This manuscript is in press. It has been accepted for publication in *Transactions of the ASABE*. When the final, edited version is posted online this in-press version will be removed. Example citation: Authors. Year. Article title. *Trans. ASABE* (in press). DOI number.

The DOI for this manuscript, active after publication, will be https://doi.org/10.13031/trans.13948.

A REVIEW ON LANDSCAPE WATER REQUIREMENTS USING A MULTICOMPONENT LANDSCAPE COEFFICIENT

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HIGHLIGHTS

- A multi-component decoupling method for the landscape coefficient is described that provides a thorough means to estimate water requirements of landscapes
- The decoupling method considers differences in vegetation type, density, local climate, and soil water management.
- Methods for incorporating managed stress and frequency of irrigation are described.
- Winter-time or dormant season ET is described.
- The ASABE S623 procedure is described that represents a more simplified and reduced form from the multi-component procedure and is complementary.

Abstract. Water requirements of landscapes are highly variable due to the heterogeneous natures of landscapes, vegetation types, influence of buildings, and nutrient and water management. Objectives for water management of landscapes are for general appearance and health rather than for maximum biomass production. A multi-component method developed for the Irrigation Association (IA) Irrigation Sixth Edition and extended from the California WUCOLS procedure is demonstrated where the landscape coefficient (K_L, equivalent to a crop coefficient) is broken down into the four components of a) vegetation type; b) vegetation density; c) microclimate; and d) managed stress. Each of these components can be estimated using readily made descriptions of a landscaped area and management objectives. One form of the K_L equation is used to determine target K_L that incorporates a target amount of soil water stress to support water conservation and to support water planning studies. A second form of the K_L equation can be used to estimate the actual K_L occurring under actual water management. The second form is used in studies of water balances and actual water conservation. The general decoupled equation is further expanded to optionally incorporate impacts of evaporation from exposed soil to assess impacts of irrigation frequency on total water consumption. The mathematics for the approach can be incorporated into software applications and smart irrigation controllers to produce improved water consumption estimates for landscape water requirements for use in irrigation scheduling, water requirements planning and water depletion studies. The ASABE S623 simplified procedure for estimating a landscape water requirement that is complementary to the IA procedure is discussed and compared. Both methods utilize a vegetation type and density system as the basis for efficiently estimating scientifically accurate landscape water requirements.

Keywords. *Evapotranspiration; Irrigation requirements; Landscape coefficients; Landscape water requirements; Managed Stress; Microclimates; NAIP areal imagery.*

INTRODUCTION

Water requirements and consumption by residential and urban landscapes have become increasingly important because of the quantity and value of water consumed. Procedures, which are similar to agriculture, are adapted to estimate evapotranspiration (ET) from landscapes. Two distinctions are made between agriculture and landscapes: 1) landscape systems often comprise mixtures of types and species of vegetation, and non-uniform spatial configurations, thereby complicating the estimation of ET, and 2) typically, the objective of landscape irrigation is to promote appearance rather than biomass production, whereas biomass production is generally maximized in agriculture.

Target ET for landscapes may incorporate intentional water stress into the baseline estimate for ET, because landscape plants are often deficit irrigated to reduce water applications without substantially reducing health or appearance. Many landscape plants can often be stressed to some degree without adverse effects. This adjustment can produce considerable water conservation, and a better defined estimate for water requirements of landscapes may reduce over-irrigation of landscapes that often occurs due to their relatively small size. Controlled stress can also reduce unneeded excessive growth, which reduces volumes of lawn and tree clippings. .

The magnitude of any managed stress in a landscape depends on physiological and morphological requirements of the plants; the goal is to sustain health and appearance with minimal irrigation. For example, water conservation studies on turfgrass have demonstrated water savings of 20 to 30% for cool-season turfgrasses and 40% for warm-season turfgrasses without significant loss of quality (Meyer and Gibeault 1986, Pittenger and Shaw 2001, 2004). Some shrubs and groundcovers can be managed for even more stress-induced reduction in ET (Kjelgren et al. 2000, 2016).

A third departure of landscape ET from agricultural ET is that few landscape sites meet the “extensive surface” requirement needed to ensure equilibrium between the lower boundary layer of the atmosphere and the vegetation that is implied in the Penman-Monteith equation. Therefore impacts of local microclimates may need to be considered in the ET estimate. The non-uniform boundary-layer equilibrium can be at the leaf level where stomates more directly regulate transpiration (Jarvis and McNaughton, 1986), such as for large specimen or street trees. Therefore, compensating adjustments are necessary to the landscape coefficient in the form of a microclimate factor to account for effects of local surroundings.

TARGET ET AND ACTUAL ET

Because of the frequent inclusion of water stress in target ET values for landscape design and management, distinction must be made between target ET values and actual ET values. Actual ET values may exceed target ET values if the landscape receives more water than required by the target that includes intentional stress. Under these conditions, landscape vegetation may exploit the additional available water, subject to some limit constrained by environmental energy available for evaporation and leaf area. The upper environmental energy limit, which follows behavior and principles used for agricultural crops, may exceed the targeted ET rate. Conversely, actual ET may be less than targeted ET values if stress levels to the landscape are more excessive than targeted. Therefore, two ET values for landscape are distinguished here. The first is the *target landscape* ET, referred to as ET_L, that is based on minimum ET levels, relative to climate, necessary to sustain a healthy, attractive landscape. The target landscape ET is useful for irrigation scheduling and water conservation planning. The second ET value is the *actual landscape* ET, $ET_{L\,act}$, that is based on landscape type and on actual water availability, which may be greater or less than water required to establish and support target landscape ET_{L}. The actual landscape ET is useful for water depletion studies and for hydrologic water balances. The decoupled methodology for the landscape coefficient is relatively straightforward to code into application software so that only the selection or specification of four readily described coefficients is required. Traditionally, landscape ET estimation is based on the standardized reference ET for short canopies (ET_o) rather than reference ET for tall canopies (ET_r) due to similarity between ET_o and turf grass ET. The ET_o concept and derivation of ET_o is presented in ASCE (2005) and in ASCE 2016).

The target ET for a landscape is calculated as

$$ET_L = K_L \, ET_o \tag{1}$$

where ET_L is the target landscape ET (in mm d^{-1}, mm month^{-1}, or mm year^{-1}), and ET_o is the ET of a 0.12 m tall, cool-season grass in the same units. K_L is the target landscape coefficient, which is similar to the crop coefficient (K_c) used in agricultural applications.

SCOPE OF THIS PAPER

A decoupled approach for estimating K_L described in this paper was formulated by Costello et al. (2000) in California and termed WUCOLS (water use classification of landscape species) (Costello and Jones 1999; 2014) and Irrigation Association (2003). The method was modified for use with the Landscape Irrigation Management Program (LIMP) by Snyder and Eching (2004, 2005) and Snyder et al. (2015). The decoupling method separates actual landscape ET into components for well-watered vegetation that are then adjusted by a deficit irrigation coefficient. Allen et al., (2011) and ASCE (2016) extended the decoupling procedure to enable the estimation of effects of watering frequency on landscape ET and estimation of target soil water depletion to meet water stress targets. The decoupling approach provides a relatively simple means to break the K_L into four terms that describe separate mechanisms impacting landscape ET. Each mechanism describes a factor involved in the landscape ET process that can be readily described by a user. The terms can be extracted from general, simplified tables or can be obtained from more rigorous, mechanical methods in the case of the managed stress coefficient and density coefficient. In addition, the ASABE S623 procedure for water requirement recommendations (ASABE Standards, 2017) that is complementary to the IA decoupled procedure, but that is more simplified and aggregated, is discussed and compared. Both methods utilize a vegetation type and density system as the basis for efficiently estimating scientifically accurate landscape water requirements.

BACKGROUND ON K_L AND K_C.

