Residential Benchmarks for Minimal Landscape Water Use

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Executive summary

This report documents the importance of irrigation on turfgrass and urban landscapes as an activity that can lead to save water resources or not. Turfgrass in urban areas has a great impact on Americans in both, positive or negative ways, like providing comfort and protection to the environment, or overusing water and fertilizers. Water requirements for turfgrasses have been established by scientific studies, and to a lesser degree for ornamental plants. Therefore, application of water to urban landscapes in amounts exceeding its requirements can be attributed to human factors, not plant needs. The objectives of the present document were to summarize scientific techniques currently accepted for estimating plant water use, and to quantify the theoretical irrigation requirements for turfgrass and landscapes. By quantifying the theoretical requirements, usually using a soil water balance equation, benchmarks can be set, meaning that the determination of potential savings can be assessed.

A general background of turfgrass and ornamental plant water requirements are introduced to the audience, followed by methodologies to estimate evapotranspiration of turfgrass and combined landscapes, emphasizing the use of crop coefficients (K_c) and landscape coefficients (K_L). Well documented studies on evapotranspiration and K_c values in turfgrasses and ornamental plants are shown, basically under Florida conditions. In addition, the standard methodology to estimate theoretical irrigation requirements was described. Residential water use analysis depended on how indoor and outdoor water use was estimated. Techniques like the minimum month method, the minimum month, or the use of irrigation meters, as well as theoretical approaches based on total water use billing at the household level are also presented. Finally, case studies of irrigation estimation in Florida and other cities in the U.S. are presented and, in some cases, benchmarked with theoretical irrigation requirements. Reported water savings ranged from 20% to 50%.

This report was written with the idea to reach a wide audience, from members of the Conserve Florida Conservation Clearing house, which includes Water Management Districts and utilities, to other interested parties. The development of this document was made at the request of the Conserve Florida Conservation Clearinghouse.

1. Introduction

In the Conserve Florida Research Agenda this research priority area encompasses establishing benchmarks for minimum water requirements of residential landscapes. This summary documents the state-of-the-art in determining water requirements for landscapes (i.e. landscape irrigation benchmarks), from turfgrasses to ornamental crops. Based on an extended literature review, emphasis is placed on methods to estimate water use by residential landscape species that have been or could be used in Florida. The benchmarks are important in determining the relative efficiency of current practices such as landscape design and irrigation methods. Benchmarks, in this case, are generally calculated using equations like a soil water balance, whose inputs are specific for every climate and crop condition. Furthermore, benchmarks allow the determination of potential savings through outdoor conservation efforts.

This literature review summarizes scientific techniques currently accepted for estimating plant water use as well as new techniques introduced specifically for landscapes. The methodology presented here can be used to quantify theoretical irrigation needs for different landscape palates and then to compare estimated landscape water requirements with estimated outdoor irrigation. Methods used to separate indoor from irrigation use in a potable meter data are shown as well as some estimates of water use for irrigation purposes in Florida and other cities in the U.S. These values were compared to theoretical irrigation requirements to evaluate potential water savings in those areas. The literature review also summarizes for techniques used in studies within Florida and the U.S. Finally, research gaps for future studies are identified.

2. Literature Review

2.1. Urban landscapes and importance of benchmarking irrigation

Natural landscapes throughout the world have been drastically transformed due to urbanization, including structure, function, and dynamics of ecological systems (Luck and Wu, 2002). In agriculture, irrigation water requirements are well established for many crops; however, in urban landscapes, irrigation requirements have been determined for turfgrasses under various growing conditions, but not for most landscape species (Costello et al., 2000). Therefore, estimation of irrigation requirements for a mixed landscape is more complicated, although new methodologies are being developed.

As water availability decreases, landscape managers and homeowners need to recognize that they are responsible for when and how much water is applied to a landscape. Water needs to be applied in accordance to the environmental demand in order to be saved, adjusting the irrigation volume depending on the type of species and level of development (Devitt and Morris, 2008). A variety of factors influence individual residential landscape choices, like costs, ecological constraints, laws, and personal preferences (Yabiku et al., 2008), impacting plant selection, density of planting, and sense of landscape scale. Currently, there is a movement toward more xeric landscapes although the Green Industry and end users responsible for water management have been slow to understand and adopt the changes necessary to maintain these xeric landscapes (Devitt and Morris, 2008).

There is a need to ensure that water used for irrigation in urban landscapes is used adequately and responsibly (Conellan, 2002). The increase in urban water demand has threatened biodiversity and the supply of water for food production and other vital human needs (Pimentel et al., 2004). Irrigation is one of the activities that can significantly increase water consumption, hence the importance that it be performed correctly (Perez et al., 2004). Issues that are needed to be addressed due to the increased consumption in landscape areas are the dependence on potable water, inefficient irrigation practices, and the low use of recycled water for irrigation (Conellan, 2002).

New water supplies are likely to result from conservation, recycling, and improved water-use efficiency rather than from large development projects, and irrigation practices need to be more efficient, productive and sustainable (Pimentel et al., 2004; Cakman et al., 2004). The ability to track water use efficiency necessitates the need for methodology to benchmark landscape water needs.

2.2. Overview of water needs

2.2.1. Turfgrasses

Turfgrasses are classified into two groups based on their climatic adaptation: warm-season grasses, adapted to tropical and subtropical areas, and cool-season grasses which are adapted to temperate and sub-arctic climates (Huang, 2006). Warm-season grasses require significantly less water than cool-season species. Cool season grasses are generally more susceptible to moisture stress than warm season grasses (Duble, 2006). This difference in water use derives from changes in the photosynthetic process that occurred in grasses evolving under hot, dry conditions. These changes, which include modifications to internal leaf anatomy, greatly enhance the photysynthetic efficiency of warm-season species and help reduce water use. Increased photosynthetic efficiency means that plants can maintain high levels of carbohydrate production and continue to grow even when stomates are partially closed, as this partial closure of the stomates slows the plant's water use. Cool-season grasses cannot maintain enough carbohydrate production to maintain growth unless their stomates are nearly wide open. When water is limited, transpiration rates are generally higher than those of warm-season grasses (Gibeault et al., 1989).

2.2.2. Landscapes

Urban landscapes can provide several advantages to the environment (increased beauty, decrease runoff, cooling effect, among others. However, they also can require significant amounts of water which often is applied inappropriately (Allen et al., 2007). They are variable in composition, size, functionality, solar radiation demand, and soils, affecting the amount of water applied and the potential to conserve water. Therefore, irrigation must satisfy transpiration and evaporation losses, irrigation inefficiencies, and any leaching requirements (Devitt and Morris, 2008).

The prediction of water use in landscapes with multiple plant species is relatively new (Havlak, 2003). Whereas water use of most turfgrasses has already been quantified, with probably only 12 major turfgrasses species used extensively in the United States, water use in ornamental species (whose number exceeds several thousand) is far less known, and even less are mixed landscapes (Devitt and Morris, 2008). Currently, there are some methodologies of estimating irrigation water needs of landscapes, based on reference evapotranspiration (ET_o) and a landscape coefficient (K_L). This K_L coefficient would incorporate a stress coefficient with the density, microclimate, and vegetation coefficients proposed by different methods like the 'landscape coefficient method' and the 'landscape irrigation management program' methods (Costello et al. 2000; Snyder and Eching, 2005), which have been developed in California. However, the landscape coefficient method includes information that is based on research and on field experience (observation) and readers are advised for some subjectivity in the method, and estimations of water needs are not exact values. Water availability for other plants associated with turfgrass irrigations might be excessive for some species native to arid climates, but inadequate for some pine species. The amount of water applied to turfgrass and taken up by shrubs and trees will depend on environmental demand and available soil moisture in the rootzones of the trees/shrubs versus turfgrass (Devitt and Morris, 2008).

2.3. Evapotranspiration

2.3.1. Definition

Evapotranspiration (ET) represents the loss of water from the soil through the combined processes of evaporation (from soil and plant surfaces) and plant transpiration under an optimal set of conditions, among which is an unlimited supply of water. Reference evapotranspiration (ETref, also known as ET_o) is the rate at which readily available soil water is vaporized from specified vegetated surfaces (Jensen et al., 1990). Reference evapotranspiration is defined as the ET rate from a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing and expanse of at least100 m of the same or similar vegetation (Allen et al., 2005). Evapotranspiration is directly measured using lysimeters which are containers with boundaries encompassing the entire soil system for a given type of plant. Lysimeters enable quantification of water fluxes in the system by volume or weight. This method provides a direct measurement of ET and is frequently used to study climatic effects on ET and to evaluate estimating procedures. Ideally, lysimeters must meet several requirements for the data to be representative of field conditions (Van Bavel, 1961; Miranda et al., 2006):

- Deep enough to allow a normal root growth;
- They should contain an undisturbed, representative soil profile;
- The vegetation inside and outside the lysimeter should be kept as similar as possible;
- Diminishing the effect of the lysimeter rim over ET measurements by reducing the lysimeter wall thickness, the gap between inner and outer walls, and the height of the lysimeter rim relative to soil surface;
- Reducing the oasis effect by providing sufficient distances of windward fetch of similar vegetation and soil moisture regimes.

