides measures to reduce water use and preserve water resources for other beneficial uses. The District then reviews the application and determines the allotment duration and amount (SJRWMD, 2002). The permits are issued for approximately 20 years, and upon expiration, must be renewed. CUPs for golf courses are usually issued for a shorter period of time because of changes that are often made to courses such as adding golf holes, or changing water sources.

The factors that cause the difference in water allotments from golf course to golf course are total irrigated acreage and soil type. The applicant reports the irrigated acreage on the CUP application, and the District uses existing soil maps to determine the soil type at the location where the golf course was built. Golf courses may use different sources of water such as: wells, lakes, and reclaimed water, but the total amount withdrawn from all sources must not exceed their CUP amount. During water shortages, the district may impose restrictions, and these restrictions supersede any conditions of the permit (SJRWMD, 2002).

Agricultural Field Scale Irrigation Requirement Simulation (AFSIRS)

Modeling Crop Irrigation Requirements

When determining the amount of water to issue on a consumptive use permit, the Water Management District must predict the irrigation requirement for the crop. Irrigation requirement (IRR) for a crop is the amount of water, in addition to rainfall, that must be applied to meet a crop's evapotranspiration needs without significant reduction in yield (Smajstrla and Zazueta, 1998). In terms of golf course turfgrass, quality must not be significantly reduced. Evapotranspiration (ET) includes water that is needed for both evaporation and transpiration. The amount of water issued on the CUP for a golf course is determined by predicting the IRR for the turfgrass on that course and any other area that may be irrigated on or around the course, e.g. home landscapes.

Estimates of IRRs can be ascertained from historical observation, or by using numerical models (Smajstrla and Zazueta, 1998). If a long term record has been kept of irrigation water applied, this record could be used to estimate future uses. But few such long-term databases exist. Another problem with historical data is that its use may be limited to the location where it was collected (Smajstrla and Zazueta, 1998). The effects of differences in climate, soil, location, time of year during which the crop was grown, as well as other factors on irrigation requirements cannot be determined from the available data (Smajstrla and Zazueta, 1998).

Numerical models may be based on statistical methods or on physical laws which govern crop water uptake and use (Smajstrla and Zazueta, 1998). A basic model that has been used is The Soil Conservation Service (SCS) procedure (SCS, 1970). This model is a statistical regression method that allows monthly crop irrigation requirements to be estimated based on three factors: monthly crop ET, monthly rainfall, and soil water-holding characteristics (SCS, 1970). Limitations of this model are: estimation of irrigation requirements for monthly or longer time periods only, that it is limited to sprinkler and surface irrigation systems which irrigate the entire soil surface, and soil types with deep water tables (SCS, 1970).

The SJRWMD uses the Agricultural Field Scale Irrigation Requirement Simulation (AFSIRS) model to predict IRR for a crop (SJRWMD, 2004). The AFSIRS model is a numerical simulation model which estimates IRR using inputs from Florida crops, soils, irrigation systems, growing seasons, climate conditions, and irrigation management practices (Smajstrla, 1990). This model is based on a water budget of the crop root zone. This water budget includes inputs to the crop root zone from rain and irrigation, and losses from the root zone by drainage and evapotranspiration. The water holding capacity in the crop root zone is the multiple of the water-holding capacity of the soil and the rooting depth of the crop being irrigated (Smajsrla, 1990).

Evapotranspiration and Weather Data Inputs

The AFSIRS model is based on the concept that actual crop ET is estimated from reference ET and crop water use coefficients. Reference evapotranspiration (ET_o) is the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, which is actively growing, completely shading the ground and not lacking water (Allen et al., 1998). A crop coefficient (Kc) is an adjustment factor which is determined by different crop characteristics, i.e. turfgrass type, quality, and height (Brown and Kopec, 2000). Daily ET_o, as well as rainfall, can be ascertained from historical climate data available in the model. Records from nine Florida locations over approximately a 20 year period ending in the 1970s are part of the AFSIRS model database (Smajstrla, 1990). AFSIRS computes IRR for the mean year over those 20 years as well as IRR for different probabilities of occurrence. The SJRWMD permits are based on an 80% probability of occurrence, which means that the permittee, or golf course, should not exceed their allotment except for a 2 in 10 year drought (V. McDaniel, personal communication, 2004).

There are many weather station networks that can be used by agricultural growers and turfgrass managers to determine ET_o (Brown et al., 2001). The California Irrigation Information System (CIMIS) (Snyder, 1986) is an integrated network of over 120 computerized weather stations located throughout California. The Arizona Meteorological Network (AZMET) provides weather-based information in southern and central Arizona (Brown et al., 1988). These networks use the modified Penman equation to determine ET_o. The commonly used modified Penman and modified Penman-Monteith methods are two of the many mathematical models that compute ET_o from measured weather data (Brown and Kopec, 2000). The Florida Automated Weather Network (FAWN) consists of 30 weather stations located throughout Florida. These stations collect data that can be use for determining ET_o (FAWN, 2004). The common data collected daily by a weather station for computing ET_o are: minimum and maximum temperature, minimum and maximum relative humidity, mean solar radiation, and mean wind speed.

There are computer programs, such as REF-ET, that can calculate ET_o from meteorological data using different mathematical models, including the commonly used modified Penman-Monteith method. REF-ET is a stand-alone computer program that calculates ET_o from meteorological data made available by the user (Allen, 2002). The program provides standardized calculations of ET_o for fifteen of the more common mathematical models that are currently in use in the United States and Europe (Allen, 2002). Daily ET_o values in the AFSIRS database were calculated using the IFAS Penman equation (Smajstrla, 1990). The IFAS Penman was developed at the University of Florida's Institute of Food and Agricultural Sciences in 1984 to better represent regional climatic tendencies. The Penman formula is based on four major climatic factors: net radiation, air temperature, and wind speed and vapor pressure deficit (Jacobs and Satti, 2001).

$$ET_o = \frac{\frac{\Delta}{\Delta+\gamma}\left[(1-\alpha)R_s - \sigma T^4\left(0.56-0.08\sqrt{e_d}\right)\left(1.42\frac{R_s}{R_{so}}-0.42\right)\right]}{\lambda} + \frac{\gamma}{\Delta+\gamma}\left[0.263(0.5+0.0062u_2)(e_a-e_d)\right] \qquad (2\text{-}1)$$

where:

	ET_o	Reference evapotranspiration (mm day^{-1})
	Δ	Slope of saturated vapor pressure curve of air (mb/^{o}C)
	γ	Psychometric constant (0.66 mb/^{o}C)
	α	Albedo or reflectivity of surface for R_s
	R_s	Total incoming solar radiation (cal. cm^{-2} day^{-1})
	σ	Stefan-Boltzmann constant (11.71 x 10^{-8} cal.cm^{-2} day^{-1} K^{-1})
	T	Average air temperature (K)
	e_d	vapor pressure at dewpoint temperature (mb)
	R_{so}	Total daily cloudless sky radiation (cal cm^{-2} day^{-1})
	u_2	wind speed at a height of 2 m (km day^{-1})
	e_a	vapor pressure of air (mb)

Jacobs and Satti (2001) reported that the IFAS Penman equation is not as consistent as the FAO 56 Penman-Monteith (Allen et al.,1998) equation for Florida conditions. In their study, fourteen models that may be used to estimate ET_o in consumptive use permitting were reviewed to identify the approaches that: best represented the physics of water losses from irrigated crops; easiest to use in terms of parameters needed; were able to consistently and accurately capture ET_o losses in growing regions of Florida; and were considered acceptable to the general scientific community. Jacobs and Satti (2001) suggested that the ET_o data available to the AFSIRS should be updated with newer weather data using the FAO 56 Penman-Monteith equation (Allen et al., 1998).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (2\text{-}2)$$

where:
- ET_o — Reference evapotranspiration (mm day^{-1})
- Δ — Slope of saturation vapor pressure temp. relationship (KPa $^oC^{-1}$)
- R_n — Net radiation (MJ m^{-2} day^{-1})
- G — Soil heat flux (MJ m^{-2} day^{-1}, generally assumed to be zero)
- γ — Psychometric constant (KPa $^oC^{-1}$)
- T — Average air temperature (^oC)
- u_2 — wind speed at a height of 2 m (m s^{-1})
- e_s — saturation vapor pressure (KPa)
- e_a — actual vapor pressure (KPa)

Turf ET rates can vary among genotypes as well as region to region. Carrow (1995) reported that ET rates for cool season grasses ranged from 1.99 - 6.05 mm d^{-1} and warm season grasses varied from 1.40 - 6.22 mm d^{-1}. ‘Tifway’ bermudagrass [*Cynodon dactylon* L. x C. *transvaalensis* Burt-Davy], the most common grass grown on Florida golf courses, had an average summer ET rate of 3.11 mm d^{-1} in Central Georgia (Carrow, 1995). Beard et al. (1992) reported summer averages of 5.10 mm d^{-1} for the same genotype in the arid west.