The vegetation cover or "crop" coefficient (K_c) that has a basis of reference crop ET (ET_{ref}) was clarified in Jensen (1968) and first used in computerized irrigation scheduling by Jensen (1969) and Jensen et al. (1970, 1971). The procedures for estimating ET for well-watered agricultural crops that employ a K_c and ET_{ref} procedure can be applied to wide range of landscape, natural and agricultural vegetation under rainfed and irrigated conditions.

Early, refined K_c values were developed based on daily ET measured in lysimeters that were then related to a grass or alfalfa reference ET. Some K_c values were refined for conditions of dry surface soil and were termed *basal crop* coefficients (Wright 1982). Accuracies of ET estimates made with a dual K_c approach where basal coefficients are adjusted daily according to wetness of the surface soil following rain or irrigation are generally greater than accuracy of ET estimates made using a single lumped K_c value (Wright 1982; Allen et al. 1998).

Somewhat limited experimental research exists on quantifying water needs and K_L for the vast and diverse array of landscape plant types (Pittenger and Henry 2005). Some of the leading work on landscape ET and K_L for groundcovers and shrubs has been done in California, where water applied to landscapes in southern California is estimated to be 25 to 30% of all water used in the region (Pittenger and Shaw 2001; Reid and Oki 2008; 2016; Reid et al. 2018). St. Hilaire et al. (2008) produced a table of K_L values for 35 landscape groundcovers and shrubs that are targeted to provide acceptable landscape performance after initial establishment and that induce a managed amount of water stress associated with deficit irrigation strategies.

LIMITATIONS ON MAGNITUDES OF LANDSCAPE COEFFICIENTS

When applying a grass reference ET equation (ASCE 2005, 2016) under humid conditions, where a majority of energy for the ET process is from net radiation, the maximum K_L or K_c for large expanses of similar vegetation does not exceed about 1.2 relative to ET_o, whereas in arid or semiarid climates, where additional advection of warm dry air can occur, increasing ET from irrigated surfaces, the K_L or K_c can reach maximum values of about 1.3 to 1.4 relative to the grass reference (Doorenbos and Pruitt 1977; Allen et al., 1998; ASCE 2005). Limiting K_L to approximately 1.3 or 1.4 for a grass reference base generally applies to large expanses of vegetation (>50 to 100 m in the direction of wind (Allen et al., 1998)).

When ET is measured from small expanses of vegetation, the internal boundary layer above the vegetation may not be in equilibrium with the underlying surface, particularly with well ventilated, tall trees (ASCE 2016). Small expanses of tall vegetation surrounded by shorter cover can result in a "clothesline effect" where the interchange between air and vegetation is much more efficient than over large expanses of homogeneous vegetation. In these cases, ET from isolated vegetation stands, on a per unit area basis, may be significantly greater than the corresponding ET_o computed for a grass reference, depending on stomatal behavior. An example of these situations is ET from a single row of trees surrounded by short vegetation or even ET from a small area of grass or flowers surrounded by a dry, vegetation-free surface. Allen et al. (1992) reported K_c values for small (6 m wide) stands of cattails and bulrushes surrounded by grass pasture equal to 1.6 to 1.8 during midseason, relative to an alfalfa reference. These measurements indicate a strong clothesline effect. An extreme illustration was by van Bavel et al. (1963), who measured ET from 1 m tall sudangrass in Arizona following cutting of the grass around a lysimeter, so that the vegetation inside the lysimeter functioned as a clothesline. After cutting, 14.7 mm of ET during a 24 h period was measured compared with 9.8 mm three days before the cutting—a 50% increase. The weather data were similar for both clear days. In a similar situation, Allen et al. (1991) measured ET from 0.6 m fescue grass that increased by 1.6 times relative to the PM equation when the surrounding grass was clipped to 0.1 m, but the vegetation inside the lysimeter remained at 0.6 m. The ET rate from the lysimeter under the clothesline condition reached 16 mm d^{-1}, whereas the PM equation estimated 11 mm d^{-1} for 0.6 m grass having extensive fetch of other 0.6 m grass.

Pruitt (personal communication, 1976) reported K_c values for a nearly isolated 4.2 m tall Monterey pine tree (*Pinus radiata*) varying from 1.4 in February-March to 2.0 during spring and summer and to 3.0 during late fall and dry, early-winter months relative to ET_o. The tree grew on a 1.83 m by 2.44 m hydraulic-pillow lysimeter located within a 1 ha dry, fallow field, thereby creating a clothesline effect.

The preceding discussion indicates the importance of knowing the type of setting for which ET estimates are needed. If ET estimates are to represent large expanses of similar vegetation or small stands of vegetation surrounded by mixtures of other vegetation having similar roughness and soil water conditions, then K_L values will generally be less than or equal to 1.3 for grass references.

ET of Heterogeneous or Integrated Landscapes ET and K_L for mixed landscapes is needed for irrigation management. In many landscapes, elevated ET from tall, narrow stands of vegetation as described in the previous section can reduce ET from adjacent shorter vegetation due to shading, blocking of wind and, to some extent, by cooling and humidifying the air. Therefore, development of an integrated and blended estimate for ET_L and K_L for a landscape should be based on a composite view of the landscape that considers the mixture of vegetation types and heights, even though water requirements for tall, narrow stands of vegetation, such as trees, may be greater or less depending on stomatal behavior. Also to be considered in developing an integrated K_L is the impact of horizontal extents of tree roots that tend to be larger than canopy extents and therefore can even out water extraction over parts of a landscape and that tend to integrate K_L of individual vegetation.

DEVELOPMENT OF THE LANDSCAPE COEFFICIENT (K_L)

The primary factor causing an increase in the landscape coefficient is an increase in plant cover or leaf-area per unit area (LAI) as vegetation develops, resulting in a decrease in bulk surface resistance and an increase in radiative capture and aerodynamic exchange. Most publications on crop coefficients (K_c) have presented K_c as a time-based function of some form of absolute or scaled time basis, such as the FAO-style example shown in Fig. 1. Other studies relate the rate of development of K_c for various crops as a function of daily weather such as cumulative growing degree days (Snyder 1985; Ritchie and NeSmith 1991; Slack et al. 1996; Snyder et al. 1999; Cesaraccio et al. 2001).

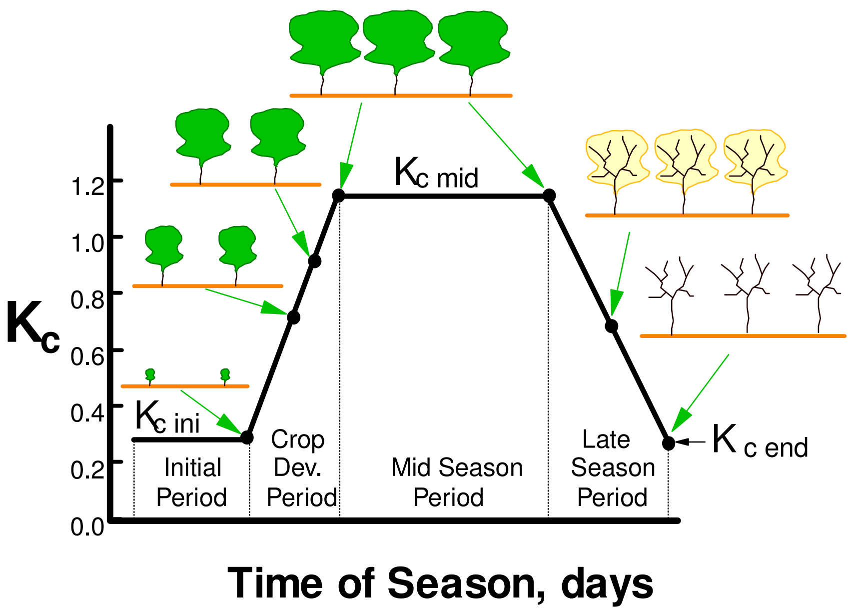

Figure 1. FAO-style crop coefficient curve and stage labeling.