Lysimeters can be grouped into three categories: (1) non-weighing, constant water-table type; (2) non-weighing, percolating-type; and (3) weighing types. Also, large and mini-lysimeters can be used for different applications. Large lysimeters are the standard instrument for measuring evapotranspiration (surface area > 0.6 m^2) (Slatyer and McIlroy, 1961). Recently many researchers have used ‘minilysimeters’ in field studies (Grimmond et al., 1992). They have the advantage that minilysimeters (1) permit the measurement of the evaporative flux from smaller areas; (2) create less disturbance to the environment during installation; (3) are cheaper to install than the large ones. But there are a big number of potential sources of error associated when using lysimeters, either related with the mechanics or electronics of the lysimeter. In general, the effect of sources of error on the accuracy of evapotranspiration measurements is inversely related to the surface area of the lysimeter (Dugas and Bland, 1989).

2.3.2. How evapotranspiration is estimated

A large number of empirical methods have been developed over the last 60 years to estimate evapotranspiration from different climatic variables. Some of these methods are derived from the now well-known Penman equation (Penman, 1948) to determine evaporation from open water, bare soil and grass (now called evapotranspiration) based on a “combination” of an energy balance and an aerodynamic formula.

Various derivations of the Penman equation included a bulk surface resistance term (Monteith, 1965) and the resulting equation is now called the **Penman-Monteith equation**, which may be expressed for daily values as:

$$\lambda ET_o = \frac{\Delta (R_n - G) + 86{,}400 \rho_a C_p (e_s^o - e_a)/r_{av}}{\Delta + \gamma \left(1 + \frac{r_s}{r_{av}}\right)} \qquad (1)$$

where ρ_a is air density in kg m^{-3}, C_p is specific heat of dry air, e_s^o is mean saturated vapor pressure in kPa computed as the mean e^o at the daily minimum and maximum air temperature in ^oC, r_{av} is the bulk surface aerodynamic resistance for water vapor in s m^{-1}, e_a is the mean daily ambient vapor pressure in kPa and r_s is the canopy surface resistance in s m^{-1}.

An updated equation was recommended by FAO 56 (Allen et al. 1998) with the **FAO-56 Penman-Monteith Equation**. Allen et al. (1998) simplified equation (2) by utilizing some assumed constant parameters for a clipped grass reference crop that is 15 cm tall. In the context of this new standardization, reference evapotranspiration, it was assumed that the definition for the reference crop was "a hypothetical reference crop with an assumed crop height of 15 cm, a fixed surface resistance of 70 s m^{-1} and an albedo value of 0.23 that is actively growing full surface cover and not short of water". The resulting equation is:

$$ET_o = \frac{\left\{\left[0.408\Delta(R_n - G)\right] + \left[\gamma \frac{900}{(T+273)} U_2 (e_s^o - e_a)\right]\right\}}{\Delta + \gamma(1 + 0.34U_2)} \tag{2}$$

where ET$_o$ is the reference evapotranspiration rate in mm d^{-1}, T is mean air temperature in ^{o}C, and U$_2$ is wind speed in m s^{-1} at 2 m above the ground. Equation 2 can be applied using hourly data if the constant value "900" is divided by 24 for the hours in a day and the R$_n$ and G terms are expressed as MJ m^{-2} h^{-1}.

In 1999, the ASCE Environmental and Water Resources Institute Evapotranspiration in Irrigation and Hydrology Committee was asked by the Irrigation Association to propose one standardized equation for estimating the parameters to gain consistency and wider acceptance of ET models (Howell and Evett, 2006). The principal outcome was that two equations (one for a short crop such as clipped grass, ETos and another for a taller crop such as alfalfa, ETrs) were developed for daily (24 hr) and hourly time periods. **The ASCE-EWRI standardized reference ET equation (Allen et al., 2005)** based on the FAO-56 Penman-Monteith equation (3) for a hypothetical crop is given as,

$$ET_{sz} = \frac{\left\{\left[0.408\Delta(R_n - G)\right] + \left[\gamma \frac{C_n}{(T+273)} U_2 (e_s^o - e_a)\right]\right\}}{\Delta + \gamma(1 + C_d U_2)} \tag{3}$$

where ETsz is the standardized reference evapotranspiration for a short reference crop (grass - ETos) or a tall reference crop (alfalfa - ETrs) in units based on the time step of mm d^{-1} for a 24-h day or mm h^{-1} for an hourly time step, C$_n$ is the numerator constant for the reference crop type and time step and C_d is the denominator constant for the reference crop type and time step (see Table 1 for values of C_n and C_d).

Table 1: Values for C_n and C_d in Eq. 3 (after Allen et al., 2005).

Calculation time step	Short reference crop ETos		Tall reference crop, ETrs		Units for ETos,ETrs	Units for R_n and G
	C_n	C_d	C_n	C_d		
Daily	900	0.34	1600	0.38	mm d^{-1}	MJ $m^{-2}d^{-1}$
Hourly, daytime	37	0.24	66	0.25	mm h^{-1}	MJ m^{-2} h^{-1}
Hourly, nighttime	37	0.96	66	1.7	mm h^{-1}	MJ m^{-2} h^{-1}

Reference evapotranspiration (ET) replaced the term potential ET. Reference evapotranspiration is defined as the ET rate from a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of the same or similar vegetation (Allen et al., 2005). On the other hand, crop evapotranspiration (ET_c) under standard conditions is the evapotranspiration from disease-free, well fertilized crops, grown in large fields under optimum soil water conditions and achieving full production under the given climatic conditions (Allen et al., 1998).

There are also simpler methods to estimate potential evapotranspiration (ET_o), like the Blaney-Criddle equation (1964) and the McCloud equation (McCloud, 1955). The former establishes that consumptive use (or potential evapotranspiration) varies with the temperature, length of day, and available moisture. However, the method is not very accurate, especially in windy, dry, summy areas, where ET_o is underestimated up to some 60%, while in calm, humid, clouded areas, ET_o is overestimated up to some 40% (Brouwer and Heibloem, 1986). The latter is a formula based only on temperature. McCloud developed a formula for predicting potential evapotranspiration, which reflected turfgrass water use under Florida conditions. However, this formula typically overestimates ET in the summer and underestimates in the winter because they do not account for the cloud cover of humid climates (Irmak et al., 2003, Jacobs and Satti, 2001).

2.4. Crop coefficients

Water requirements for a crop can be determined by multiplying ET_o by K_c. K_c is the crop coefficient, determined as the ratio of crop evapotranspiration (ET_c) to the reference evapotranspiration (ET_o) that varies over crop growth stage and horticultural practices. K_c has been developed to simplify and standardize the calculation and estimation of crop water use. The potential crop ET is calculated by multiplying ET_o by the crop coefficient:

$$ET_c = K_c ET_o \tag{4}$$

Monthly coefficients can be averaged to yield quarterly, semi-annual, or annual crop coefficients (Richie et al., 1997), although averaging crop coefficients reduces monthly precision. Since coefficients can vary substantially over short time periods, monthly averaged coefficients are normally used for irrigation scheduling (Carrow, 1995). The simple, linear FAO K_c curve (Doorenbos and Pruitt, 1977) is also widely used and generally provides sufficiently accurate description of linear crop growth.. Factors influencing the crop coefficient for turfgrasses and all plant types are seasonal canopy characteristics, rate of growth, and soil moisture stress that would cause coefficients to decrease, root growth and turf management practices (Gibeault et al., 1989; Carrow, 1995). Crop coefficients will exhibit considerable variation throughout the season which is due in part to plant cover, growth rate, root growth and stage of the plant development and turf management practices (Gibeault et al., 1989; Brown et al., 2001). If an annual average K_c is desired, 0.8 should be used for cool-season turfgrasses and 0.6 for warm-season turfgrasses according to Gibeault et al., 1989). Another factor contributing to the variation in K_c values is the differing computation procedures used by the various researchers to estimate ET_o. Recently, the FAO and ASCE have identified this disparity in ET_o computation procedures and have recommended using a standardized computation procedure based on the Penman-Monteith Equation to ensure uniform estimates of ET_o (Allen et al., 1998).

2.5. Methods to estimate evapotranspiration for combined landscapes

Irrigation requirements are well established for agricultural crops; however, landscapes are nearly always comprised of multiple types and species of vegetation (Allen et al., 2007). In urban landscapes, irrigation requirements for optimal growth have been determined for many turfgrasses but not for most landscape species. Landscape irrigation increases dramatically during summer months and contributes substantially to peak demand placed on municipal water supplies, and outdoor water use may account for 40 to 60% of residential water consumption (White et al., 2004). Estimates of landscape water needs are important to preserve water resources, maintain landscape quality and reduce costs. The potential for plant injury caused by water deficits or excess can be minimized by identifying plant water needs (Costello et al., 2000).