Studies have indicated that turf ET increases with water availability. According to Kneebone and Pepper (1982), ET rates of bermudagrass [*Cynodon dactylon* (L.)] increased with increased irrigation application rates and increased water-holding capacities of soils. Also, turf ET rates increased with increased light levels, increased temperatures, lowered humidity, moderate to high wind speeds, and long days (Carrow, 1995).

Cultural and fertilization practices influence turf ET rates. There have been a number of studies showing turf ET rates decrease as the cutting height was lowered (Kim and Beard, 1983; Parr et al., 1984; Unruh et al., 1999). High rates of nitrogen have produced an increase in shoot growth and a reduction in root growth (Beard, 1973; Goss and Law, 1967). The reduced root growth results in less available water to the turf and the increase in shoot growth requires more water to be taken up. Therefore, more frequent irrigation is needed to supply enough moisture for growth (Beard, 1973).

Crop Coefficient Inputs

Crop Coefficients (Kc) are available in the AFSIRS database for 60 different crops (Smajstrla, 1990). The Kc value in the database for golf course turf is one, and therefore the AFSIRS computes the actual evapotranspiration rate of golf course turf being equal to the reference evapotranspiration rate (Smajstrla, 1990). According to Jacobs and Satti (2001), the AFSIRS model should have additional Kc values for turfgrasses because the additional research conducted since the model was designed indicates differing turfgrass Kc values between grasses and months. In Georgia, Carrow (1995), using the FAO Penman, reported Kc values during the summer for Tifway bermudagrass varied from 0.53 to 0.97. Crop coefficient values for Tifway bermudagrass in Arizona, using the Penman Monteith, ranged from 0.78 to 0.85 and intermediate ryegrass [*L. hybridum*] ranged from 0.78 to 0.89 (Brown and Kopec, 2000). Because ryegrass is seeded in the winter time in some parts of Florida as the bermudagrass goes dormant, different Kc values within the year may need to be used for computing turf ET.

Irrigation Application Efficiency and Uniformity Inputs

There are eight types of irrigation systems in the AFSIRS database. Each system has a corresponding efficiency (Smajstrla, 1990). Irrigation application efficiency refers to the effectiveness of the irrigation system in applying water to the crop root zone where it can be utilized in production (Smajstrla, 1990). A multiple sprinkler system design, as used on golf courses, has a 75 percent efficiency value in the model (Smajstrla, 1990). Jacobs and Satti (2001) reported that there is a lack of irrigation efficiencies to choose from in the simulation. Previous research indicates that there is a high variability between irrigation efficiencies of multiple sprinkler systems on golf courses due to several factors, such as head spacing, nozzle type, pressure, maintenance, etc. (Miller et al., 2003). Improvements in the design and installation of these systems, such as head-to-head spacing, may enhance a coverage or efficiency.

Because it is difficult to determine irrigation application efficiency in the field, irrigation distribution uniformity is often measured to determine the effectiveness of a system. Although the efficiency of a system can vary from its uniformity, coverage uniformity, is an indicator of the systems application efficiency. The more uniform a water application, the less operating time an irrigation system needs to make up for poor coverage (Wilson and Zoldoske, 1997). Precipitation rate can also be measured while determining uniformity. Precipitation rate is the amount of water applied over a specific area, in a specific amount of time (Bowman et al., 2001). If the precipitation rate varies significantly over the area being irrigated, then uniformity is poor (Huck, 1997; Meyer and Camenga, 1985; Pira, 1997).

The method most commonly used to calculate distribution uniformity for turfgrass is called the Lower Quarter Distribution Uniformity or DU_{LQ} (IA, 2003). The DU_{LQ} is the average water applied in the twenty-five percent of the area receiving the least amount of water, divided by the average water applied over the entire area (IA, 2003). Pitts et al. (1996) evaluated 385 residential irrigation systems, and reported that the average DU_{LQ} for agricultural sprinklers, micro-irrigation, furrow irrigation and turf irrigation were 65, 70, 70, and 49 percent, respectively. Of the 37 turf irrigation systems evaluated, 40% had DU_{LQ}'s less than 40%. Golf courses have historically had DU_{LQ}'s ranging from 55 to 85 percent (Thompson, 2002). The Irrigation Association (2003) suggests that a 70 percent uniformity is a good (expected) value when evaluated using their methodology.

Rooting Depth Inputs

Each of the 60 crops in the AFSIRS database has irrigated (average) and maximum rooting depth values. The model uses these values, along with soil properties, to compute how much water needs to be applied to reach field capacity. The AFSIRS model assumes that 70 percent of water uptake occurs in the irrigated root zone and the remaining 30 percent occurs below the irrigated root zone (Smajstrla, 1990). For golf course turfgrass, the model uses 15 and 61 cm (6 and 24 in), irrigated and maximum rooting depths (Smajstrla, 1990). Jacobs and Satti (2001) reported that the AFSIRS model needs additional rooting depths for turfgrasses because rooting depths can vary from golf course to golf course.

Beard (1973) reported that the majority of a turfgrass root system mowed regularly at less than 5 cm, is located in the upper 7 cm of the soil. Reduced rooting depth is directly correlated with a decrease in cutting height. The very close cutting heights required to meet performance demands by today's golfers, may result in shallow rooting. There is very limited research currently available documenting effective rooting depths of golf course turfs.

Soil Type Inputs

There are 766 soil types and corresponding minimum (permanent wilting point) and maximum (field capacity) water holding capacities (volumetric) in the AFSIRS database (Smajstrla, 1990). Existing soil maps are used to determine the type of soil in which a crop is growing. The model can compute IRR using minimum, average, or maximum water holding capacities for the soil. Plant available water is a combination of rooting depth and the amount of water between minimum and maximum holding capacities for the soil. According to Jacobs and Satti (2001), the soil database needs to be improved for the most widely used soils. An alternative to the soil database is manual input of soil water characteristics measured or approximated for the soil type at the site.

Using a soil map to determine soil type, and assuming that the characteristics of the soil at a site remain the same after construction of a golf course, can also be a concern. Earthmoving, the use of fill from excavation (lakes), and bringing in off-site materials can have a great impact on the soil characteristics of a site when construction is complete. Also, because of most golf courses being built with USGA greens mix, the available water on those greens is not the same as the native soil. According to the USGA (Hummel, 1993), the average soil water content of a green built to USGA specifications is 0.13 m^3 m^{-3}.

Sensitivity Analysis

To determine how input parameters influence model outputs, a sensitivity analysis can be utilized. A sensitivity analysis requires varying selected parameters individually through an expected range of values and then comparing the range of output values from each input variable (James and Burges, 1982). A sensitivity analysis aims to ascertain how the model depends upon inputs, upon its structure, and upon the framing assumptions made to build it. As a whole, sensitivity analysis is used to increase the confidence in a model and its predictions, by providing an understanding of how the model's response variables respond to changes in the inputs (A forum on sensitivity analysis, 2004).

The input parameters with the greatest influence on the model output need to be measured with the highest accuracy. The South Florida Water Management District used sensitivity analysis to assess the impact of parameter errors on the uncertainty in output values for the South Florida Water Management Model and the Natural Systems Model (Loucks and Stedinger, 1994). Engineers in the District use these models to predict possible hydrologic impacts of alternative water management policies under a variety of hydrologic inputs. Once the key errors were identified, it was possible to determine the extent to which parameter uncertainty can be reduced through field investigations, development of better models, and other efforts (Loucks and Stedinger, 1994).

CHAPTER 3
PREDICTING IRRIGATION REQUIREMENTS ON GOLF COURSES USING THE AGRICULTURAL FIELD SCALE IRRIGATION REQUIREMENT SIMULATION (AFSIRS)

Introduction

Florida's five Water Management Districts issue consumptive use permits to all golf courses within their areas of jurisdiction. These permits are based on the irrigation requirement (IRR) of the turfgrass on the golf course. Historical observations and computer models are tools that are used to predict IRR. The St. Johns River Water Management District (SJRWMD), South Florida Water Management District, and North Florida Water Management District use the Agricultural Field Scale Irrigation Requirement Simulation (AFSIRS) model to predict IRR for golf courses.

The AFSIRS model is a numerical simulation model which estimates IRR using inputs from Florida crops, soils, irrigation systems, growing seasons, climate conditions, and irrigation management practices (Smajstrla, 1990). This data is input into the model from datasets that were constructed using historical data and previous research. Due to the dependency on these datasets, there are some limitations to operational use of the model.