The FAO-style K_L function shown in terms of an equivalent K_c in Fig. 1 can be used to represent most landscape vegetation that has an annual cycle of low vegetation cover or vigor during wintertime, with regrowth or return of vigor during spring. During periods of low cover or vigor, the K_L or K_c can be as low as 0.1 to 0.3 when averaged over the period termed in Fig. 1 as "initial." The K_L will reach a maximum or near-maximum value during the "mid-season" period when ground cover is maximum. In the case of year-round vegetation in warm climates, the K_L may remain at or near the midseason K_L value. Values for $K_{L\,ini}$ and $K_{L\,end}$ (i.e., $K_{c\,ini}$ and $K_{c\,end}$ in Fig. 1) can be scaled from $K_{L\,mid}$ (i.e., $K_{c\,mid}$ in Fig. 1) in proportion to the health and leaf condition of the vegetation at termination and the length of the late season period (i.e., whether leaves senesce slowly or are killed by frost).

A DECOUPLING APPROACH FOR K_L

The above discussion describes the potentially wide range in values for K_L that can be caused by the surroundings of vegetation and/or dryness of the surrounding environment. K_L can also have broad ranges in values due to variation in density of vegetation. As a result, Costello et al. (2000) developed and described the procedure from California termed WUCOLS (water use classification of landscape species), where the K_L was decoupled into reproducible and visually apparent components representing the effects of four factors that determine the value for K_L. The decoupling was done to facilitate application to the wide diversity of vegetation types and environments of landscape systems. Snyder and Eching (2004, 2005) and Snyder et al. (2015) proposed a similar decoupled procedure for estimating a formulated K_L that uses different ranges for the K_L components than does Costello et al. (2000), where the ranges for the K_d and K_{sm} factors are normalized to limit their ranges to 0 - 1.0. Snyder and Eching (2004) and Snyder et al. (2015) modified the WUCOLS procedure in the Landscape irrigation management program (LIMP) to the form:

$$K_L = K_v\, K_d\, K_{sm}\, K_{mc} \tag{2}$$

where K_v is a vegetation species factor (0.7 – 1.2), K_d is a vegetation density factor (0 – 1.0), K_{mc} is a microclimate factor (0.5 – 1.5), and K_{sm} is a managed stress factor (0 – 1.0). K_v is the ratio of ET_v to ET_o for a specific single or mixture of plant species under full soil water supply, and where ET_v is the vegetation ET assuming no water deficits and essentially full ground cover, defined by Snyder and Eching (2004) and Snyder et al. (2015) as having more than 70 to 80% of the ground covered or shaded by vegetation. K_v therefore represents the maximum K_L expected for vegetation or for a mixture of vegetation under no soil water stress and where there are no microclimate adjustments required. Factors K_d, K_{sm}, and K_{mc} modify K_v for less than effective full ground cover (K_d), for intentional water stress (K_{sm}), and for micro-climate differences due to shading, light reflection from structures, fetch and wind exposure, and slope and aspect impacts on radiation (K_{mc}). Each of these factors can be estimated separate from the others based on visual observation of the landscape (for K_d and K_{mc}) and based on user experience for K_{sm} (Reid and Oki 2008; 2016; Reid et al. 2018).

Following the estimation of the individual factors, K_L is calculated using Eq. (2) to produce a landscape-specific estimate of relative landscape ET. The landscape-specific K_L can improve water conservation efforts by better matching irrigation additions to landscape-specific conditions including a targeted soil water stress level. The form of the K_L equation in Eq. (2) is used to determine target K_L that may include a targeted amount of soil water stress to support water conservation and to support water planning studies. A second form of the K_L equation provided later as Eq. (17) can be used to estimate the actual K_L occurring under actual water management. The second form is used in studies of water balances and actual water conservation where the actual *ET* from the landscape is needed.

An alternative form of Eq. (2) from Irrigation Association (2011) adds the variable effects of evaporation from soil in between vegetation that may be significant during frequent wetting by rainfall or irrigation and is patterned after the dual K_c procedure of FAO56 (Allen et al. 1998):

$$K_L = \left((1 - K_d)K_{soil} + K_v K_d K_{sm}\right)K_{mc} \quad (3)$$

where K_{soil} is the evaporation coefficient representing evaporation from the soil surface (relative to ET_o) caused by wetting by precipitation or irrigation. K_{soil} is included in Eq. (3) to consider the impact of evaporation occurring between plants. In the context of Eq. (3), the K_v coefficient represents the, potential transpiration from the vegetation component when the soil surface is infrequently wetted and mostly dry, so that evaporation from soil is treated separately by K_{soil}. The impact of K_{soil} is strongest when plant density (K_d) is low and frequency of soil wetting is high. K_{soil} is less impactful with greater plant density or greater K_v. K_{soil} is estimated as a function of soil wetting frequency and magnitude of ET_o from Fig. 2 originating from Fig. 29 of FAO-56 (Allen et al., 1998). K_{soil} can also be estimated using equations from ASCE (2016) and in Allen et al., (1998; 2005), where K_{soil} is referred to as K_e or K_{ini} for bare soil conditions.

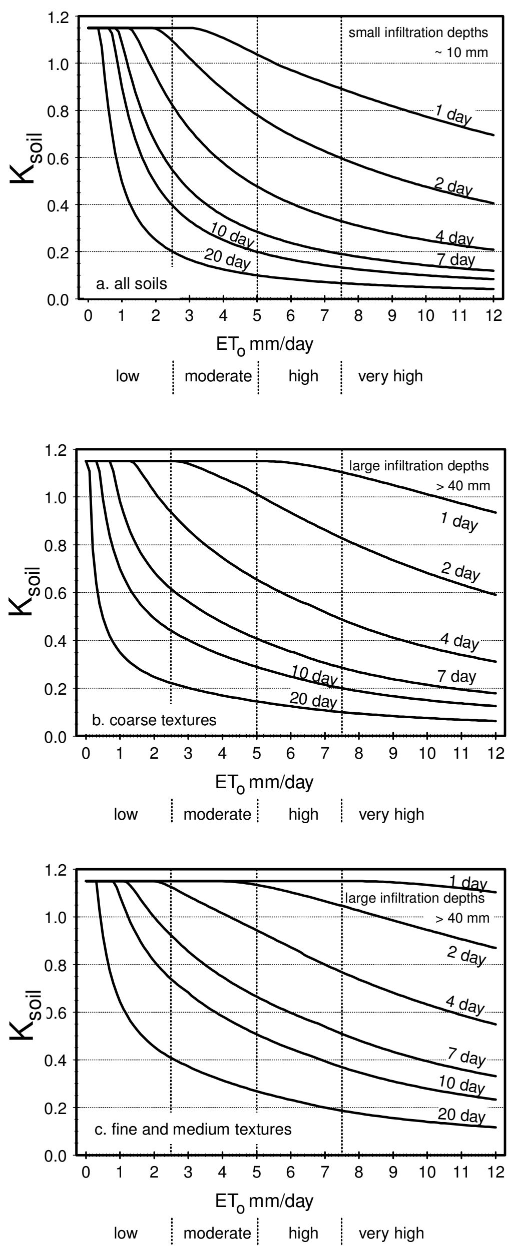

Figure 2. Average K_{soil} for a bare soil surface as related to the level of grass reference ET_o and the interval between irrigations or significant rain (a) all soil types when wetting events are about 10 mm per event, (b) coarse-textured soils when wetting events are greater than about 40 mm, and (c) medium and fine-textured soils when wetting events are greater than about 40 mm (after FAO-56 - Allen et al., (1998)).