Landscape evapotranspiration is complicated to estimate due to the mixture of plant types and, because the objective of landscape irrigation is to promote appearance rather than biomass production, as is the case in agriculture. As a consequence, the target ET replacement for landscapes may include an intentional “stress” factor where landscapes plants are watered less than they would be if they were irrigated like a crop and this adjustment can result in significant water conservation (Allen et al., 2007). The target ET may be lower than actual ET values if the landscape receives more water than required by the target than includes intentional stress. Or, actual ET may be less than target ET values if actual stress levels to the landscape are greater than targeted.

Either the target ET of the actual ET for a landscape is calculated as:

$$ET_L = K_L\, ET_o \qquad (5)$$

where ET_L is the target landscape (in mm d^{-1}, mm $month^{-1}$, or mm $year^{-1}$), and ET_o is the grass reference in the same units. K_L is the target landscape coefficient, similar to the crop coefficient used in agricultural applications (Allen et al., 2007).

A crop coefficient known as landscape coefficient was created to determine irrigation scheduling in landscapes. It is calculated as the ratio of actual evapotranspiration (ET_a from turfgrasses plus ornamentals) to ET_o and includes a stress, density, microclimate, and vegetation coefficients (Costello et al., 2000; Snyder and Eching, 2005). Once such coefficients have been generated, either for a single crop like turfgrass or a landscape, only estimates of ET_o are required to estimate actual ET needed for scheduling irrigation for a similar climate (Devitt and Morris, 2008). Thus, using different ET_o equations will generate different K_c values, which is one reason the ASCE-EWRI Standardized Reference ET methodology was developed (Allen et al., 2005). Allen et al. (2005) stated that there can be considerable uncertainty in K_c-based ET predictions due to uncertainty in quality and representativeness of weather data for the ET_o estimate and uncertainty regarding similarity in physiology and morphology between specific crops and varieties in an area and the crop for which the K_c was originally derived.

Several authors have proposed different procedures for estimating a formulated K_L, using different ranges for their components.

2.5.1. The Landscape Coefficient Method and WUCOLS

The Landscape Coefficient Method (LCM, Costello et al., 2000) was derived specifically to estimate water loss from landscape plantings. It has the same function as the crop coefficient, but is not determined in the same way. This landscape coefficient is used in the landscape evapotranspiration formula to estimate irrigation needs of a landscape. Landscape coefficients (K_L) are calculated from three factors: species (k_s), density (k_d), and microclimate (k_{mc}):

$$K_L = (k_S)\,(k_d)\,(k_{mc}) \tag{6}$$

By assigning numeric values to each factor, a value of K_L can be determined. These values are available in the Water Use Classification of Landscape Species (**WUCOLS**), which is a list that provides guidance to landscape professionals in selecting and maintaining plants based on their irrigation water needs. The selection of each numeric value will depend on the knowledge and gained experience of the landscape professional, which makes the method largely subjective. Differences in observed plants showing high evaporative loss stress from lack of soil moisture based plant stress are not specified. This guide provides irrigation water needs evaluation for over 1,900 species used in California landscapes, based on the observations and field experience of 41 landscape horticulturists. The guide contains different sections which include background info needed to use the Guide effectively, like “categories of water needs”, “plant types and “regions”. Water needs categories assigned for each species were determined by consensus of the committee. These are: high “H” (70-90% ET_o), moderate “M” (40 -60% ET_o), low “L” (10-30% ET_o) and very low (<10% ET_o). Assignments were made for each of six regions in California: region 1: north-central coast; region 2: central valley; region 3: south coastal; region 4: south inland valleys and foot hills; region 5: high and intermediate desert; region 6: low desert. All of these regions are based on different climate zones in California. Each plant of the species list falls into one or more of the following vegetation types: trees (T), shrub (S), groundcovers (Gc), vines (V), perennial (P) and biennals (Bi). Cultivars with some exceptions are not mentioned. Turfgrasses were not evaluated by the committee, although

WUCOLS includes a list of irrigation requirements for turfgrasses from the University of California ANR public 24191.

The landscape coefficient factors can be described as follows:

The species coefficient (k_s): This factor ranges from 0.1 to 0.9 and is divided into 4 categories, very low, low, moderate and high. The species factor ranges apply regardless of vegetation type (tree, shrub, herbaceous) and are based on water use studies, and from agricultural crops. Relative water need requirements for plants have been completed for over 1,800 species (Costello and Jones, 1999).

The density coefficient (k_d): This factor is used in the landscape coefficient formula to account for differences in vegetation density among landscape plantings. This factor is separated into three categories: low (0.5–0.9), average (1.0) and high (1.1–1.3). Immature and sparsely planted landscapes, with less leaf area, are assigned a low category k_d value. Planting with mixtures of trees, shrubs and groundcovers are assigned a density factor value in the high category. Plantings which are full but are predominantly of one vegetation type are assigned to the average category.

The microclimate coefficient (k_{mc}): This factor ranges from 0.5 to 1.4 and is divided into three categories: low (0.5–0.9), average (1.0) and high (1.1–1.4). An 'average' microclimate condition is equivalent to reference ET conditions: open-field setting without extraordinary winds or heat inputs atypical for the location. In a 'high' microclimate condition, site features increase evaporative conditions (e.g. planting near streets medians, parking lots). 'Low' microclimate condition is common when plantings are shaded for a substantial art of the day or are protected from strong winds.

The assignment of species coefficients was done by asking members of a committee to place the species under different water use categories and no actual field measurements support the values given in the study (Garcia-Navarro et al., 2004). Readers are advised that the landscape coefficient method calculations give estimates of water needs, not exact values, and adjustments to irrigation amounts may be needed in the field (Costello et al., 2000). Water needs of landscape plantings can be estimated using the landscape evapotranspiration formula:

$$ET_L = (K_L)\ (ET_o) \tag{7}$$

where landscape evapotranspiration (ET_L) is equal to the landscape coefficient (K_L) times reference evapotranspiration (ET_o). The ET_L formula differs from the ETc formula since the landscape coefficient (K_L) has been substituted for the crop coefficient (K_c). This change is necessary because of important differences existing between crop or turfgrass systems and landscape plantings.

2.5.2. The Landscape Irrigation Management Program (LIMP)

Another tool designed to help landscape professionals to calculate ET_o rates to develop irrigation schedules for homeowners, determine landscape coefficient (K_L) values, estimate landscape evapotranspiration (ET_L) and determine irrigation schedules is the LIMP program (Snyder and Eching, 2005). This tool provides a more quantitative approach to estimating landscape irrigation needs, as opposed to the relative and subjective WUCOLS approach. Evapotranspiration from landscape vegetation is estimated by using a regional measure of evaporative demand (e.g. reference evapotranspiration), a microclimate coefficient (K_m) to adjust the ET_o for the “local” microclimate, a vegetation coefficient (K_v) that accounts for the difference in ET between well watered vegetation (no stress due to lack of water) and the local ET_o, a density coefficient (K_d) that adjusts the ET estimate for plant density, a stress (K_s) coefficient) that adjusts for reductions in ET due to water stress and an evaporation coefficient (K_e) that defines a baseline coefficient value. Just to clarify, water stress is the condition when plants are unable to absorb enough water to replace that lost by transpiration (Zaid et al., 1999). Initially, the coefficient (K_w) to estimate ET of a well-watered vegetated cover is estimated as:

$$K_w = K_m \; x \; K_v \; x \; K_d \tag{8}$$

Then K_w is multiplied by a stress coefficient (K_s) to adjust for reductions in ET below that of well-watered vegetation. However, the evaporation coefficient serves as a baseline, so the landscape coefficient is calculated as:

$$K_L = K_w \; x \; K_s > K_e \tag{9}$$

Then the landscape evapotranspiration (ET_L) for the vegetation in that location is calculated as:

$$ET_L = ET_o \; x \; K_L \qquad (10)$$

The LIMP program calculates the regional daily mean ET_o rates by month using the regional mean climate data from CIMIS (California Irrigation Management Information System). The program also has the capability to adjust ET_o values for differences in slope and aspect of hills to determine the microclimate correction for undulating landscape features.

The LIMP coefficient factors can be described as follows:

The microclimate coefficient (K_m)

The microclimate coefficient is the ratio between "local" over "regional" ET_o computed by LIMP by using the Penman-Monteith (Monteith, 1965) equation if solar radiation (MJ m^{-2} d^{-1}), air temperature (^oC), wind speed (m s^{-1}) and dew point temperature (^oC) data are available, or the Hargreaves-Samani equation (1982) is used if only temperature data are input in the model. The Hargreaves-Samani equation is a simple equation used to estimate solar radiation. A smooth curve fitting procedure is used to estimate daily K_m values for the year.