The limitations specifically pertaining to golf courses were postulated during a study at the University of Florida by Jacobs and Satti (2001). They found that the major problem with the simulation is that it does not have the ability to input actual rainfall and climate data from the site of interest. They also found that the mathematical model used to calculate the reference ET rates for the datasets, the IFAS Penman Equation, is not as consistent as the FAO 56 Penman-Monteith equation (Allen et al., 1998) for Florida conditions.

Jacobs and Satti (2001) reported that the crop coefficient values and rooting depths available to the model need to be updated. There has been more research conducted on crop coefficients since the model was designed, and rooting depths can vary from golf course to golf course. They also indicated that there is a lack of irrigation efficiency values available to the user. Previous research indicates that there is a high variability between distribution uniformities of multiple sprinkler systems on golf courses due to several factors such as head spacing, nozzle type, pressure, maintenance, etc. (Miller et al., 2003).

The AFSIRS model has a soil database which is made up of 766 soil types found in Florida. Because most golf courses are constructed with the USGA greens mix, that has different soil water characteristics than native Florida soils, IRR for golf course greens can not be accurately predicted using the soil dataset. The objective of this study was to compare AFSIRS water requirement estimates made with default data to estimates made with actual data collected from golf courses.

Materials and Methods

Data were collected from five golf courses located in Central Florida. Irrigation system performance data measured included distribution uniformity and precipitation rates. Because it its extremely difficult to determine irrigation system efficiency in a field setting, distribution uniformity values were collected and used in the model to replace the default efficiency value. To determine irrigation distribution uniformities, irrigation audits were performed on three golf holes at each of the five courses in March through May 2002 (Pressler, 2003). The audits were conducted using the methods of ANSI/ASAE

S436.1 MAR 01 Standards (ASAE, 2001), and using the evaluation methodology described in the Irrigation Association of America's Certified Golf Course Irrigation Auditor training manual (IA, 2003).

The catch-cans used in this study had an opening diameter of 7.6 cm (3.0 in) and a depth of 10.8 cm (4.25 in). For tee complexes (all tees) and greens, catch-cans were placed in a grid pattern on 3-m centers over the entire surface. For fairways, catch-cans were placed in a grid pattern on 9-m centers throughout the entire fairway and primary rough, if irrigated (Pressler, 2003).

The number of sprinklers operating at one time was representative of the normal operating conditions of that particular system. Each location within individual courses received the same amount irrigation runtime. The runtime on fairway and tees ranged between 20 and 30 minutes per zone, and greens between 10 and 30 minutes per zone. Once it was determined that all the zones had run for a certain location, the collected water in each can was measured and recorded using a 500 mL graduated cylinder. Lower quarter distribution uniformity (DU_{LQ}) was determined by (Pressler, 2003):

$$DU_{LQ} = \frac{Avg.LQ}{V_{avg}} x100 \qquad (3\text{-}1)$$

DU_{LQ} = Lower Quarter Distribution
Avg. LQ = Average volume of lowest 25% of observations
V_{avg} = Average catch can volume

For modeling purposes, an average DU_{LQ} for each of the three holes on the five courses was determined by weighting the DU_{LQ} based on the total areas of tees, fairway, and green. Areas were determined from global positioning system maps, produced within 60 days of uniformity testing.

Precipitation rates were also collected for each location on a golf course. The net precipitation rate (PR) is the rate that sprinklers apply water to a given area per unit time and can be calculated as follows:

$$PR_{net} = \frac{V_{avg} \times 60}{TR \times CDA} \tag{3-2}$$

PR_{net} = Net Precipitation Rate, (cm h^{-1})
V_{avg} = Average catch can volume (mL)
TR = Testing run time (min)
CDA = Catch can opening (cm^2)

The precipitation rates were used to determine how much water golf courses actually applied during the study. Those values were then compared to the IRR predicted by the model for each golf course.

Maximum and average rooting depths were measured at three locations (tees, fairways, and greens) at each golf course. Measurements were taken in September and November 2002 and February and May 2003. Three random samples were taken at a 15 cm depth from each location using a Mascaro soil profiler (Turf-Tec International, Coral Springs, FL). The maximum rooting depth was determined by physically measuring the longest root in each of the three samples. Measurements were taken from the top of the thatch layer to the tip of the root. These values were then averaged and the mean maximum rooting depth of the three samples was recorded as the maximum rooting depth for that location. Average rooting depth was determined by visually assessing the samples where the majority of the roots were present. A ruler was then used to measure the distance to the top of the thatch layer. These measurements were then averaged and a mean rooting depth was calculated for each location (Pressler, 2003).

Weather stations were installed to monitor environmental parameters from June 2002 to May 2003. The weather stations were located in flat-grassed areas so that the nearest obstruction was at least ten times its height away from the station. The stations were placed in irrigated areas on the golf course property. The stations recorded the date, time, temperature, soil heat flux, (HFT3, Radiation Energy Balance Systems, Bellevue, WA), solar radiation (LI-200SZ, Licor Inc. Lincoln, NE), wind speed and direction (WAS425, Vaisala, Inc., Sunnyvale, CA), relative humidity (HMP 45C, Vaisala, Inc., Woburn, MA), and precipitation (TE525 Tipping Bucket, Texas Electronics, Inc., Dallas TX) at 15 minute intervals via a CR10X datalogger (Campbell Scientific, Inc., Logan Utah).

The data collected by the weather stations was used to develop five site specific weather datasets containing daily reference ET rates and rainfall. Reference ET (ET_o) rates were calculated using the computer program REF-ET. REF-ET was developed as a stand-alone computer program to calculate ET_o from meteorological data made available by the user (Allen, 2002). Because the FAO 56 Penman-Monteith equation (Allen et al., 1998) was found to be the most consistent model for determining ET_o for Florida conditions (Jacobs and Satti, 2001), this equation was used to calculate ET_o for the site specific weather datasets.

Because it is difficult to determine site-specific crop coefficients (Kc) in the field, updated Kc values were determined from a literature review to replace the default values in the model. Kc values for bermudagrass were determined from Carrow's (1995) study in Georgia, and overseeded ryegrass Kc values were determined from Brown and Kopec's (2000) study in Arizona.

The AFSIRS model was run separately for each golf course using default and actual/updated (site-specific) data. The default runs mimicked the procedure that the SJRWMD uses to predict IRR for golf courses. Therefore, for the default runs, the only input parameter that differed between the golf courses was soil type. The soil type for each course was determined by using county soil survey maps created by the Soil Conservation Service, and assessing what soil type is most prevalent at that site. For golf courses with greens built to United States Golf Association (USGA) specifications (sand and peat mix), runs were made using the average soil water content (volumetric) for USGA greens mix instead of the average soil water content (volumetric) of each courses native soil type.

The default model runs were used to compare with runs made with actual/updated data. Model runs were made in a stepwise manor where each input parameter was changed to actual/updated data while the remaining parameters used default values. Combinations were made where some or all inputs were changed to actual/updated data. Rooting depths influenced by month, golf course, and location within golf course were analyzed using analysis of variance procedures in SAS (SAS Institute, 1999).

Results and Discussion

Default Values

The first AFSIRS model runs were made using default values for each golf course. The default values for each input were: 1.0 for crop coefficient (Kc), 75% for irrigation system efficiency, 15 and 61 cm (6 and 24 in) for avg. and max. rooting depths, and 20 year historical weather data for Orlando (nearest collection location for historical datasets to the five golf courses). The soil type was the only input that varied between golf courses. According to the SCS county soil survey maps, three of the five courses had the same soil type average water contents (Table 3-1).

Updated/Actual Values

Based on crop coefficient (Kc) research reported by Carrow (1995) and Brown and Kopec (2000) on bermudagrass and ryegrass monthly crop coefficients, updated Kc values were entered into the model for each corresponding month to replace the default value of 1.0. Crop coefficients inputted for bermudagrass were: 0.62 in May, 0.54 in June, 0.53 in July, 0.65 in August, 0.97 in September, and 0.73 in October. Crop coefficients inputted for ryegrass were: 0.83 in November, 0.80 in December, 0.78 in January, 0.79 in February, 0.86 in March, and 0.89 in April.

Measured DU_{LQ} for each golf course were used to replace the default (75%) irrigation system efficiency for a multiple sprinkler system. An average DU_{LQ} for each of the three holes on the five courses was determined by weighting the DU_{LQ} for each location (tee, fairway, green) based on their total areas. Because the fairway occupies the most area, the DU_{LQ} for a hole was similar to the DU_{LQ} of the fairway on that hole. The weighted average DU_{LQ}'s for the three holes on the five courses were calculated as follows: golf course A = 32, 37, and 59%, golf course B = 40, 42, and 49%, golf course C = 45, 55 and 62%, golf course D = 62, 67, and 67%, and golf course E = 41, 44, and 54%.