Eq. (3) reverts to Eq. (2) when $K_{soil} = 0$. However, in that case, the K_v should include impacts of evaporation from soil. Eq. (3) is useful to assess the impact of irrigation frequency on total ET of a landscape having less than full ground cover. Effects of evaporation of water intercepted by vegetation following irrigation or precipitation are estimated with Eqs. (20 to 22) described later. Eq. (3) provides estimates for K_L over an extended period of time where effects of evaporation from soil, over time, are averaged through the estimate for K_{soil}. More refined estimates, when needed, can be made using a daily water balance for the surface soil layer using the dual $K_{cb} + K_{soil}$ procedure described in Allen et al., (1998; 2005) and ASCE (2016), where the basal crop coefficient, K_{cb}, of the FAO procedure is set equal to a K_v that represents a relatively dry soil surface, and K_{soil} is estimated daily in accordance with wetting frequency. Refined, daily estimates might be desirable during computer modeling for specific landscapes where the daily water balance and associated equations can be scripted into software code and where specific wetting frequency is known or can be estimated. Ordinarily, Eq. (3) will provide satisfactory and sufficient estimates for K_L for purposes of irrigation scheduling, estimation of water conservation impacts and for general water depletion studies.

Reference ET_o as influenced by the microclimate

Reference ET_o, which represents weather-based effects on potential ET, is influenced by the microclimate of a landscape. A local environment that is surrounded by dry areas or by buildings and walk-ways are often subjected to more long-wave radiation and local advection of sensible heat compared to areas surrounded by vegetation due to the surrounding elevated surface temperatures. This can cause the potential demand for the area to exceed that for the standardized ET_o that represents near maximum ET from an extensive surface of short grass. An altered reference ET_o, termed $ET_{o\ mc}$ is defined as the ET_o within the microclimate where the vegetation grows. Local $ET_{o\ mc}$ can deviate from the regional ET_o that represents a regional estimate of reference evapotranspiration based on measured weather data from an open, vegetated area. Thus, $ET_{o\ mc}$ is a local ET_o corrected for microclimate differences. The microclimate coefficient, $K_{mc} = ET_{o\ mc}/ET_o$, is estimated or determined experimentally and is described in a following section.

The Vegetation Coefficient

The K_v for landscape vegetation represents the ratio of ET_v to $ET_{o\ mc}$ that occurs when generally 70% or more cover (shading) of the ground exists and the soil water supply is full. $ET_{o\ mc}$ is used as the basis for K_v because the ET_v represents the ET for the vegetation in the same microclimate as represented by $ET_{o\ mc}$. In contrast, the K_v is expected to have a relatively constant and consistent value over ranges in microclimate because both ET_v and $ET_{o\ mc}$ are impacted by the same microclimatic factors. As a result, K_v defines the maximum ratio $K_L = ET_v/ET_{o\ mc}$ for vegetation under non-deficit irrigation conditions. The K_v is the fraction of $ET_{o\ mc}$ when the foliage has $K_d = 1.00$ and full water availability ($K_{sm} = 1.00$). Many types of landscape vegetation tend to exhibit similar values for K_v due to similarities in total leaf area, stomatal response, and energy absorption. Therefore, condensed tables of typical values for general species types are employed to provide general estimates for K_v, where K_v typically ranges from 0.8 to 1.2. Because landscape vegetation is commonly taller and rougher than turf grass, the upper limit for K_v can exceed 1.00 for well-watered landscapes. Table 1 contains general values for K_v for general types of landscape vegetation. Primary sources for values in Table 1 are listed in the table footnote.

Table 1. General vegetation factors, K_v, for general plant types for high density cover of the ground and full water supply (Irrigation Association (2011); ASCE (2016)).

Vegetation Category[1]	K_v
Trees	1.15
Shrubs	
—desert species	0.70
—non-desert	0.80
Groundcover	1.00
Annuals (flowers)	0.90
Mixture of trees, shrubs, and groundcover[2]	1.20
Cool season turfgrass[3]	0.90
Warm season turfgrass[4]	0.90

[1] The tree, shrub, and groundcover categories listed are for landscapes composed solely or predominantly of one of these vegetation types with somewhat dense coverage (shading) of the ground.

[2] Mixed plantings are composed of two or three vegetation types (i.e., where a single vegetation type does not dominate).

[3] Cool season grasses include Kentucky blue grass, fescues, and perennial ryegrass

[4] Warm season grasses include Bermuda grass, St. Augustine grass, buffalo grass, and blue grama
Primary sources of data include cool season turfgrass (Aronson et al. 1987; Brown et al. 2001); warm season turfgrass (Brown et al. 2001; Jia et al. 2009); other vegetation (Irrigation Association 2011). The K_v value for warm season grass is a maximum expected value under full water supply. In practice, K_L for grass is lowered by inducing some degree of stress so that K_{sm} in Eq. (2) and (3) is less than one, for example K_{sm} = 0.7.

The typical K_v values in Table 1 represent full effective ground cover where the fraction of the surface covered by vegetation, f_c, is greater than about 0.70 and for no water deficit conditions. The K_v values in Table 1 are general, assume that K_d = 1.00, and assume no ET reducing water stress, so K_{sm}=1.00. The K_v values apply for the full range of microclimate factor K_{mc}. The soil factor K_{sm} is less than 1.00 when the landscape is deficit irrigated (Brown et al. 2001; Jia et al. 2009). The K_v value for trees applies most readily to species adapted to abundant soil water, such as Populus and other riparian species, while many other tree species may fall closer to the K_v of shrubs. More information is given in Kjelgren et al., (2016) and in the WUCOLS literature cited earlier.

The K_v values for both cool season (CS) and warm season (WS) grasses are less than 1.00 in Table 1 due to the tendency for their mean height to be less than that of the standardized 0.12 m clipped grass reference. Differences in water use rates have been noted between cultivars of CS and WS grasses (Harivandi et al., 2009), so that values in Table 1 represent averages for typical cultivars. The K_v value for WS grass in Table 1 is equal to that for CS grass because both of these grass types tend to have similar $ET_v/ET_{o\ mc}$ when under conditions of no water stress (Brown et al., 2001; Smeal et al. 2005). Warm-season grasses utilize C4 photosynthesis mechanisms as compared to C3 mechanisms for cool-season grasses (Qi and Redmann 1993; Way et al., 2014). As a result, WS grasses tend to have more effective stomatal control and survive water stress better than CS grasses due to their physiology and superior drought avoidance and drought resistance mechanisms (Harivandi et al., 2009, Way et al., 2014). As a consequence, it is not necessary to irrigate WS grasses as much as CS grasses. Also, WS grasses are more heat tolerant, so they can warm more than CS grasses without adverse effects to photosynthesis or growth. However, if WS and

CS grasses are irrigated frequently, ET rates between CS and WS grasses will be comparable, but frequent irrigation is not necessarily a good practice.

Users are encouraged to manage irrigation of WS grasses where a managed stress factor of about 0.7 is targeted (Harivandi et al., 2009) so that, given K_d = 1.00 and K_{mc} = 1.00, the K_L from Eq. (2) is 0.90 (1.00) (0.70) (1.00) = 0.63. In other words, some level of stress can be applied to WS grasses with little visual effect, as is illustrated later in Table 3. The K_v value for WS grass is listed as 0.90 in Table 1 to provide for best accuracy when calculating ET_L in water balances for hydrology and water conservation studies, where K_{sm} may have a value of 1.00 during times of frequent rainfall and therefore a WS grass may transpire similarly to a CS grass during well-watered periods. Comparison of K_L for WS grasses from Eq. (2) and Tables 1–3 with measurements in a Florida application are presented in Fig. 4 that shows K_L for WS grass close to 0.60 during summer when water stress occurs. There is an increase in September due to rainfall.

K_v values for groundcover and annuals or flowers are assumed equal to 1.0, reflecting the likely K_v when the vegetation completely covers the ground and when no ET reducing stress occurs. Because of the hundreds, if not thousands, of species of flowers and groundcover types, estimating or establishing K_v values for each of these species is not feasible. Instead, a general expected upper limit for K_v is established and lower values are possible if specific information on a species is available.