The vegetation coefficient (K_v)

K_v represents well-watered vegetation with a full canopy and accounts for morphological and physiological differences between the vegetation and the reference surface (ET_o). ET_L is commonly estimated using $K_v = 0.8$. It is assumed that the plant physiology changes little during the year, so one value is used for K_v all year. Although this assumption might generally hold for some ornamental species, it would not hold for turfgrass.

The density coefficient (K_d)

It is estimated by the following equation:

$$K_d = sin \; [C_G \, \pi \, / \, (70 \; x \; 2)] \qquad (11)$$

where C_G is the percentage of ground covered by green growing vegetation. It is assumed that this relationship accounts for differences in light interception by canopies with cover less than 70%. For canopies with more than 70% cover, $K_d = 1.0$.

The stress factor (K_s)

K_s is used to reduce the ET rate of vegetation during dormant periods (e.g., ET rates for warm-season turfgrass are about 75% of cool-season turfgrass but the ET rate is near zero during the winter when the grass is dormant. A coefficient $K_s = 0$ would force $ET_L = 0$ and a $K_s = 1$ implies no reduction in ET_L. Therefore, reasonable estimates of the stress coefficient by month is input into the “Weather” worksheet in the LIMP model and the daily values are estimated using a curve fitting technique. Then, the landscape coefficient values for a warm-season turfgrass would be calculated as $K_L = K_m \times K_v \times K_d \times K_s$.

The evaporation coefficient (K_e):

K_e defines a baseline landscape coefficient factor. This evaporation coefficient is used to estimate bare-soil evaporation as a function of ET_o and rainfall frequency based on the bare soil evaporation model (Stroosnijder, 1987) using K_e model described by Snyder et al. (2000). Then the landscape coefficient K_L for estimating ET_L is computed as:

$$K_L = K_m K_v K_d K_s > or = K_e \tag{12}$$

The general conclusion is that the LIMP program can determine runtimes needed for irrigation of urban landscape vegetation using daily ET_o calculated from monthly climate data. However, one can also input the current ET_o data into the ET_o worksheet.

The LIMP program used in the University of California-Davis differs from that of WUCOLS (Costello et al. 2000) in the ranges used to define K_d. In addition, the procedure of WUCOLS combines the values for K_v and K_{sm} into a “species” coefficient which can make the combined product difficult to estimate. The procedure and factor ranges of LIMP may be more likely to produce more accurate and reproducible estimates of landscape ET (Allen et al., 2007).

2.5.3. The methodology from Texas Water Resources Institute, Texas A&M University

This methodology had the objectives of determining the relationship between ET_a and ET_o for a multiple plant species landscape, using this relationship to calculate a landscape coefficient (L_c) for use in the development of residential irrigation water budgets, and comparing actual residential water use to residential water budgets for municipal water consumers for three years (White et al., 2004).

The methodology used 192 volumetric soil moisture sensors in 64 locations at 3 different depths (0 to 20, 20 to 40, and 40 to 60 cm) in an approximately 850 m^2 landscape comprised of multiple plant species at the Texas A&M University Research and Extension Center in Weslaco, Texas. The soil type was a fine sandy loam and the vegetation types included a St. Augustinegrass (*Stenotaphrum secundatum*), dwarf yaupon (*Ilex vomitoria nana*), ficus (*Ficus benjamina*), and rose (*Rosa sp*.)

The landscape was maintained by staff members at the site. The fertilization program was based on soil nutrient analyses and the turf was mowed weekly at 8 cm. Trees and shrubs were pruned as needed. Supplemental irrigation was applied as plants began to wilt through an in-ground sprinkler irrigation system plus a drip irrigation line for the roses. Both systems were equipped with totalizing water meters.

Actual evapotranspiration (ET_a) was determined by adding soil water loss from each of the three depths, while reference evapotranspiration (ET_o) was estimated by the Penman-Monteith equation and meteorological data from a Texas ET network. Landscape coefficients (L_c) were estimated from the daily average ratios of ET_a to ET_o and from using the slope of the linear regression of ET_a with ET_o for all days.

Actual monthly water use, lot size and heated area for 979 homes were obtained from College Station Water Utilities in College Station, Texas, for years 2000, 2001 and 2002. Landscape size was estimated by:

$$\textit{Landscape area} = \textit{lot size} - (1.5 \times \textit{heated area}) \quad (13)$$

where heated area is multiplied by 1.5 as an estimate of driveways, sidewalks, patios, garages, etc, plus heated area for each residence. Landscapes less than 100 m^2 and greater than 900 m^2 were excluded from the data set.

Water budgets for each residence were developed from estimates of landscape area, specific L_c values, and ET_o and precipitation from a Texas ET Network weather station. The monthly water budget for an L_c of 1.0 for each residence was estimated by:

$$MWB = 7{,}000\ g + \{LA\ ft^2 \times [(ET_o - \textit{precipitation}) \times (27{,}154\ g/43{,}560\ ft^2)]\} \quad (14)$$

where MWB is the monthly water budget (or predicted water use) in gallons, 7,000 is the base indoor use in gallons, LA is landscape area in square feet, ET_o is reference evapotranspiration in inches, precipitation is in inches, 43,560 is the square feet per acre, and 27,154 g is the gallons of water that covers an acre one inch deep. Monthly water budgets so derived were then compared with actual monthly water use for each residence.

The main conclusion of this study was that the comparison of actual water used by residential municipal water customers in College Station, Texas with landscape water budget estimates demonstrated a potential savings of 24 to 34 million gallons of water per year (or 90,840 to 128,690 m^3 per year) if all 800 customers had irrigated based on ET_o and an L_c of 1.0. Using ET_o combined with L_c has the potential to provide realistic water budgets for individual residential landscapes and greatly reduce landscape water use. Showing the amount of water that landscapes need, compared to how much water is actually applied to landscapes, will help utilities target their conservation efforts for maximum results.

2.6. Data sources of evapotranspiration and crop coefficients for turfgrasses in Florida and the U.S.

With the introduction of irrigation systems, many residential communities built recently are looking for the desired high-quality landscapes in Florida. Turfgrasses play an important role since they are the most common species in the residential landscape (Haley et al., 2007). According to a survey carried out in 1992, the total turfgrass area in Florida was about 1.8 million hectares, with 75% of this area in the residential sector (Hodges et al., 1994). Recently, another survey (Satterthwaite et al., 2009) showed that sod production in the area of Florida has grown since 2003, but harvested area has remained steady. However, the population is increasing with a projected number of 35 million in 2060 from a starting population of 17 million in 2005. By 2060, the urban area is also projected to more than double compared to the actual urban area observed in 2005 (Zwich and Carr, 2006) with an increase of landscaped surfaces as a consequence.

Florida is characterized by its sandy soils with low water holding capacities, and rainfall is not evenly distributed throughout the year but concentrated in the summer season. Drought-sensitive plants may experience drought stress after only a few days without rain or irrigation (Knox et al., 1991). On the other hand, overwatering can damage or even kill the lawn, leading to a shallow root system, increasing a lawn's vulnerability to weeds, insects, and diseases (Trenholm and Unruh, 2008) As it was previously stated, water needs to be applied reasonably in order to be saved, adjusting irrigation volumes depending on the type of species, for the benefit of the lawns and landscapes and also for the viability of Florida's water resources. Water use measurements for turfgrasses and ornamental plants are necessary to efficiently calculate water budgets for efficient operation of irrigation systems (Stewart et al., 1969).

2.6.1. Turfgrasses

Water requirements of most turfgrasses have been established by scientific study and any application of water in amounts exceeding its requirements can be attributed to human factors, not plant needs (Beard and Green, 1994). Water use of turfgrasses is the total amount of water required for growth and transpiration plus the amount of water lost from the soil surface (evaporation), but because the amount of water used for growth is so small, it is usually referred to as evapotranspiration (Huang, 2006; Augustin, 2000). Few studies on evapotranspiration have been carried out in Florida. Jia et al. (2007) reported monthly turf ET values for Bahiagrass in Central Florida, using the Eddy correlation method to estimate crop evapotranspiration rates, under well-watered conditions (Table 2). The study showed a variation in turf ET from a maximum of 4.3 mm d^{-1} to a minimum value of 0.8 mm d^{-1}, in May and January, respectively. The multiannual average K_c value was minimum in January (0.35) and maximum in May (0.90) (Table 3). Stewart et al. (1969) studied ET rate as a function of plant density and water table depth in South Florida using Tifway bermudagrass growing in non-weighing evapotranspirometers. Depth to water table was 24 in the first year, 36 in the second, and 12 in the third year during the 3-year study. Water replacement ranged from well-watered conditions at a 12 in water table to partial stress at a 36 in water table depth. The plant cover treatments were established by killing part of the sod to give the preselected 0-, 1/3-, 2/3-, and full-sod cover treatments. An annual water balance showed a linear decrease between degree of plant cover and annual ET rate. ET rates increased with sod cover at water-table depths of 24 in (from 42 in y^{-1} (0.11 in d^{-1})-full sod- to 16 in y^{-1}(0.04 in d^{-1}) -no sod-), and 36 in (from 35 in y^{-1}(0.09 in d^{-1}) -full sod- to 19 in y^{-1}(0.05 in d^{-1}) -no sod-) (Table 2). ET rates decreased with cover for the water table depth of 12 in (from 42 in y^{-1}(0.11 in d^{-1}) -full sod- to 46 in y^{-1}(0.13 in d^{-1}) -no sod. Evaporation from bare soil (no sod, 46 in y^{-1} (0.13 in d^{-1})), with a 48 in water table was about 11% more than from full sod cover (42 in y^{-1} (0.11 in d^{-1})) in 1967. The ground surface of this treatment was moist continuously, indicating that the capillary fringe reached the soil surface. Similar results were shown in Stewart and Mills (1967).