Average and maximum rooting depths measured at each golf course were entered into the model in-place of the default values of 15 and 61 cm (6 and 24 in). Because two of the three holes on each golf course had reduced runtimes, in accordance with a concurrent irrigation conservation study (Pressler, 2003), only the rooting depths from the control holes (typical irrigation practices) were used for modeling. Analysis of variance indicated differences in rooting depths by month at a 95% probability level (Table 3-2).

Rooting depths measured in August, 2002 were significantly less than depths measured in November, 2002, and February and May 2003. But because these rooting depth differences may have been caused by the extremely wet summer in 2002, rooting depths from each month and location were averaged together to get an average and maximum rooting depth for each golf course. The average (irrigated) and maximum rooting depths from the five golf courses, used for modeling, were (avg. and max.): golf course A = 4.3 and 6.6 cm (1.7 and 2.6 in), golf course B = 4.3 and 7.1 cm (1.7 and 2.8 in), golf course C = 4.6 and 7.4 cm (1.8 and 2.9 in), golf course D = 4.6 and 6.6 cm (1.8 and 2.6 in), and golf course E = 4.3 and 6.9 cm (1.7 and 2.7 in).

The five weather datasets, created via on-site weather stations and the use of REF-ET, were used to replace the 20 year historical data from the Orlando area. Each golf course had a corresponding dataset with actual reference ET rates (ET_o) and rainfall for one year. During the study period, there was an unusually low ET_o for three of the golf courses (Figure 3-1A), as well as a high amount of rainfall at all five courses (Figure 3-1B). The yearly average ET_o (mm day^{-1}) for golf courses A, C, and D were below the lower limit of the 95% probability of occurrence interval for the historical data. The yearly average rainfall (mm day^{-1}) was higher than the upper limit of the interval for all five golf courses. The average amount of rainfall in the historical weather dataset for Orlando is 129 cm (50.7 in) per year; whereas, the average rainfall recorded at the five courses from June 2002 to May 2003 was 199 cm (78.4 in).

Default Versus Updated/Actual Irrigation Requirements

Irrigation requirements (IRR) for the five golf courses were calculated by the AFSIRS model using default and updated/actual values for comparison. The only parameter that differs by golf course in the default runs is soil type. Because golf courses A, B, and C have the same soil type, they have the same IRR for the default run (Figure 3-2). Golf course E has a soil type with a higher average water content (0.10 $m^3 m^{-3}$) than golf courses A, B, and C (0.07, 0.07, and 0.07 $m^3 m^{-3}$, respectively), and therefore requires less water (lower IRR) to reach field capacity.

When using the historical weather data, IRR was estimated for the average year and for the 80% probability values (two in ten year drought) for the 20 years of data. Because drought years, requiring higher amounts of irrigation, are factored into the 80% probability IRR, those irrigation requirements are higher than estimates for the average year. Irrigation requirements estimated using actual weather data do not predict the 80% probability values because there was only one year worth of data in each dataset.

Estimates were made using Kc values reported in the literature. Predicted IRR for all five courses dropped approximately 25 cm (10 in) per year from the default run (Figure 3-2). This was due to the updated monthly Kc values, which range from 0.53 to 0.97, being lower than the default Kc of 1.0 for turfgrass.

Additional model runs were conducted with actual weighted DU_{LQ} values for each course replacing the default irrigation system efficiency of 75%, for a multiple sprinkler system. Each course had three DU_{LQ} values, one for each hole, and therefore had three estimates with the actual DU_{LQ} model runs. To determine an average IRR for the golf course, the IRR values obtained from the model runs for each hole (separate DU_{LQ}

values) were averaged. With actual DU_{LQ} values, the IRR for all five courses increased compared to the default run values (Figure 3-2). The IRR for courses B, C, and E went up 38 to 64 cm (15 to 25 in) per year when actual uniformities were used in the model. This is due to these courses having uniformities between 40% and 60%. The IRR for golf course A increased approximately 76 cm (30 in) per year from the default run values. The increase was a result of golf course A having two holes with low uniformities (32% and 37%) that reduced its average DU_{LQ} to 43%. The IRR for golf course D increased by approximately 13 cm (5 in) per year. This golf course had uniformities from 62% to 67%, which were much closer to the default value.

Actual root depths from each course were used for IRR estimations. All five IRR predictions increased about 18 cm (7 in) per year with actual rooting depths replacing the default root depths (Figure 3-2). The actual average and maximum rooting depths were 4.3 and 6.9 cm (1.7 and 2.7 in), and the default irrigated and maximum rooting depths for golf course turf are 15.2 and 61 cm (6 and 24 in), respectively. This difference in actual and default root depths, led to the increase in IRR for each golf course. The low mowing heights on the golf courses may have contributed to the shallow rooting depths when compared to the default depths.

Actual weather datasets for each course were difficult to input with the programming structure of the AFSIRS model. It was apparent from comparing the historical weather data to the year's weather data collected that the short-term weather data sets represented a much wetter year than average (Figure 3-1). The on-site weather data sets represented between 56 and 109 cm (22 and 43 in) more than the average rainfall compared to the 20 year historical weather dataset. Wet years are not factored into consumptive use permits as are drought years. Using the actual weather data from the golf courses decreased the irrigation water needed estimate by approximately 51 cm (20 in) per year (Figure 3-2).

The model was also run for the five golf courses using all actual/updated data except for weather data, and all actual/updated data including weather data. Due to the wet year, it seemed appropriate to use the historical weather data rather than predict irrigation needs based on one year's data. Since the actual weather datasets are not historically typical for the Orlando area, a better comparison to the default data set is to estimate water needs with actual data combined with the historically weather dataset. That comparison showed that actual/updated data with the historical weather data increased IRR between 15 and 46 cm (6 and 18 in) per year for golf courses A, B, C and E (Figure 3-2). This is primarily a direct result of these courses having low distribution uniformities. Golf course E's IRR increased approximately 15 cm (6 in) per year with an average DU_{LQ} of 54%, and course A's IRR increased approximately 46 cm (18 in) per year with an average DU_{LQ} of 43%. Golf course D with an average DU_{LQ} of 65% was predicted with no increase in IRR compared to running the model with default data.

Irrigation requirements were estimated for the three golf greens built with sand and peat as per USGA specifications. Default IRR was included for comparison purposes. DU_{LQ} of each green was used instead of the weighted DU_{LQ} for each golf course except for the default. The model was run with the USGA green average soil water content (0.13 m^3 m^{-3}) inputted in place of the average water content of the native soils. The IRR was decreased approximately 13 cm (5 in) per year for all three courses due to the increase in the average soil water content value (Figure 3-3).

Predictions with all actual data, including USGA greens mix average water content, and historical weather data resulted in IRR approximately the same for all three courses when compared to the default IRR (Figure 3-3). This is because the average DU_{LQ} on the three greens at each course (ranged from 50% to 69%) was higher than the weighted DU_{LQ} of each golf course, and the higher average soil water content makes up for the DU_{LQ} being lower than the default 75%. The model was run with all actual data including USGA greens mix average water content. Because actual weather datasets had high rainfall amounts, IRR was decreased about 51 cm (20 in) per year for all three golf courses.

Golf courses A, B, C, and D each had a mean predicted IRR of about 86 cm (34 in) and golf course E had an IRR of 74 cm (29 in) (Figure 3-2). Based on rainfall and ET_o, the mean IRR was predicted to be about the same additional amount (depth) as the ET_o values (Table 3-3). The IRR on the District issued consumptive use permit (CUP) for golf courses C, D, and E are slightly higher than the mean IRR because the permit accounts for a two in ten year drought. According to their respective permits, golf course A received 30% more water than the mean IRR because of a deep water table, and golf course B received 21% more than the 80% predicted value because a 70% irrigation efficiency value was used instead of 75%. Using the measured precipitation rates and run times, the depth of irrigation water applied to the fairway (largest irrigated area) of the control hole was determined. The golf courses managers irrigated from 12 to 67% less than what the model (default values) predicted was needed. Two golf courses irrigated approximately half of what the model (default values) predicted as the IRR. This was due to the rainfall of above normal, which was not accounted for by the model. Accounting for the actual rainfall received on each golf course, the turf managers irrigated from 42% less than they needed to 58% more than they needed.

Conclusions

Investigations of the AFSIRS model indicate that when actual data (crop coefficients, distribution uniformity, and rooting depth) was included in the model it predicted similar water needs compared to the default prediction for only one of the five golf courses evaluated. The use of actual data resulted in IRR increasing between 15 and 46 cm (6 and 18 in) per year for the golf courses. This was typically a direct result of those courses having low distribution uniformities. When only distribution uniformities were substituted for the default irrigation efficiency, IRR increased between 13 and 76 cm (5 and 30 in) per year. Although DU_{LQ} provides an estimate of irrigation efficiency, the true efficiency of the system may be higher or lower than the measured DU_{LQ}.