Carrow (2004) suggested common target values for K_L for cool-season grasses range from 0.70 to 0.95 in the SE United States as compared with K_L for warm-season turfgrasses of 0.65 to 0.85 when the irrigation regime is 3 to 7+ days between events, which allows mild water stress during hot periods. Costello et al., (2000) and Harivandi et al. (2009) recommended 0.80 and 0.60 for CS and WS grasses in California where there is less rainfall and less dew deposition than in the SE United States. At these K_L values, turf generally maintains acceptable quality and growth. As K_L values fall below these general ranges using a similar irrigation schedule but with smaller doses per irrigation, turf performance and appearance may rapidly decline. Carrow (1995) reported turfgrass ET_L to be 40 to 60% less in a humid environment compared with the same cultivar in an arid environment, but with similar K_L values for both environments. The data of Carrow (1995, 1996) apply to K_L estimated from Eq. (2) and (3), rather than to values for the K_v factor in Table 1, which represent starting points in the K_L estimation process.

Density Factor

Landscapes can vary considerably in terms of vegetation density, with potential for variation in plant spacing, size, and maturity. Vegetation density is impacted by the collective leaf area of all plants in the unit landscape area and the structure of the leaf area. More densely growing vegetation with larger fraction of ground shaded by vegetation will have a greater K_d and will transpire and require more water. Immature and sparsely planted landscapes tend to have less total leaf area per unit landscape area than mature landscapes and have a lower value for K_d. Often, landscapes have two and three tiers (horizontal levels) of vegetation including turf or groundcover, shrubs, and trees. Overlapping tiers are capable of more radiative absorption and other energy exchange and tend to increase ET, as shown by the K_v value of 1.20 in Table 1 for the "mixture" class. The important factor is the fraction of the sunlight intercepted by plants and by the ground. By observation at different times of the day, one can estimate the fraction of direct sunlight reaching the ground, which represents 1 - $f_{c\ eff}$, where $f_{c\ eff}$ is the effective fraction of ground shaded by vegetation and is impacted by plant height and sun angle. The plant light interception is usually slightly more than the percentage of ground cover due to sun angle effects, so that the observed light interception can be used to estimate the K_d factor. If more than 80% of the sunlight onto the landscape is intercepted by the plants over the day, then one should expect the K_d factor to be close to 1.00 (Snyder et al. 1999; 2015, Kjelgren et al. 2016).

Initial estimates for the plant density factor, K_d, can be made using a direct relationship between K_d and the effective fraction of ground covered by vegetation, $f_{c\ eff}$, with some adjustment for vegetation height. $f_{c\ eff}$ and the approximated K_d both range from 0 to 1.00.

An estimate for K_d that considers the effects of vegetation height and shading uses a relationship by Allen and Pereira (2009):

$$K_d = \min\left[1, M_L\, f_{c\,eff}, f_{c\,eff}^{\left(\frac{1}{1+h}\right)}\right] \tag{4}$$

where $f_{c\ eff}$ is the effective fraction of ground covered or shaded by vegetation (0.01–1.00) near solar noon, M_L is a multiplier on $f_{c\ eff}$ describing the effect of canopy density and stomatal conductance on maximum, sustainable relative ET per fraction of ground shaded (1.50–2.00), and h is the mean height of the vegetation in m. Eq. (4) suggests that, as h increases, total leaf area and resulting net radiation will increase, for the same level of $f_{c\ eff}$, thereby increasing K_d and consequently, K_L. In addition, as h increases, there is more daily light interception and more opportunity for micro-advection of heat from soil to canopy, which increases turbulent exchange within the canopy for the same amount of ground coverage. Both increasing net radiation and turbulent exchange will increase the relative magnitude of K_L via the K_d factor. The $f_{c\ eff}$ parameter and h are relatively easy parameters to estimate. When two substantial tiers of vegetation are present, for example trees shading grass or flowers, the value for h can be approximated in proportion to the $f_{c\ eff}$ for each tier (Snyder and Eching, 2004, 2005; Costello et al. 2000). Eq. (4) is congruent with the Snyder-Eching (2005) definition and range for K_d, where K_d ranges from 0.00 to 1.00.

For canopies such as trees or randomly planted vegetation, $f_{c\ eff}$ can be estimated from Allen et al. (1998) as

$$f_{c\,eff} = \frac{f_c}{\sin(\beta)} \le 1 \tag{5}$$

where f_c is the fraction of ground shaded by vegetation from a view directly overhead of the vegetation, and β is the mean angle of the sun above the horizon during the period of maximum ET (generally between 11:00 and 15:00 hours). Generally, $f_{c\ eff}$ can be assigned to solar noon (1200 hours), so that β can be calculated as

$$\beta = \arcsin\left[\sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\right] \tag{6}$$

where ϕ is latitude and δ is solar declination defined in standard texts (Allen et al., 1998; ASCE 2005; ASCE 2016).

The M_L multiplier on $f_{c\ eff}$ in Eq. (4) imposes an upper limit on the relative, sustainable magnitude of transpiration per unit of ground area as represented by $f_{c\ eff}$ (Allen et al., 1998) and is expected to range from 1.5 to 2.0, depending on the canopy density, thickness, and maximum conductance. Parameter M_L is an attempt to simulate the physical limits imposed on water flux by the plant root, stem, and leaf systems (Allen and Pereira 2009). The value for M_L can be modified to fit the specific vegetation. Fig. 3 shows values for K_d by Eq. (4) over a range of $f_{c\ eff}$ and a range of h for M_L = 1.5 and for M_L = 2 when h = 5 m. The estimates agree with those previously suggested by Fereres (1981) and Hernandez-Suarez (1988) for orchards and for vegetables which represent two near extremes in typical plant height.

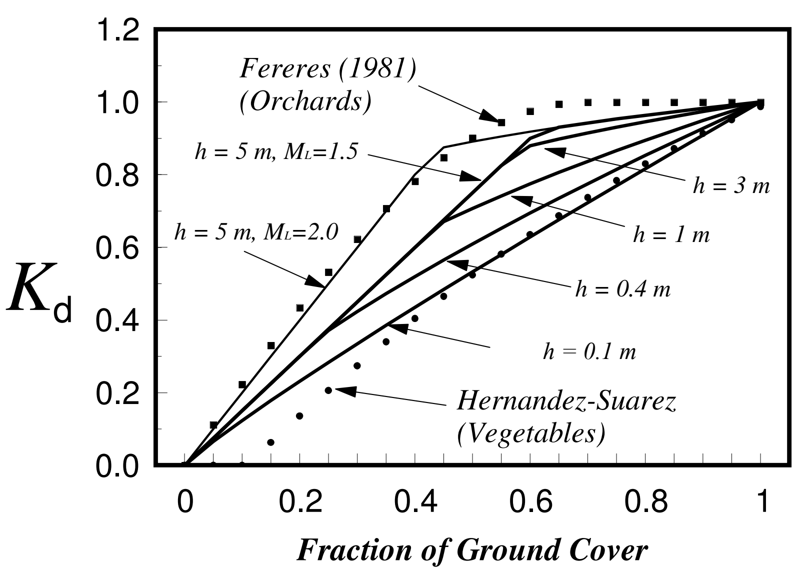

Figure 3. Density coefficient, K_d, estimated from Eq. (4) with M_L = 1.5 over a range of ground cover fractions and various plant heights and compared with estimates by Fereres (1981) for orchards and Hernandez-Suarez (1988) for vegetables. Source: Comparative data from Fereres (1981) and Hernandez-Suarez (1988).