Turfgrass K_c values for South Florida were estimated by Jia et al. (2007) using Stewart and Mills (1967) water use data for two warm-season grasses (Table 3). Reference ET values were calculated using climate data for Miami, FL (USDC, 2007). The results showed that calculated K_c values for southern Florida were higher than those in north Florida, especially in winter months. K_c was maximum in May (0.99) and minimum in December (0.70).

Bahiagrass used 11% more water than St. Augustinegrass under well watered conditions when UF/IFAS recommendations were followed (Dukes et al., 2008; Zazueta et al., 2000); however, water uses for both grasses were similar when water was scarce (Dukes et al., 2008). Augustin (2000) reported that mean summer ET for bermudagrass and St. Augustinegrass sod in Florida was 3.9 mm d^{-1}, which is lower than ET for these species reported from more arid climates. Another study showed that evapotranspiration increased with sod cover at water table depths of 60 and 90 cm, from 1 mm d^{-1} without grass cover to 2.8 mm d^{-1} for full grass cover in the former case, and from 1.3 to 2.3 mm d^{-1} in the latter case. Research over the last 30 years provides a clear understanding of turfgrass water use rates throughout U.S. Warm-season species like hybrid bermudagrass, zoysiagrass, buffalograss, and centipedegrass had the lowest water use rates, ranging from 3 to 9 mm d^{-1}. Several studies indicated that considerable inter- and intra-species variation existed in ET rates (Green et al., 1990a). An extended literature review about ET in turfgrasses in Florida and the U.S. has been reported by Romero and Dukes (2008).

Table 2: Summary table showing turfgrass species mean daily evapotranspiration rate (ET_o) in Florida, methodology used to determine ET_o, water availability, and respective references.

Turfgrass species	ET rate (in d^{-1})	Study period length	Methodology & water availability	Reference/ Location
Bahiagrass	Jan (0.03) Feb (0.03) Mar (0.08) Apr (0.14) May (0.17) Jun (0.13)	July 2003 through December 2006.	Eddy correlation method. Well-watered conditions.	Jia et al., 2007 Central Florida, FL.

	Jul (0.12) Aug (0.11) Sep (0.09) Oct (0.07) Nov (0.06) Dec (0.03)			
Tifway bermudagrass (original data in in y^{-1})		Full sod treatment:	Non-weighing evapo-transpirometers.	Stewart et al., 1969.
	0.11	1965		Ft. Lauderdale, FL.
	0.09	1966	Water stress conditions.	
	0.11	1967		
		2/3 sod treatmnt:		
	0.09	1965		
	0.09	1966		
	0.12	1967		
		1/3 sod treatmnt:		
	0.07	1965		
	0.07	1966		
	0.12	1967		
Tifway bermudagrass		5-yr average (1963-67).	Non-weighing evapo-transpirometers.	Stewart et al., 1967.
		Depth to water table:	Water stress conditions.	Ft. Lauderdale, FL.
	0.12	12 in		
	0.11	Depth to water table: 24 in		
	0.11	Depth to water table: 36 in		

Table 3: Summary chart showing turfgrass species, K_c, methodology used to determine K_c and respective references.

Turfgrass species	K_c	Study period length	Methodology & water availability	Reference/ Location
Bahiagrass	Jan (0.35) Feb (0.35) Mar (0.55) Apr (0.80) May (0.90) Jun (0.75) Jul (0.70) Aug (0.70) Sep (0.75) Oct (0.65) Nov (0.60) Dec (0.45)	July 2003 through December 2006.	ETc: Eddy correlation method. ETref: ASCE-EWRI equation (Allen et al.,2005) K_c: ETc/ETo. Well-watered conditions.	Jia et al., 2009. Central Florida, FL.
St. Augustinegrass + Bermudagrass	Jan (0.71) Feb (0.79) Mar (0.78) Apr (0.86) May (0.99) Jun (0.86) Jul (0.86) Aug (0.90) Sep (0.87) Oct (0.86) Nov (0.84) Dec (0.71)	5 years.	ETc: data from Stewart and Mills, 1967 (5-yr average montly data). ETref: Hargreaves equation (Allen et al., 1998) using data for Miami. Water stress conditions.	Jia et al., 2009 (using 5-yr average monthly ETc data from Stewart and Mills, 1967 for South Florida.

2.6.2. Ornamentals

Few studies show evapotranspiration and K_c values for ornamental plants. Erickson et al. (2001), carried out a study in Florida, comparing nitrogen runoff and leaching between a turfgrass landscape (St. Augustinegrass) and an alternative residential landscape which included twelve different ornamental plant types (50% native from Florida). ET_c was determined for each landscape treatment based on rainfall, irrigation, and percolate data measured during the experiment. The mean dry season ET_c was estimated to be 43 y 21 mm month^{-1} for both St. Augustinegrass and mixed-species, respectively, while the mean wet season ET_c was 105 mm mo^{-1} and 97 mm month^{-1} for the same landscapes. With these data, the estimated total annual ET_c for the turfgrass landscape would be 892 mm y^{-1} and for the ornamental landscape 711 mm y^{-1}.

Values of ET_c and K_c of *Viburnum odoratissimum* (Ker.-gawl) was reported by Irmak, 2005. The plants grown in both white and black multi-pot box system (MPBS) during summer and fall in Florida. From a previous study (Irmak et al., 2004) it was reported that the plants grown in the white MPBS had significantly higher growth rates and plant biomass production, since the black MPBS had heat induced stress caused by high root-zone temperatures. In the summer, the measured ET_c ranged from 308 to 334 mm for the black and white MPBS plants, respectively; in fall, it ranged from 346 to 351 mm for the black and white MPBS plants, respectively. K_c values of plants growing in the black and white MPBS ranged from 16 to 33 mm, respectively, during the summer and from 14 to 43mm for the black and white MPBS, respectively, during the fall. For both seasons, the highest K_c values were obtained at the end of the growing season.

Another study carried out in Florida using *Viburnum odoratissimum* (Ker.-gawl), *Ligustrum japonicum* Thunb., and *Rhaphiolepsis indica* Lindl. growing into 3 gal containers for 6 months were irrigated under different irrigation regimes consisting of an 0.7 in daily control and irrigation to saturation based on 20%, 40%, 60% and 80% deficits in plant available water (management allowed deficits – MAD) (Beeson, 2006). The results recommended 20%, 20% and 40% MAD for the previously mentioned woody ornamentals, respectively, for commercial production. The actual evapotranspiration for these results were 25% lower than the control conditions for *Viburnum odoratissimum* (Ker.-gawl) (125 vs 150 liters); 28.9% higher than the control conditions for *Ligustrum japonicum* Thunb. (136 vs 106 liters) and 10.4% higher than the control conditions for *Rhaphiolepsis indica* Lindl. (87 vs 76 liters).

A list of nearly 350 low-maintenance landscape plants for South Florida were described by Haynes et al. (2004), as a response to request from participants in the Florida Yards & Neighborhoods program in Miami Dade County. The term 'low-maintenance" refers to a plant that does not require frequent maintenance, such a regular watering, pruning or spraying, has low fertilizer requirements and few pest and disease problems, to maintain an acceptable aesthetic quality. However, information on evapotranspiration and K_c data were not available in this publication. Shrubs growing in Florida like wild coffee (*Psychotria nervosa*), copperleaf (*Acalypha wilkesiana*) and orange jasmine (*Murraya paniculata*) were recommended to be irrigated no less frequently than every 4 days with 3 liters of water for 28 weeks after transplanting for optimum canopy growth and development (Moore et al., 2009). After 28 weeks with irrigation, normal rainfall is sufficient to keep these shrubs alive when growing in the ground. A similar study showed that shrubs of three taxa, *Ilex cornuta* Lindl. & Paxt. 'Burfordii Nana'. *Pittosporum tobira* Thunb. "Variegata' and *Viburnum odorotissimum* Ker Gawl, needed 3 liters of water for irrigation applied every 4 days until roots reach the edge of the canopy under above normal rainfall conditions (182 mm extra rainfall) (Gilman et al., 2009). Native Floridian shrubs like beautyberry (*Callicarpa americana*), fringe tree (*Chionanthus virginicus*), yaupon holly (*Ilex vomitoria* 'Nana'), Virginia sweetspire (*Itea virginica*), wax myrtle (*Myrica cerifera*), Chickasaw plum (*Prunus augustifolia*), saw palmetto (*Serenoa repens*), and Coontie *(Zamia floridana*), and exotic golden dewdrop (*Duranta erecta*), cape jasmine (*Gardenia augusta*), crape myrtle (*Lagerstroemia indica*), oleander (*Nerium oleander*), Japanese pittosporum (*Pittosporum tobira*), Indian hawthorn (*Rhaphiolepis indica*), sweet viburnum (*Viburnum odoratissimum*), and sandwankwa viburnum (*V. suspensum*)] species responded equally to irrigated and nonirrigated treatments as they were aesthetically similar (Scheiber et al., 2008). Most of woody plants may require between 6 and 12 months to become established, and their survival and growth into landscapes depend on adequate irrigation until they develop a root system capable of compensating for evapotranspiration losses (Wiese et al.2009).