Weather has a significant potential to influence inputs and predicted values but since the AFSIRS is used primarily as a prediction equation, it is difficult to use current weather patterns to predict long-term future needs. Weather datasets consisting of more than one year of data would provide a better comparison to estimates calculated using long-term, historical weather data.

Although a green built with USGA greens mix may require less water than the rest of the golf course, IRR issued on consumptive use permits do not account for this difference. But because of the stresses to a green (low mowing heights and high traffic), these areas may need the same, or more, water than the rest of the course on a per acre basis.

Precipitation rates and run times can provide an estimate for how much water actually was applied to certain areas on golf courses. Because of the high rainfall amounts during the year, golf course managers used less water than the predicted irrigation requirements with default data. The high rainfall was not accounted for in the predicted IRR using default data. When comparing water use to irrigation requirements with updated/actual data, managers used less and more water than what was predicted. This is a result of courses receiving different amounts of rainfall, and having different DU_{LQ} values.

Table 3-1. Soil types and average water contents for the five golf courses, average water content of all soil types in the model database, and average water content of a USGA green

Golf course	Soil type	Average water content ($m^3\ m^{-3}$)
A	Astatula sand	0.07
B	Astatula sand	0.07
C	Astatula sand	0.07
D	Candler sand	0.06
E	Blanton fine sand	0.10
Avg. of all soil types in	--	0.12
USGA green	--	0.13

Table 3-2. Mean squares for the analysis of variance on rooting depths as influenced by golf course, location within golf course, and month

Source of variation	df	F value †
Golf course	4	0.57 ns
Location (golf course)	10	1.40 ns
Month	3	5.83 **
Error	42	

† *, **, *** significant at the 0.05, 0.01, 0.001 levels, respectively.
ns, nonsignificant at the 0.05 level

Table 3-3. Mean rainfall, reference ET, estimated mean irrigation requirement, irrigation requirement issued on consumptive use permit, mean irrigation requirement using updated/actual data, and applied irrigation

Golf Course	Rainfall	ET_o	IRR†	CUP IRR‡	IRR§	Irrigation
	---------------------cm---------------------					
A	175	84	86	145	45	28
B	145	106	86	104	43	38
C	124	97	86	91	48	76
D	145	92	86	97	36	53
E	132	98	74	94	77	45

† irrigation requirements predicted using AFSIRS with default values
‡ CUP = District issued consumptive use permit
§ irrigation requirements predicted using updated/actual data

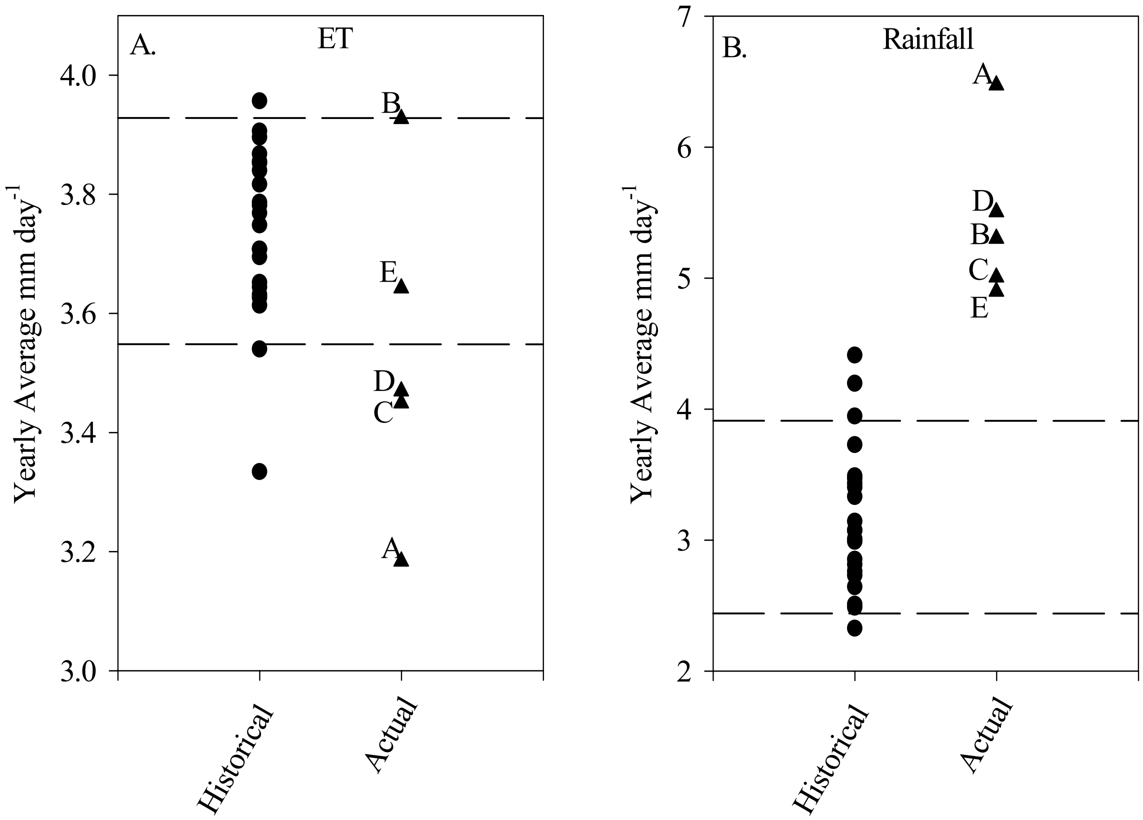

Figure 3-1. Yearly average reference ET (A) and rainfall (B) for the 20 year historical weather dataset (Orlando), and for the one year of on-site weather data from each of the five golf courses. Letters denote the five courses. Horizontal dashed lines indicate the upper and lower limits of the 95% probability of occurrence for the historical data.

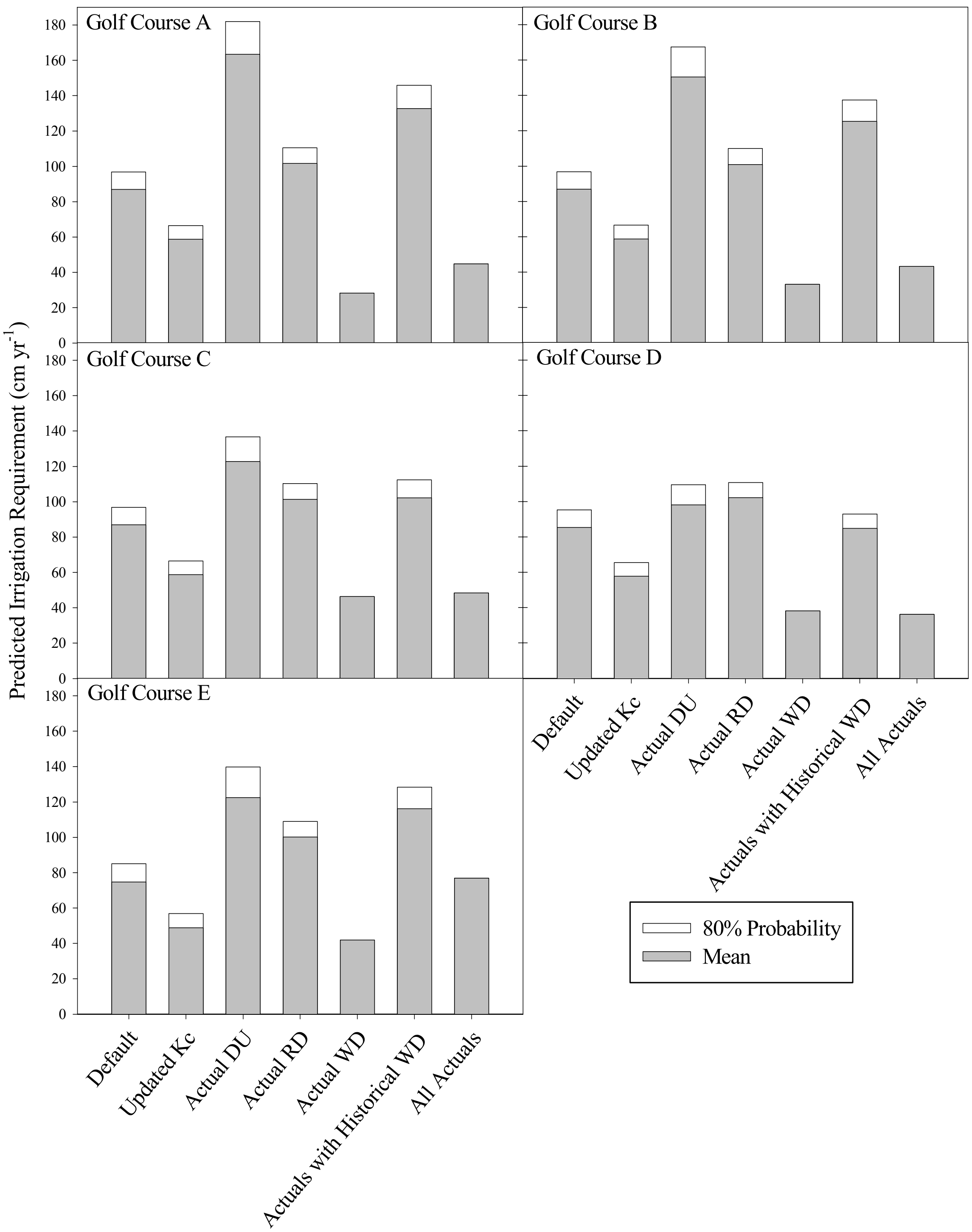

Figure 3-2. AFSIRS predicted irrigation requirements (IRR) for five golf courses. Default: model run with all default data. All others were run with actual values collected on-site or in the case of crop coefficients, published values.