When the mean stomatal control by landscape vegetation (i.e., stomatal resistance, r_l), particularly for freestanding and taller trees, is greater than that for agricultural vegetation which is often bred to maximize stomatal opening and biomass production, then FAO 56 (Allen et al., 1998) suggests that the estimate by Eq. (4) be reduced by about 10 or 20% for each doubling of r_l above 100 s m^{-1}.

Microclimate Factor

The microclimate factor, K_{mc}, accounts for impacts on ET by sun, external shading, protected areas, hot and cool areas, reflected and emitted radiation from structures, wind, and transfer of heat energy from low ET surroundings. Structures and paved areas, that are typical of urban landscapes, can have pronounced effect on the local energy balance due the transfer of energy for evaporation from these surfaces to local vegetation. The environmental conditions of a landscape can vary significantly across a landscape, for example, areas on the south side of a building vs. areas on the north side. Plantings adjacent to paved, open areas may have 50% greater ET demand (Costello et al., 2000) than similar plantings bordered by other vegetation due to the transfer of energy to the vegetation from the nonevaporating areas. However, for woody plants, this response depends on ventilation and stomatal behavior (Kjelgren and Montague, 1998). Conversely, plantings in areas shaded from sun and wind may have ET rates that are only one-half as high as those for open settings (Costello et al., 2000; Snyder et al., 2015). Another important factor is wind blockage by buildings and vegetation. Reference evapotranspiration weather stations are typically placed in well-exposed areas to measure wind speeds that represent the region. If the landscape is exposed to less wind due to shielding by buildings or vegetation, then the $ET_{o\,mc}$ (see earlier definition) may be less than ET_o. The LIMP program from Snyder and Eching (2004, 2005) and Snyder et al. (2015) provides a methodology to address these microclimate factors.

Values for K_{mc} are listed in Table 2 for general classes of vegetation. The "high" category ($K_{mc} > 1$) reflects harsh microclimate conditions such as planting in direct sunlight near paved or other non-vegetated surfaces, near reflective or heat-absorbing surfaces such as windows or buildings, or in exposed, windy conditions. The "low" category ($K_{mc} < 1.00$) represents environments where the plantings are shaded, shielded from wind, and are away from dry, hot surfaces. The average or medium category ($K_{mc} = 1.00$) represents reference conditions that are similar to open settings, e.g. parks, where conditions caused by buildings, pavement, shade, and reflection do not influence the ET by the landscape. The values given for K_{mc} are approximate, and local measurements can confirm or be used to derive local values. Values for K_{mc} can be interpolated between the high, average, and low classes and should be selected for each sector of a landscape.

Table 2. Microclimate factor, K_{mc}, for landscape plant types, after Irrigation Association (2003, 2011), Costello et al. (2000) and ASCE (2016).

Vegetation	High (hostile environment)	Average (reference condition)	Low (protected or shaded environment)
Trees	1.4	1.0	0.5
Shrubs	1.3	1.0	0.5
Groundcover, flowers	1.2	1.0	0.5
Mixture of trees, shrubs, and groundcover	1.4	1.0	0.5
Turfgrass	1.2	1.0	0.8

Source: Data from Irrigation Association (2003, 2011).

Managed Stress Factor

Typically, the objective of landscape irrigation is to promote appearance rather than biomass production, unlike agriculture where biomass is generally maximized. Therefore, target ET for landscapes can include an intentional and managed "stress" factor in the baseline value for ET_L, where landscape plants are watered less than they would be if they were irrigated like an agricultural crop. This management is done by adjusting irrigation water schedules to apply less water than the vegetation will potentially transpire.

The magnitude of the stress factor depends on physiological requirements and morphological characteristics of the plants and the desired or minimum acceptable appearance.

The managed stress factor, K_{sm}, represents the fraction of the full ET rate targeted to obtain the functional and visual characteristics of the landscape vegetation. Parameter K_{sm} has a range of 0.00 to 1.00, where 1.00 represents conditions of no water stress and 0.00 represents no plant transpiration and probable plant death or dormancy. High values for K_{sm} will sustain predominately lush, high leaf-area vegetation stands that tend to maximize ET. Low values for K_{sm} represent substantial managed plant water stress and reduction in ET, generally at the cost of biomass accumulation and potentially loss of pleasant visual effects (Richie and Pittenger 2000, Harivandi et al., 2009). Typical, approximate values for K_{sm} are presented in Table 3. Those values, when inserted into Eq. (2) with values for K_v from Table 1, produce values for K_L that are similar to those reported by Meyer and Gibeault (1986), Smeal et al. (2001), Carrow (2004), and Pittenger and Shaw (2007).

Table 3. Managed stress factors, K_{sm}, for general landscape plant types and the soil water depletion fraction (p) for no transpiration reducing stress

Vegetation Category	High stress	Average managed stress	Low stress	Depletion fraction, p, for no stress
Trees	0.4	0.6	0.8	0.6
Shrubs				
—desert species	0.3	0.4	0.6	0.6
—nondesert	0.4	0.6	0.8	0.6
Groundcover	0.3	0.5	0.8	0.5
Annuals (flowers)	0.5	0.7	0.8	0.4
Mixture of trees, shrubs, and groundcover[1]	0.4	0.6	0.8	0.6
Cool season turfgrass	0.7	0.8	0.9	0.4
Warm season turfgrass	0.6	0.7	0.8	0.5

[1]Mixed plantings are composed of two or three vegetation types and where a single vegetation type does not predominate.
Source: Data from Irrigation Association (2011).

Many landscape species exercise significant stomatal control over transpiration and can be forced toward lower levels of ET (Jarvis and McNaughton, 1986). For instance, the low range for K_{sm} for groundcover is 0.3 which may be appropriate for a select group of drought-tolerant groundcover species. This value may not be appropriate for some ornamental groundcovers that require more water (and less water stress) to maintain health and appearance. Also, dry air (high vapor pressure deficit) can impose evaporative stress on many woody species, resulting in stomatal closure (Choudhury and Monteith, 1986). One can consult local or regional sources to determine appropriate values for K_{sm}. Pittenger and Shaw (2007) suggest K_L for more than 30 groundcovers and shrubs grown in southern California that contain low K_{sm} components and thus provide good water conservation. Many of the vegetation types listed by Pittenger and Shaw are native desert vegetation types that tolerate water stress. Other sources of target K_L information for specific species that include a recommended K_{sm} include the WUCOLS publications by Costello and Jones (1999) and Costello et al. (2000) and ASABE S623 where the K_L includes an implied $K_{sm} < 1.0$. Costello and Jones (2014) and https://ucanr.edu/sites/UCLPIT/ provide categorized levels for K_L (low, medium, high) for a large number of landscape vegetation, where K_L includes an implied K_{sm}.

Management of landscape vegetation to implement a particular K_{sm} requires selection of a target depletion fraction prior to irrigation that produces the K_{sm}, on average. Typically, trees, shrubs, and groundcover managed for the high stress category are not irrigated, but rely on rainfall. In situations where irrigation is practiced, the irrigation interval must be sufficiently long to produce increasingly greater stress as soil water is depleted between irrigations so that the stress factor, averaged over the entire interval, equals the desired value for K_{sm}.

Computational derivation of K_{sm}.

Refined estimates for the K_{sm} parameter in Eq. (2) and (3) can be derived by employing a daily water balance of the rooting zone of vegetation where a daily stress coefficient, K_s, is defined as the ratio of actual ET to potential ET (ET_{pot}) for the vegetation, so that $ET_{act} = K_s\ ET_{pot}$, where ET_{pot} represents the maximum ET expected for landscape vegetation under non-water limiting conditions. $ET_{pot} = K_L\ ET_o$

from Eq. (2) and (3), when K_{sm} = 1.0. The refined estimates for K_{sm} are recommended for computer modeling of irrigation water management to meet target K_L and for developing recommended water schedules specific to individual landscapes.