2.7. Landscape irrigation needs

There is a need to ensure that water used for irrigation in urban landscapes is not wasted and is used in an environmentally responsible manner. Good irrigation practices imply the following principles: amount of water applied is appropriate to plant and soil; timing of water application to suit plant and weather; water is applied uniformly and effectively; and water is applied to the plant root zone without wastage through runoff, deep drainage, ineffective coverage and other sources (Connellan, 2002).

All landscape shrubs and trees need to be irrigated frequently while grown in the nursery and when first planted; once roots are established in native soil, irrigation can cease (Gilman et al., 2009). Under ideal conditions like non-compacted soils surrounded by extensive irrigated areas, many Florida-friendly plants do not require further irrigation due to frequent rainfall, except in prolonged drought (Moore et al, 2009; Shober et al., 2009; Wiese et al., 2009; Scheiber et al. 2008). . Turfgrasses require irrigation at least once a week to maintain quality although due to the sandy soils, some grasses may need to be irrigated two days a week to ensure acceptable quality.

2.7.1. Estimating theoretical irrigation needs

Irrigation can be estimated through the use of a soil water balance equation. Inputs in the equation, like precipitation, crop evapotranspiration and soil hydraulic parameters, should be based on high quality information so the outputs can be expected to be appropriate for irrigation recommendations. A landscape with only turfgrass as a main cover uses, potentially, more water compared to a mixed landscape (Cisar, 2004; Haley et al., 2007; Yabiku et al., 2008; Sovocol and Rosales, 2009). Even some ornamental plants utilized for landscapes have the ability to maintain acceptable aesthetic quality under reduced irrigation (Scheiber et al., 2008; Pittenger et al., 2001). Then, theoretical irrigation requirements are estimated based on a turfgrass only, not considering a mixed landscape.

2.7.1.1. Soil water balance

Irrigation scheduling by the soil water balance approach is based on estimating the soil water content. Daily crop evapotranspiration (ET_c) amounts are withdrawn from storage in the soil profile, and any rainfall or irrigation is added to storage. The soil water holding capacity and the effective root zone are the parameters that need to be determined to estimate the total soil water available to plants, to assure that the amount of irrigation applied is correct (Broner, 2010).

The soil water balance can be represented as follows (Dukes, 2007):

$$SW_t = SW_{t-1} - ETc_{t-1} + R_{t-1} + I_{t-1} - D_{t-1} - Roff_{t-1} \tag{15}$$

where SW_t is the soil water on day '*t*', SW_{t-1} is the soil water content on day '*t-1*', $ET_{c(t-1)}$ is the crop evapotranspiration on day '*t-1*', R_{t-1} is rainfall on day '*t-1*', I_{t-1} is net irrigation, D_{t-1} is drainage on day '*t-1*' and $Roff_{t-1}$ is runoff on day '*t-1*'. ET_c is calculated as the product of ET_o by a K_c which varies monthly. K_c could be substituted with a K_L for a specific landscape. ET_c is subtracted from the soil water store on a daily basis until the root zone reached a maximum allowed depletion (MAD) level. The MAD level is the percent of available soil water that is allowed to be depleted before irrigation is applied. Daily gain and loss of water is computed by the equation once the maximum allowed depletion (MAD) value was reached. The MAD value is established for a specific crop (e.g. for turfgrasses MAD value has been suggested as 0.5 (Allen et al., 1998).

A landscape with only turfgrass as a main cover uses, potentially, more water compared to a mixed landscape (Cisar, 2004; Haley et al., 2007; Yabiku et al., 2008; Sovocol and Rosales, 2009). This scenario can be assumed if neither K_c nor ET_c values for ornamental species is available.

2.7.1.2. Irrigation efficiency and calculating the total amount of water to apply

Irrigation estimated by using the soil water balance is known as net irrigation. Net irrigation is the quantity of water necessary for crop growth and it is expressed in mm per year or in m^3 per hectare per year. Some water is lost while transporting it from its source to the crop root zone as losses occur due to such causes as leakage from pipelines, seepage, evaporation from open channels, and evaporation from droplets sprayed through the air. Therefore, the irrigated area will require water in excess of that estimated because of these losses. The gross irrigation requirement is the amount that must be pumped. Gross irrigation is greater than net irrigation by a factor which depends on the irrigation efficiency (Smajstrla and Zazueta, 2002):

$$\textit{Gross irrigation} = \textit{Net irrigation}/\textit{Irrigation efficiency} \qquad (16)$$

Dukes et al. (2006) recommended an irrigation efficiency of 80% for sprinkler irrigation. This value, which is equivalent to a low half distribution uniformity of 0.80, was determined from soil moisture measurements using time domain reflectometry (TDR) probes on plot testing of bare soil. This technique has been shown to be a better approach than the catch can method, which has been recommended as an irrigation system performance indicator and also for irrigation scheduling, although it has been found to unrealistically overestimate irrigation requirements. The uniformity as determined from catch can data was consistently lower than post irrigation soil moisture uniformity. The study concluded that a low half distribution uniformity of 0.8 (i.e. 80% efficiency) resulted in an adequate moisture distribution for plant growth.

2.8. Residential water use analysis

Household water use includes water used for indoor and outdoor household purposes. Indoor water uses include drinking, preparing food, washing clothes, bathing, washing dishes, and flushing toilets, while outdoor uses are principally watering lawns and gardens (Hutson et al, 2004). Most single family residential water customers are served by a single meter that records total water use in a household, regularly on a monthly basis (Palenchar et al., 2009). But some residential communities have two meters to meter "indoor" and "outdoor" (irrigation) water uses, especially those built in recent years, which include irrigation systems due to the high-quality landscapes that are typically installed, for example in Florida (Haley et al., 2007). Currently, there has been interest in estimating how much water is used for irrigation to assess over-irrigation of landscapes. In theory, a customer exceeding the benchmark established by the theoretical requirements for his/her landscape conditions would be considered as an over-irrigator. The benchmarking procedure assumes no limiting factors for plant growth, so the expected results will recommend well-watered irrigation estimates.

There are some methods established to estimate indoor water use, in case dual-metering available. As a consequence, outdoor water use can also be estimated. Future average water use is determined by multiplying population projections by a gallons per capita per day coefficient derived from historical metered data (Dzurik, 2003). That is why these methodologies need to be applied correctly for best estimations of water use in future applications involving water conservation.

2.8.1. Indoor water use estimation methods:

- Minimum winter month method: or AWC (average winter consumption) approach. It assumes that outdoor water use ceases in the winter because irrigation water is not needed (Dziegielewski et al., 1993). In this approach, AWC is used as a proxy for indoor use by assuming that there is no outdoor use during the period which the AWC is calculated. In many southern locations, this can lead to over estimates of indoor use since many people use water outdoors during the winter months (Mayer et al., 1999).

- Minimum month: or leveraged approach (Mayer et al., 1999). In this approach, the lowest-use month is assumed to represent indoor use and all differences between the other month and the lowest month is considered to be outdoor use. It is based on the minimum winter month method, this approach works better in areas with warmer climates like Florida (DeOreo et al., 2008; Meyer et al., 2009).

- Irrigation meter: In some cases, some residential units have two meters so that the regular metered "indoor" and irrigation metered "outdoor" uses are recorded separately. This is a direct way to measure irrigation water.

- AMR techniques: Automatic meter reading (AMR) devices are designed to monitor water use at sub-daily intervals. Irrigation water use can be determined from the total household water use by removing any water that was less than the smallest application rated determined during the irrigation evaluation. Therefore, indoor water use is determined daily by subtracting outdoor water use from total household water use (Mayer et al., 1999).

2.8.2. Outdoor (irrigation) estimation

Irrigation accounts for nearly one third of all residential water use in the U.S. and this percentage increases in warmer climates (Mayer et al., 1999). It is an important and increasing component of average and peak water use in the single family residential sector. Knowing irrigation estimates could help in the development of water conservation planning methodologies (Palenchar, 2009).