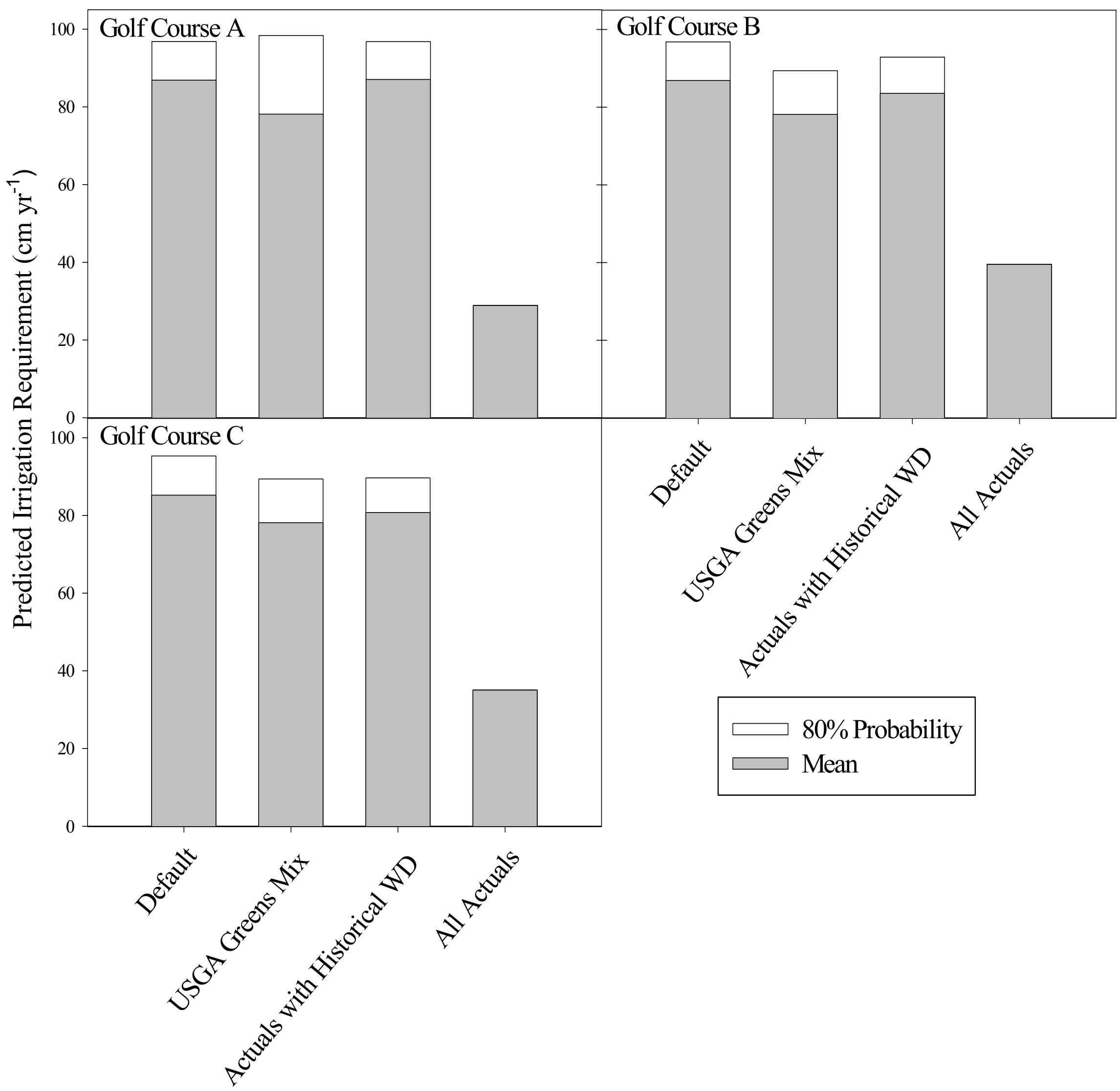

Figure 3-3. AFSIRS predicted irrigation requirements (IRR) for three golf greens built with USGA greens mix (sand and peat). Default: model run with all default data. USGA greens mix: model run with average soil water content (0.13 m^3 m^{-3} by volume).

CHAPTER 4
SENSITIVITY ANALYSIS OF THE AGRICULTURAL FIELD SCALE IRRIGATION REQUIREMENT SIMULATION (AFSIRS) AND THE FAO 56 PENMAN-MONTEITH EQUATION

Introduction

To provide a better understanding for how a model works and how the input parameters influence the outputs, a sensitivity analysis can be utilized. A sensitivity analysis requires varying selected parameters individually through an expected range of values and then comparing the range of output values from each input variable (James and Burges, 1982). This analysis technique determines which parameters have the greatest impact on the output, therefore determining the level of measurement accuracy of each input variable. The South Florida Water Management District used a sensitivity analysis to assess the impact of parameter errors on the uncertainty in output values for the South Florida Water Management Model and the Natural Systems Model (Loucks and Stedinger, 1994). Once the key errors were identified, it was possible to determine the extent to which parameter uncertainty can be reduced through field investigations, development of better models, and other efforts (Loucks and Stedinger, 1994).

The Agricultural Field Scale Irrigation Requirement Simulation (AFSIRS) is the model used by the St. Johns River Water Management District, South Florida Water Management District, and North Florida Water Management District to predict irrigation requirements (IRR) for golf courses. It is a numerical simulation model which estimates IRR for Florida crops, soil, irrigation systems, climate conditions, and irrigation management practices (Smajstrla, 1990). The FAO 56 Penman-Monteith equation (Allen et al., 1998) was found to be the most consistent model for determining reference evapotranspiration (ET_o) for Florida conditions (Jacobs and Satti, 2001). This equation can be used to calculate ET_o in a computer program such as REF-ET (a stand-alone computer program that calculates reference ET from meteorological data made available by the user (Allen, 2002)). These calculated reference ET rates can be used to create site-specific datasets for use with the AFSIRS model.

To establish how the output from the AFSIRS model and the FAO 56 Penman-Monteith equation (Allen et al., 1998) respond to changes in their inputs, a study was conducted using sensitivity analysis. The objective of this research was to determine what parameters have the greatest impact on the irrigation requirement predicted with the AFSIRS model and reference evapotranspiration (ET_o) using the FAO 56 Penman-Monteith equation (Allen et al., 1998).

Materials and Methods

Agricultural Field Scale Irrigation Requirement Simulation (AFSIRS)

Crop Coefficient (Kc), distribution uniformity (DU_{LQ}) (in place of irrigation application efficiency), average and maximum rooting depth, and average soil water content were the parameters that were analyzed for sensitivity on the AFSIRS model. Individual model runs were made using a range of values for each parameter. The values were changed in increments from the starting point, in both directions, depending on the size of the range. Each of the four input parameters were analyzed separately, while the other parameter values remained constant. The constant value for the parameters not being analyzed was the average value observed for each parameter from a concurrent golf course water use study where site-specific data was collected from five golf courses for predicting IRR using the AFSIRS model (Pressler, 2003).

Starting values and ranges were chosen for the four parameters based on the data collected in the concurrent water use study. The starting value for each parameter was the average value calculated for each parameter. The Kc value starting point for this study was 0.7. This value was changed in increments of 0.1 in both directions, and ranged from 0.5 to 1.0. The DU_{LQ} starting point value was 50%. The values were changed in increments of 10% in both directions, and ranged from 20% to 100%. Rooting depths had two starting points. The average depth starting point was 12.7 cm and maximum depth starting point was 50.8 cm (5 and 20 in, respectively). These depths were changed in increments of 2.54 and 10.2 cm (1 and 4 in) in both directions, and ranged from 2.54 and 10.2 to 20.3 and 81.3 cm (1 and 4 to 8 and 32 in), respectively. Average soil water content starting point was 0.09 m^3 m^{-3}, was changed in increments of 0.02 m^3 m^{-3} in both directions, and ranged from 0.03 to 0.17 m^3 m^{-3} (by volume).