A simple linear model for estimating K_{sm} described in FAO 33 (Doorenbos and Kassam 1979) is commonly used:

$$K_{sm} = \frac{\theta - \theta_{wp}}{\theta_t - \theta_{wp}} \quad \text{for } \theta < \theta_t \tag{7}$$

where θ is mean volumetric soil water in the root zone in m^3 m^{-3}, and θ_t is the threshold θ below which transpiration is decreased linearly due to water stress. K_{sm} = 1.00 for $\theta \geq \theta_t$. The wilting point, θ_{wp}, is the soil water at the lower limit of soil water extraction by plant roots in m^3 m^{-3}. The θ_t is estimated from the relationship:

$$\theta_t = (1 - p)(\theta_{fc} - \theta_{wp}) + \theta_{wp} \tag{8}$$

where *p* is the average fraction of available soil water that can be depleted before water stress and ET reduction occur. Variable *p* is similar to the management allowed depletion (MAD) term used by some approaches, although the value set for MAD can involve some water stress, if that is a desired outcome. MAD can also consider other factors such as salinity (Hunsaker et al. 2011). Variable θ_{fc} is the soil water content at field capacity or the drained limit of the soil in m^3 m^{-3}. Values for all θ parameters should represent averages over the effective root zone. Typical values of θ_{wp} and θ_{fc} are listed in standard texts such as Doorenbos and Pruitt (1977); Allen et al., (1998) and ASCE (2016) for various soil texture classes.

The parameter *p* normally ranges from 0.30 depletion of available soil water ($\theta_{fc} - \theta_{wp}$) for shallow-rooted plants or plants having low root density at high rates of ET_c (> 8 mm d^{-1}) to 0.70 for deep-rooted plants having high root density at low rates of ET_c (< 3 mm d^{-1}) (Raes et al. 2009; Appendix B). A value of 0.50 is commonly used for p for many agricultural crops.

An equivalent expression to Eq. (7) for daily calculation, but in terms of depletion, D_r, of available water in the root zone is, for $D_r > RAW$:

$$K_{sm} = \frac{TAW - D_r}{TAW - RAW} = \frac{TAW - D_r}{(1-p)TAW} \quad \text{for} \quad D_r > RAW \tag{9}$$

where TAW is the total depth of available soil water in the root zone in mm, RAW is the depth of readily available water in the root zone in mm, and p is the fraction of TAW that a crop can extract from the root zone without suffering water stress. When $D_r \leq RAW$, K_{sm} = 1.00. The total available water in the root zone is estimated as the difference between the water content at field capacity and wilting point:

$$\mathrm{TAW} = 1{,}000\ (\theta_{fc} - \theta_{wp})\ z_r \tag{10}$$

where z_r is the effective rooting depth in m. The 1,000 factor converts from m to mm. RAW is estimated as

$$RAW = p\,TAW \tag{11}$$

where RAW has the same units as TAW (mm).

A soil water balance for the root zone in terms of depletion is required to estimate daily D_r (Allen et al., 1998; 2005 and ASCE 2016):

$$D_{r,i} = D_{r,\mathrm{i\text{-}1}} - (P - \mathrm{RO})_i - I_i - CR_i + ET_{\mathrm{act},i} + DP_i \tag{12}$$

where $D_{r,i}$ is root zone depletion at the end of day i in mm; $D_{r,i-1}$ is root zone depletion at the end of the previous day, i-1, in mm; P_i is precipitation on day i in mm; RO_i is runoff from the soil surface on day i in mm; I_i is net irrigation depth on day i that infiltrates the soil in mm; CR_i is capillary rise from the groundwater table on day i in mm; $ET_{act,i}$ is actual ET on day i in mm; and DP_i is water loss out of the root zone by deep percolation on day i in mm.

Although soil water content might temporarily exceed field capacity following heavy rain or irrigation, in the previous equation, the total amount of water exceeding field capacity is assumed to be lost the same day via deep percolation, following any ET for that day. This permits the extraction of one day's ET from this excess before percolation. That assumption can be modified by delaying *DP* used in Eq. (12) for several days. The root zone depletion will gradually increase due to ET and deep percolation. In the absence of a wetting event, the root zone depletion will ultimately reach the value *TAW* that is defined from rooting depth, θ_{fc} and θ_{wp} from Eq. (10). At that moment, no water is left for ET, and K_{sm} becomes zero, from Eq. (9). Limits imposed on $D_{r,i}$ are consequently

$$0 \leq D_{r,i} \leq TAW \tag{13}$$

To initiate the water balance for the root zone, the initial depletion $D_{r,i-1}$ can be derived from measured soil water content by

$$D_{r,i-1} = 1{,}000\,(\theta_{fc} - \theta_{i-1})\, z_r \tag{14}$$

where θ_{i-1} is the average soil water content at the end of day *i*-1 for the effective root zone. The 1,000 factor converts from m to mm. Following heavy rain or irrigation, the user can assume that the root zone is near field capacity, i.e., $D_{r,i-1} \approx 0$. Daily precipitation in amounts less than about 0.2 ET_o is normally entirely evaporated and can generally be ignored in depletion calculations (in both the computation of $D_{r,i}$ and computation of $ET_{c\ act}$) (Allen et al., 1998; ASCE 2016). I_i is equivalent to the mean infiltrated irrigation depth expressed for the entire landscape surface. Runoff from the surface during precipitation can be estimated using standard procedures from hydrologic texts.

Capillary Rise (CR).

The amount of water transported upward by capillary rise from the water table to the root zone or soil surface depends on the soil type, the depth of the water table, and the wetness of the root zone. *CR* can normally be assumed to be zero when the water table is more than a few meters below the bottom of the root zone. Figures that can be used to estimate CR are available in the literature, for example, from Doorenbos and Pruitt (1977), Brutsaert (1982) and ASCE (2016).

Deep Percolation from the Root Zone (DP).

Following heavy rain or irrigation, the soil water content in the root zone may exceed field capacity. In application of Eq. (12), *DP* is assumed to occur within the same day of a wetting event, so that the depletion $D_{r,\,i}$ becomes zero. Therefore,

$$DP_i = (P_i - RO_i) + I_i - ET_{act,i} - D_{r\,,\,i-1} \tag{15}$$

where DP_i is limited to $DP_i \geq 0$. As long as the soil water content in the root zone is below field capacity (i.e., $D_{r,\,i} > 0$), the soil is assumed to not drain and $DP_i = 0$. If drainage from the root zone is expected to be delayed by a day or more following a large infiltration event, then daily DP_i in Eq. (15) can be estimated as

$$DP_i = max\{min[(P_i - RO_i) + I_i - ET_{act,i} - D_{r,i-1}, DR_i], 0\} \tag{16}$$

where DR_i is an expected maximum rate of drainage from the root zone on day *i*, with units for DR_i the same as *P* and *I*. Limiting $DP_{r,i}$ to DR_i has the effect of causing $DP_{r,i}$ in Eq. (16) to be negative for one or more days. Values for DR_i can be estimated from hydraulic conductivity characteristics for the root zone soil layer.

Calculation of average K_{sm}

The stress factor K_{sm} equals 1.0, for no ET reduction stress, for a period following irrigation (assuming that the irrigation depth was substantial) until the soil water depletion from the root zone exceeds *RAW*. Following that point in time, K_{sm} will progressively decrease until the next irrigation or precipitation event.

The K_{sm} just prior to the next event will be less than the K_{sm} used in Eq. (2), because K_{sm} in Eq. (2) represents the average K_{sm} over the entire interval or growing period.