- Method to estimate irrigable landscape area

The total area (TA) of a parcel is the sum of the impervious area (IA), pervious area (PA), and non-applicable area (NA) (Palenchar, 2009). In this method, TA is calculated using GIS parcel geometry, NA is estimated from land use maps, and PA is the calculated residual pervious area and is equivalent to the irrigable area of a parcel.

Irrigable area can be measured, which involve methodologies that use GIS applications such as Google Earth® (Peng and Tsou, 2003), or determining irrigable areas over aerial photographs (Milesi et al., 2005). Other methods would require highly detailed imagery in order to classify parcel sub-areas accurately (Palenchar, 2009). Mayer et al. (1999) calculated irrigable area as the lot size minus the building footprint and associated impervious area. They estimated that non-irrigable areas such as driveways and sidewalks to be 7.5% of the total lot size. For studies involving a large number of households (e.g. at County level), where no irrigable area data is available another approach was applied by Romero and Dukes (2010, unpublished data). They assumed a range of non-irrigable areas, from 5% to 20% of the total green area, covering the uncertainty generated by this unknown parameter. The estimated irrigation is, as a consequence, a range of possibilities. This methodology could be considered more 'flexible', especially when comparing the estimated irrigation with observed values.

- Conversion of volume to depth

To estimate irrigation, the basic monthly indoor water use found for a household is subtracted from the monthly metered water use. This amount is divided by the final estimated irrigable area. The obtained volume of irrigation is then converted to depth (mm) over the irrigated area and per month. Irrigation can be expressed in mm d^{-1}, mm $month^{-1}$ or mm y^{-1}. Then, irrigation data can be compared to to rainfall, ET_o or ET_c data to calculate the water budget for a specific location.

2.9. Benchmarking irrigation in the literature

2.9.1. Florida

A complete study on irrigation use of potable water by the single family residential sector was carried out for Gainesville, Florida (Palenchar, 2009). This study involved many steps, from the compilation of water use from the Florida Department of Environmental Protection, climatic data from FAWN and NOAA/NCDC, parcel data from the Florida Department of Revenue (FDOR) used to characterize individual accounts. In addition, data from the U.S. Census Bureau was used to determine the household size as well as data from the Alachua County Property Appraiser. All these databases were used to support urban water supply evaluations. This study used data from single family residences built after the mid 1980s. The results showed an indoor water use with an average daily flow of 70 gallons per person (equivalent to 0.3 m^3 per person), an irrigation regime with an average peak month use of 684 gallons per day (or 2.6 m^3 d^{-1}) per account, and an annual average use of 320 gallons per day (1.2 m^3 d^{-1}) per account. The median irrigable area for homes using the potable system for irrigation was 10,383 sq.ft. (or 964 m^2) from an average lot size of 15,000 sq. ft. (or 1,400 m^2) (approximately 70% irrigable area or 30% impervious area). Thus, the expected water use coefficient, for the Gainesville observations were: an annual average of 38.1 mm per month per square foot of irrigable area and a peak rate of 78.7 mm per month per square foot of irrigable area. The occurrence of in-ground sprinkler systems in new homes has increased from 10% of homes in the mid 1980's to 80% of homes built in 2007. This cumulative percentage is expected to increase if the popularity of in-ground irrigation remains at current levels.

Another study to benchmark irrigation in Florida was carried out by Haley et al. (2007). The objective was to document residential irrigation water use on typical residential landscapes, where the homeowner set their own controller run times (T1), in the Central Florida ridge region for a time frame of 30 months, beginning in January 2003. Positive displacement flow meters were installed on the irrigation main line of each of the 27 cooperating residential homes and monitored monthly. Results showed that irrigation accounted for 64% of the residential water use volume over all homes monitored during this project. These homes had an average monthly water use of 149 mm/month. A second treatment (T2) involved the use of irrigation controllers based on historical ET to evaluate any reductions in irrigation water. This treatment resulted in a 30% reduction (105 mm/month) in monthly water use. A last treatment (T3) tested irrigation controllers based on historical ET and reducing the percentage of turf area and its effect on reduced irrigation. In this last case, average monthly water use had a 50% reduction compared to the typical residential landscape, with 74 mm/month. The actual irrigation water use of each treatment was compared to the theoretical irrigation requirement calculated with a simple soil water balance equation, whose value was 62 mm/month. T3 homes applied irrigation water similar to calculated needs, because T3 had less actual area irrigated. Over-irrigation occurred in treatments T1 and even in T2. The scheduling could be improved by using real time weather data to calculate ET, rather than historical data. Turfgrass quality was not negatively impacted by irrigation reductions.

Another study was carried out in Southwest Florida with the objective of estimating the amount of water used for landscape irrigation and comparing those values with a theoretical irrigation requirement calculated by a daily water balance equation (Romero and Dukes 2010, unpublished data). The upper 50% of water use billing records of homeowners in eleven locations in Hillsborough County, Florida, were analyzed, from 2001 through 2007. There were, on average, approximately 28,900 records of homeowners evaluated per year. The basic indoor water use was estimated using two methodologies: the minimum month and an indoor water use value of 0.25 m^3 per capita per day, as recommended by Mayer et al. (1999). Irrigable area was determined by subtracting the lot size minus the footprint of the house. Three non-irrigable areas were assumed due to the lack of information in this component at the household scale (Robbins and Birkenholtz, 2003). Impervious area was established as 5%, 10% and 15% of the total green area (lot size – footprint of the house). Irrigation was estimated monthly by subtracting the basic monthly indoor water use from the monthly metered water use. There were three irrigation depth estimates due to the three irrigable areas. The average estimated irrigation was 52 mm/month when 15% impervious area was used, whereas the theoretical irrigation requirement was 72 and 78 mm/month when 30 and 20 cm of root zone were used in the water balance equation. However, maximum estimated irrigation values exceeded the theoretical requirements. Results showed that 44% of the households exceeded the theoretical irrigation limits. Also, estimated over-irrigation volume increased over time in areas under urban development due to the green area expansion (i.e. new home construction). The irrigation requirements were estimated using the minimum month method in Hillsborough County. As DeOreo et al. and Meyer et al. suggested, wet months like July and August showed minimum water use per household, as low as in the winter months.

2.9.2. Colorado

Another study carried out by Qualls et al. (2002) in Colorado reported the performance of soil moisture sensors for landscape irrigation in 1997. The aims of this study were first, to document the efficiency of soil moisture sensors to modulate irrigation effectively after several years in the ground; to test irrigation systems operation with and without soil moisture sensors; to calculate evapotranspiration, and finally how to determine the theoretical irrigation requirement for comparison with actual water use. Watermark™ Electronic Modules (WEM) and granular matrix sensors (GMS) were employed in this study, being installed in 1994. GMSs are electrical resistance sensors in which stainless steel electrodes are protected with both gypsum and granular silica media. These moisture sensors were buried at mid-root depth at 23 homes located at residential communities in the City of Boulder in 1997. A WEM receives the sprinkler clock signal at the start of each irrigation cycle, measuring the resistance across the soil moisture sensors, and overrides the clock signal when soil moisture is above the user selected threshold. The durability of the systems exceeded expectations.

The effective irrigation requirement (Ie), equal to net potential evapotranspiration (ET_N), was determined by the Blaney- Criddle method, with correction for effective precipitation. In order to measure the performance of the soil moisture sensors it was necessary to have a standard or a theoretical irrigation requirement (I). I was obtained by dividing ET_N by the assumed irrigation efficiency of 90%, which amounted to 726 mm per year (61 mm per month). Water use data were collected manually from water meter readings associated with each sprinkler clock. The results indicated the GMSs were successful at saving water. During this period, the Watermark^{TM} systems allowed an average of 533 mm per year (44 mm per month) of water to be applied, or 73% of I. Sixteen of the twenty three sensors used less than 80% of I, and only three sites had applications equal to or greater than the theoretical requirements, which made the results quite variable. Possible reasons were that the same theoretical requirement was assumed for all sites and individual variations in microclimate, soil type and slope were not considered at individual sites. The corresponding monetary savings due to reduction of water consumption averaged $ 7,627 over the entire season, equivalent to $331 per installed sensor.

2.9.3. California (Evaluation of California weather-based 'smart' irrigation controller programs)

The impact of installing 3112 smart controllers at 2294 sites in northern and southern California was evaluated in a study by Mayer et al. (2009). In an effort to maximize potential water savings, agencies in northern California targeted customers with historically high outdoor water use demands; the southern California smart controller programs were devoted to interested and motivated customers. Smart irrigation controllers (or weather-based irrigation controllers) utilize prevailing weather conditions, current and historic evapotranspiration, soil moisture levels, and other relevant factors to control water applications to meet the estimated needs of plants (Mayer et al., 2008) Only 17.9% of the controller sites were located in northern California. The rest 82.1% were located in southern California. The smart controller brands that were dominant in the study were Weathermatic (36.5%), followed by HydroPoint (23.4%), Accurate WeatherSet (14.9%) and Agua Conserve (12.6%). The rest of controller brands (Acclima, Calsense, ET Water, Hunter, HydroEarth, Irritrol, LawnLogic, Nelson, Rain Master and Toro) did not even exceed 5% of the study sites. A very detailed list of characteristics of these smart controller technologies is described by Mayer et al. (2009).