FAO 56 Penman-Monteith Equation

Maximum and minimum temperature, maximum and minimum relative humidity, mean solar radiation, mean soil heat flux, and mean wind speed were parameters that were analyzed for sensitivity on the FAO 56 Penman-Monteith equation (Allen et al., 1998) in the REF-ET program. Each of the eight input parameters were analyzed separately, while the other parameter values remained constant. The starting values for each parameter were the average values observed from collected weather data during the concurrent water use study. The values were changed in increments from the starting point, in both directions, depending on the size of the range.

Because the temperature data collected by the weather station and analyzed in REF-ET was in Fahrenheit, the values used and reported in the sensitivity analysis are also in Fahrenheit. The min. temperature starting point was 60^{o}F. The values were changed in increments of 10°F in both directions, and ranged from 20 to 80°F. The max. temperature starting point value was 80°F. The values were changed in increments of 10°F in both directions, and ranged from 40 to 100°F. The min. relative humidity starting point was 50%. The values were changed in increments of 10% in both directions, and ranged from 10 to 90%. The max. relative humidity starting point was 95%. The values were changed in increments of 10% in both directions, and ranged from 60 to 100%. The mean solar radiation starting point value was 160 W/m^2. The values were changed in increments of 40 W/m^2 in both directions, and ranged from 0 to 320 W/m^2. The mean soil heat flux starting point was 0 W/m^2. The values were changed in increments of 5 W/m^2 in both directions, and ranged from -25 to 15 W/m^2. The mean wind speed starting point value was 8 km/hr. The values were changed in increments of 1.61 km/hr in the decreasing direction and 4.8 km/hr in the increasing direction, and ranged from 3.2 to 37 km/hr.

Results and Discussion

Agricultural Field Scale Irrigation Requirement (AFSIRS) Sensitivity Analysis

Changes in DU_{LQ} resulted in the largest changes in IRR (Figure 4-1). Changing a DU_{LQ} from 40% to 80%, a 100% increase, resulted in a 65% decrease in irrigation requirement. The Irrigation Association suggests that a 70% DU_{LQ} is expected and an 80% DU_{LQ} is achievable for a golf course. Modifying Kc values had the second largest impact on IRR. IRR increased linearly as Kc values decreased. A 15% increase or decrease of the starting point resulted in a 20% change in IRR in the respective direction.

Changes in rooting depth and average soil water content had very little impact on IRR. As rooting depth and average soil water content increase, IRR decreases. Increasing and decreasing both inputs by 60% of the starting points resulted in less than 16% increases and decreases in IRR.

FAO 56 Penman-Monteith Equation Sensitivity Analysis

A change in max. temperature resulted in the largest change in ET_o (Figure 4-2). A 25% increase of the starting point resulted in a 45% increase in ET_o. Modifying mean solar radiation had the second greatest impact on ET_o. A 50% increase of the starting point resulted in a 33% change in ET_o.

Changes in min. relative humidity and mean wind speed had the third and fourth largest impact on ET_o, respectively. Increasing both inputs by 60% of the starting points resulted in a 25% decrease in ET_o for min. relative humidity, and a 15% increase in ET_o for mean wind speed. Changes in min. temperature, mean soil heat flux, and max. relative humidity had very little impact on ET_o. A 25% decrease of the starting points for each of the three parameters resulted in a less than 8% increase in ET_o.

Conclusions

Sensitivity analysis further indicated that there can be significant differences between default values and true values when using the AFSIRS model. This was most apparent with DU_{LQ} (in place of efficiency) and crop coefficients. Because these parameters have the most impact on IRR, the data used in these inputs needs to have the highest accuracy. By collecting site-specific data, a true picture can be illustrated for irrigation requirements, and as a result, more water may be conserved. According to the AFSIRS, by attaining a relatively high DU_{LQ} (60 to 80%), golf course managers can greatly reduce wasteful water use, and as a result, meet or stay within their water allotments.

Because it is difficult to determine site-specific crop coefficients in the field, published data is the best alternative. More research needs to be conducted to determine Kc values for different types of turfgrasses grown under Florida conditions.

When determining reference ET rates using REF-ET and the FAO 56 Penman-Monteith equation (Allen et al.,1998), daily maximum temperature and mean solar radiation have the greatest effect on the output, followed by minimum relative humidity and mean wind speed. The data collected for these parameters with the most influence on ET_o, should be measured with the highest accuracy to reduce variability.

If the reference ET rates calculated by the FAO 56 Penman-Monteith equation (Allen et al., 1998) are used in the AFSIRS model, DU_{LQ} and Kc values as well as daily maximum temperature and mean solar radiation have a great impact on predicted irrigation requirement. But because three of those parameters are out of a golf course manager's control, the focus should be on improving DU_{LQ} to conserve water.

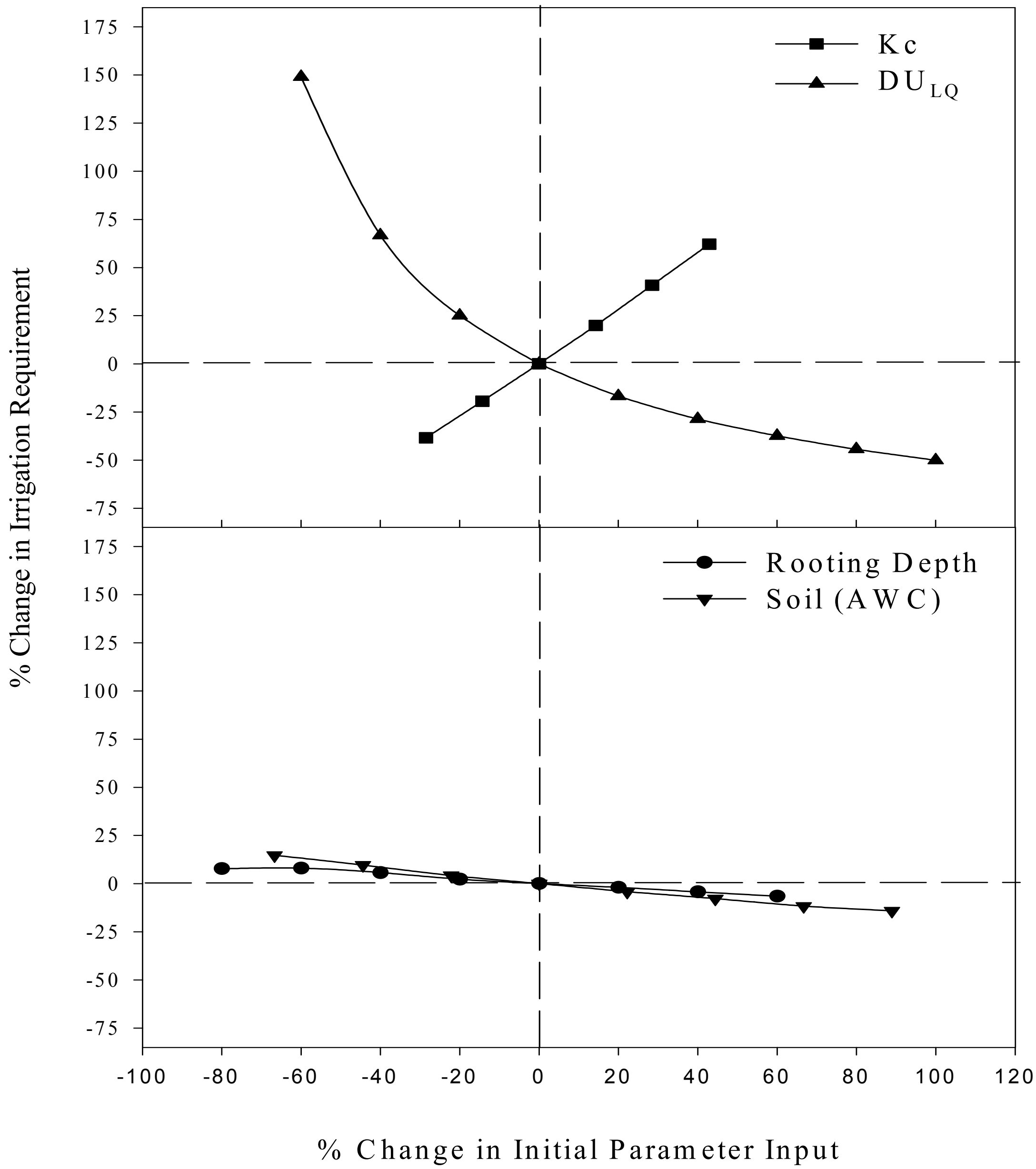

Figure 4-1. Sensitivity analysis of the AFSIRS model output. Values across x-axis represent a typical value as the starting point (0) and a range of values in the % change of the initial value.

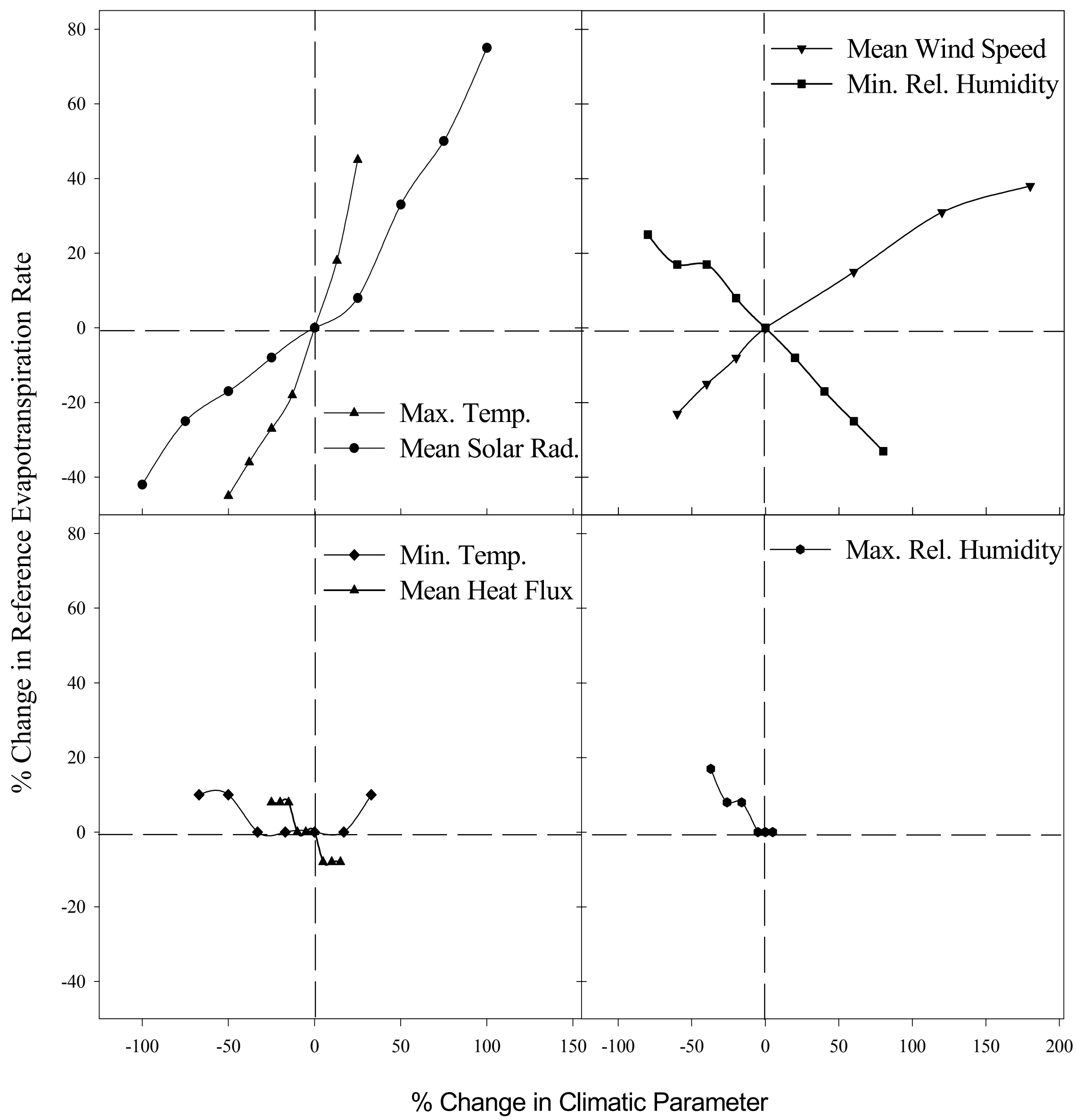

Figure 4-2. Sensitivity analysis of the FAO 56 Penman-Monteith equation (Allen et al., 1998). Values were changed across a range of typical values. Values across x-axis represent a typical value as the starting point (0) and a range of values in the % change of the initial value.

CHAPTER 5
SUMMARY AND CONCLUSIONS

Using site-specific data instead of default values in the AFSIRS model can result in site-specific estimates of irrigation requirements on golf courses. For prediction purposes it is better to use long-term (historical) weather data rather than short-term data.

It is important for golf course managers to be familiar with how their Water Management District determines golf course irrigation requirements. Knowing what data goes into the AFSIRS model, can allow a manager to use their allotted water more effectively, e.g. improving distribution uniformity. Evaluation of the AFSIRS model and its effectiveness in predicting irrigation requirements using default and actual (on-site) data from five golf courses was discussed in Chapter 3. The following results were obtained:

- Updated crop coefficients resulted in IRR predictions to drop approximately 25.4 cm (10 in) from the default estimates. Actual rooting depths caused IRR predictions to increase approximately 17.8 cm (7 in).

- Replacing distribution uniformities with the default irrigation efficiency, caused the greatest change in IRR predictions (increase between 12.7 to 76.2 cm or 5 to 30 in depending on the golf course).

- The one year of weather data collected at each golf course represented 56 and 109 cm (22 and 43 in) more than the average rainfall compared to the 20 year historical weather dataset. As a result, the estimates using the actual weather data decreased IRR predictions by approximately 51 cm (20 in).

- Due to the wet year, the model was run with all actual data and with the historical weather dataset. This combination of actual and historical data resulted in an increase in IRR predictions of 15 to 46 cm (0 to 18 in).

- Predictions with all actual data, including USGA green soil substrate average water content, and historical weather data resulted in little to no change in IRR for the three courses with USGA specification greens.

Sensitivity analysis allowed for a better understanding of how the AFSIRS model and FAO 56 Penman-Monteith equation (Allen et al., 1998) work. It indicated what inputs had the greatest impact on the outputs. The inputs with the most influence on outputs of interest needs to be measured with the highest accuracy to reduce variability. Sensitivity analysis on the AFSIRS model and FAO 56 Penman-Monteith equation (Allen et al., 1998) was discussed in Chapter 4. The following results were obtained:

- Sensitivity analysis on the AFSIRS model further indicated that distribution uniformity (irrigation efficiency input) had the greatest influence on the IRR prediction value, followed by: Kc, rooting depth, and average soil water content. Changing a DU_{LQ} from 40% to 80%, a 100% increase, resulted in a 65% decrease in irrigation requirement.

- Sensitivity analysis on the FAO 56 Penman-Monteith (Allen et al., 1998) using the REF-ET program to predict ET_o illustrated that changes in daily max. temperature resulted in the largest changes in ET_o, followed by: mean solar radiation, min. relative humidity, mean wind speed, min. temperature, max. relative humidity, and mean soil heat flux. A 25% increase of the starting point for max. temperature resulted in a 45% increase in ET_o, and a 50% increase of the starting point for mean solar radiation resulted in a 33% change in ET_o.

APPENDIX
SAS PROGRAMS

Program to organize weather station data into columns for REF-ET.

```
data ds1;
infile 'd:\glm test 91803.prn' firstobs=2;
input year day min Temp RHb solar soil soil2 windsp @@;
/*drop bar;*/ drop min;
soilmean=(soil+soil2)/2;
drop soil soil2;

/*proc print; run;*/
cards;
proc sort;
  by year day;
proc means noprint;
  by year day;
  var temp RHb;
  output out=data1 min=mn_t mn_RH max=mx_t mx_RH;
proc means data=ds1 noprint;
by year day;
var solar soilmean windsp;
output out=data2 mean=m_sol m_soil m_wind ;
proc sort data=data1;
  by year day;
proc sort data=data2;
  by year day;
data all;
  merge data1 data2;
  by year day;
/*proc print;*/
proc print data=all;
var year day mn_t mx_t mn_RH mx_RH m_sol m_soil m_wind;
run;
```

Rooting depths influenced by month, golf course, and location within golf course using analysis of variance procedure.

```
Title 'Mean Rooting Depth';
Data;
Input GC $ trt $ loc $month $ RD;
Cards;

proc sort; by trt;
proc glm;by trt;
class loc gc month;
model RD= gc loc(gc) month;
test h=gc e=loc(gc);
means loc(gc)/lsd lines;
means month/lsd lines;
run;
```

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BIOGRAPHICAL SKETCH

Mark Mitchell was born in Palm Beach Gardens, Florida, June 4, 1980. Mark graduated in 2002 with a Bachelor of Science in Turfgrass Science. Mark enrolled in the horticultural science graduate program in the Fall of 2002. After graduation in 2004, he plans to work as an assistant superintendent in Jacksonville, FL.