Water savings constituted only one evaluation measure. Another important evaluation parameter was the post-application ratio, which is to match the actual irrigation application to the theoretical irrigation requirement (post-application ratio of 1.0).

The evaluation research found that on average, smart controllers are a moderately effective measure for reducing the amount of water applied by automatic irrigation systems, and although a valuable tool, they are not a ‘magic bullet’ for achieving perfect water savings. The results also showed that smart controllers are likely to achieve a high degree of customer acceptance although most of them have no knowledge of smart irrigation control yet. Overall, outdoor water use was reduced by an average of 47.3 kgal per site (-6.1% of average outdoor use) across the 2294 sites. Water saving were reported for some controllers and are shown in Table 4.

2.9.4. WaterSense® Water Bugdet Approach

The WaterSense® Water Bugdet Approach is a design tool that defines the amount of water to be applied in a landscape based on a regionally appropriate amount of water (EPA/WaterSense, 2009). The use of this tool by a builder is one of the options to meet the Landscape Design Criteria developed by EPA (EPA/WaterSense, 2009b) in order to earn the WaterSense label. The other option would be that turfgrass shall not exceed 40% of the landscaped area.

The intended purpose of the WaterSense® Water Budget is to promote a conservative landscape design by comparing the landscape water requirements to a baseline amount of water. The water budget tool set the baseline amount of water at the amount of water required by a site if the landscaped area is watered at 100% of local reference evapotranspiration (ET_o) under well watered conditions:

$$\text{Baseline} = ET_o \text{ x } A \text{ x } Cu$$

where: ET_o = local reference evapotranspiration; A= landscape area, and Cu= conversion factor. The units used by this tool are English.

The landscape water allowance (LWA) is the amount of supplemental water allotted for the designed landscape and it was set as 70% of the baseline amount of water that would be needed if the entire landscape was covered by a well-maintained expanse of average-height green grass.

$$LWA = 0.70 \text{ x Baseline}$$

where: LWA = landscape water allowance (gallons/month)

EPA has assumed that a landscape will have a variety of vegetation that have different water needs and that none of the vegetation in a residential landscape will need 100% of ET_o.

Landscape water requirements (LWR) by hydrozones in the landscape are also calculated by the tool. A hydrozone is defined as areas having the same vegetation type (turfgrasses, shrubs, trees). K_L coefficients, irrigation type and irrigation efficiency are considered by hydrozone, and water requirements by hydrozone are added to get a final total water amount.

Finally, the theoretical results are analyzed. If the landscape water requirement is less than the landscape water allowance, then the water budget criterion was met. If not, then the landscape and/or irrigation system needs to be redesigned to use less water. In the end, the recommended irrigation requirements by the WaterSense® Water Budget is intended to save 30% of water use from the baseline calculated at the beginning of the process.

2.9.5. Reported water savings relative to baseline

Reported water savings relative to baseline are shown in Table 4 based on information described in the previous section.

Table 4: Observed irrigation, theoretical irrigation requirements, and reported water savings at different cities in Florida.

Author	City	Observed irrigation/ Theoretical irrigation requirement	Reported water savings
Qualls et al., 2001	Boulder, Colorado	Avg. irrig.: 44 mm $month^{-1}$ Theoret. requirement: 61 mm $month^{-1}$	28%
Haley et al., 2007	Marion & Orange Counties, Central Florida	T1*(Avg. irrig.): 149 mm $month^{-1}$ T2*(Avg.irrig.): 105 mm $month^{-1}$ T3*(Avg.irrig.): 74 mm $month^{-1}$ Theoret. requirement: 62 mm $month^{-1}$	T2: 30% T3: 50%
Palenchar, 2009	Alachua Co., North Central Florida	Avg. irrig.: 38 mm $month^{-1}$ Peak irrig.: 79 mm $month^{-1}$	Not reported
EPA/WaterSense, 2009	Nationwide	Specific according to region in the US	30%
Romero and Dukes, 2010	Hillsborough Co., Southwest Florida	Est. avg. irrig.: 52 mm $month^{-1}$ Theoret. requirements: 72 and 78 mm**	Not reported
		Irrigation controller§	
Mayer et al., 2009	California	Hydropoint weathertrak Aqua Conserve ETWater Rain Master	59 to 71% 21 to 28% 20 to50% 27%

*T1: typical landscape and irrigation systems where homeowner set their own controller run times; T2:controller run times adjusted based on historical ET; T3: adjusted controller run time settings and incorporation of micro-irrigation in bedded areas.
** Using root zones of 30 and 20 cm, respectively.
§ Neither values of irrigation nor theoretical irrigation requirements were reported.

3.0. Research needs and recommendations

In order to evaluate water savings in outdoor water use more research studies would be recommended because there is a lack of information in the area. Water consumption for irrigation should be monitoring at household level, and irrigable areas measured through the use of satellites or radar images to improve irrigation estimation of pre-existing methodologies. It is critical to normalize volume applied over irrigated areas so that factors such as demographics, seasonality, etc. can be compared across data sets. Irrigation management and water applied must be evaluated over time periods long enough to remove seasonal bias. Crop coefficients for ornamental plants and trees need to be determined in order to improve the irrigation requirement determination. In particular, stress coefficients need to be studied that would allow the minimum amount of water to maintain a given acceptable plant quality. In addition, more data is needed when theoretical irrigation requirements are estimated. Spatial and temporal weather information (e.g. rainfall and temperatures) must be gathered to study the variability on irrigation requirement according to a specific year (dry or wet). Use of seasonal climate forecast (3 to 6 months) to dynamically establish the irrigation requirements tailored for a given year could a valuable forecasting tool. Further research on the impacts of irrigation efficiency on turfgrass and/or landscape quality is needed. Last but not least, more studies on the social behavior component affecting the efficiency of the irrigation systems are also needed.

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4. Glossary

Cool-season grasses: grasses that grow most vigorously at temperatures below 60 to 70 degrees F and goes dormant and turns brown in hot weather. Cool-season grasses include Kentucky bluegrass, perennial ryegrass, and the fescues.

Crop coefficient: Is simply the ratio of ET observed for the crop studied over that observed for the reference crop under the same conditions.

Crop evapotranspiration: Crop evapotranspiration refers to the evapotranspiration of a disease-free crop, grown in a very large field, not short of water and fertilizer. Crop evapotranspiration can be obtained multiplying the reference evapotranspiration by the crop coefficient of the interested crop.

Evapotranspirometer: An evapotranspirometer is an instrument which measures the rate of evapotranspiration. An example of evapotranspirometer is a lysimeter.

Hargreaves-Samani equation: Method to estimate solar radiation from latitude and maximum and minimum temperature.

Hydrozone: a distinct grouping of plants with similar water needs and climatic needs.

Impervious surface: a land cover- or artificial structures- that prevents filtration of water or sediments down into the grown. For example, asphalt, roads, sidewalks, driveways and parking lots.

Landscape coefficient: It is a coefficient, like the crop coefficient, created to determine irrigation scheduling in landscapes. It is calculated as the ratio of actual evapotranspiration (ET_a from turfgrasses plus ornamentals) to ET_o and includes a stress, density, microclimate, and vegetation coefficients.

Lysimeter: A lysimeter is a measuring device which can be used to measure the amount of actual evapotranspiration which is released by plants, usually crops.

Plant stress: is the effect of any factors that could lead to the deathe of the plant. For example, the lack of (or too much) cold, heat, water, sunlight, shade or fertilizer.

Potential evapotranspiration: It is the amount of water transpired in a given time by a short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile. In this case, the evapotranspiration rate is not related to a specific crop.

Reference evapotranspiration: Reference evapotranspiration (ETref) is the ET rate from a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short or soil water, and representing an expanse of at least 100 of the same or similar vegetation.

Smart irrigation controllers: (or weather-based irrigation controllers) that utilize prevailing weather conditions, current and historic evapotranspiration, soil moisture levels, and other relevant factors to control water applications to meet the estimated needs of plants.

Urban landscape: Green areas located on residential areas that vary not only in size, comporsition, functionality, microenvironments, and edaphic factors, but also in the cultural management practices imposed.

Warm-season grasses: grasses which are most productive during the warmer months, i.e., summer. This type of grass grows vigorously at temperatures above 70 to 80 degrees F and goes dormant in cool weather. Warm-season grasses include Bermudagrass and St. Augustinegrass.

Xeric landscape: It is a landscape specifically designed for areas that are susceptible to drought, or for properties where water conservation is practiced. 'Xeriscape' means literally 'dry landscape'.

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