Tables 4 and 5 list target values for management-allowed depletion fraction, *MAD*, at the time of irrigation to produce the desired average managed stress factor K_{sm} to be used in Eq. (2). The target values for *MAD* at the initiation of irrigation are a function of the depletion fraction, *p*, when the particular vegetation begins to experience stress. Tables 4 and 5 represent two different strategies for implementing water stress and thereby reducing K_{sm} to below 1.0. Table 4 assumes that irrigations are made as infrequently as possible, with subsequent complete refilling of the rootzone each irrigation. The complete refilling will result in a period following the irrigation event where there is no stress until the *p* depletion level is reached and then with progressively increasing stress as the root zone continues to be depleted. Following Table 4 will minimize evaporation from the soil surface by extending time between irrigation events, which is a commonly recommended practice (Harivandi et al., 2009). However, the plant appearance and performance may suffer since relatively extreme soil water depletion may be required prior to irrigation to obtain the average K_{sm} target value over the total period between irrigations. In some cases, the vegetation may enter into a temporary or permanent dormancy when *MAD* is set at high values.

Table 5, on the other hand, endeavors to establish a controlled, more continuously sustained level of water stress where soil water content is held within a range that is near a targeted soil water content that produces some water stress. This strategy can be implemented in an automated, soil-water-sensor-based irrigation system by applying frequent, small doses of water but with the trigger soil water level (MAD) set to a “dry” level. However, the percentage of water lost from evaporation from the soil surface increases as the irrigation frequency increases, especially when the irrigation doses are small and sprinkler irrigation is practiced. Therefore, evaporation of water from the soil surface, which is not nearly as effective in sustaining vegetation health and appearance as is transpiration through the plant system, will be greater with this second strategy and the degree of water conservation will likely be less than with the first strategy, where increasing irrigation doses and the time between irrigations is beneficial to overall water conservation.

Research is needed to evaluate the method that best sustains appearance and health of the landscape vegetation. Some vegetation types, such as turf grass, may benefit from application of the full-replenishment method, where the grass has the opportunity to periodically recover from stress and produce new growth and vigor that maximizes density and discourages weed growth. Sustained stress to turf, as under the approach of Table 5, may cause some degradation in turf health over time, with reduced turf density, increasing opportunities for weed invasion. Shrubs and trees are expected to exhibit different behaviors.

The values for *MAD* in Table 4 were derived by integrating Eq. (9) over a range in depletion, D_r, from 0 to *MAD,* that produced an average value for K_s equal to the targeted K_{sm}. Values in Table 5 were derived by integrating Eq. (9) over a range of $MAD - 0.1$ to $MAD + 0.1$ that produced an average value equal to K_{sm} and represents attempts to maintain root zone water at levels that continuously and consistently create some stress-based reduction to K_L. One can modify Tables 4 and 5 for specific vegetation types or species when information is available. The values for *MAD* in the tables exceed the values for p where stress is first initiated. More research is needed on assessing best methods to reduce landscape ET and yet retain acceptable or desirable plant health and appearance. Research is also needed to assess or confirm total ET requirements by the two strategies or by a mixture of strategies.

A review of Tables 4 and 5 shows the differences in the extent of *MAD* required to produce average, targeted values for K_{sm} between the two strategies. For example, for a p of 0.5 (indicating that water stress begins at a soil water depletion level of 50%), and a target K_{sm} of 0.8, Table 4 suggests that the *MAD* prior to full irrigation needs to be 0.83. This indicates that relatively severe stress needs to occur prior to irrigation to accomplish an average K_{sm} of 0.8. Depleting soil water to 0.83 of available water may be considered to be risky in that, by definition, a depletion of 1.0 will result in permanent wilting and generally plant death or dormancy.

In contrast, for the same $p = 0.5$ and $K_{sm} = 0.8$, Table 5 suggests that a targeted and sustained MAD = 0.58 prior to a lighter irrigation depth can achieve the same K_{sm}. Given the MAD – 0.1 to MAD + 0.1 range used to develop Table 5, the maximum MAD prior to irrigation for Table 5 would be 0.58 + 0.1 = 0.68. The MAD = 0.68 value represents about 0.15 less stress to the vegetation prior to irrigation as compared to the MAD = 0.83 from Table 4. However, it keeps the vegetation in a continuously stressed condition, which may or may not be desired. Given a rooting depth of 0.5 m and water holding capacity of 0.1 m/m, so that TAW = 0.5 x 0.1 = 0.05 m, the strategy of Table 4 would add TAW x MAD = 0.05 x 0.83 = 0.042 m (42 mm) of net water depth each irrigation. The strategy of Table 5 would add 0.05 x 0.2 = 0.01 m (10 mm) of water to the root zone each irrigation. As a result, the strategy of Table 5 would require at least four times as many irrigations, with associated evaporation losses from intercepted water on plant leaves and soil surface that would increase the overall ET consumption and reduce some of the benefits of the strategy.

Methods to estimate total ET that includes evaporation following wetting are described later in the section entitled Impact of Canopy Wetting and Irrigation Frequency on K_L. In general, increasing irrigation doses and the time between irrigations will reduce total ET consumption by reducing evaporation occurring after each irrigation event. This supports common recommendations to professional landscape irrigation managers and home gardeners to irrigate "deep and infrequently" (Qian and Fry 1996, McDonald 1999, Richie et al., 2002, Jordan et al., 2003, Lee 2014).

The +0.1 to -0.1 range used to derive Table 5 can be expanded to stretch irrigation events further apart.

The result will be targeted *MAD* levels that are closer to those of Table 4.

Table 4. Management-allowed depletion fraction, MAD, to produce the stated managed stress factor (K_{sm}), given the depletion fraction for no ET reducing stress (p) and assuming complete refilling of the root zone each irrigation (MAD is expressed as a decimal)

Managed stress factor, K_{sm}	Depletion fraction, *p*, for no ET reducing stress 0.3	0.4	0.5	0.6	0.7
1.00	0.30	0.40	0.50	0.60	0.70
0.95	0.47	0.57	0.66	0.75	0.86
0.90	0.55	0.65	0.73	0.81	0.88
0.85	0.62	0.71	0.79	0.86	—
0.80	0.68	0.76	0.83	0.89	—
0.75	0.74	0.80	0.87	—	—
0.70	0.78	0.84	0.89	—	—
0.65	0.82	0.88	—	—	—
0.60	0.86	0.90	—	—	—
0.55	0.90	—	—	—	—
0.50	__1	—	—	—	—

Note: — indicates that the value for *MAD* approaches or exceeds 1 so that the soil water content approaches or exceeds the permanent wilting point and the vegetation is, by definition, in danger of death or dormancy.
Source: Data from Irrigation Association (2003, 2011).

Table 5. Average management-allowed depletion fraction, MAD, to produce the stated managed stress factor (K_{sm}), given the depletion fraction for no ET reducing stress (p) and <u>assuming only partial refilling of the root zone each irrigation</u>, where the depletion between wetting events is managed to range from MAD – 0.1 to MAD + 0.1 (MAD is expressed as a decimal)

Managed stress factor, K_{sm}	Depletion fraction, *p*, for no stress 0.3	0.4	0.5	0.6	0.7
1.00	0.20	0.30	0.40	0.50	0.60
0.95	0.30	0.39	0.48	0.57	0.66
0.90	0.35	0.44	0.53	0.61	0.69
0.85	0.39	0.47	0.56	0.64	0.72
0.80	0.43	0.51	0.58	0.66	0.74
0.75	0.46	0.54	0.61	0.68	0.76
0.70	0.50	0.57	0.64	0.70	—
0.65	0.53	0.59	0.66	0.72	—
0.60	0.57	0.62	0.68	0.74	—
0.55	0.60	0.66	0.71	0.76	—
0.50	0.64	0.68	0.73	—	—
0.45	0.67	0.71	0.76	—	—
0.40	0.70	0.74	—	—	—
0.35	0.74	—	—	—	—

Note: — indicates that the value for *MAD* approaches or exceeds 1.00 so that the soil water content approaches or exceeds the permanent wilting point and the vegetation is, by definition, in danger of death or dormancy.
Source: Data from Irrigation Association (2003, 2011).

ACTUAL ET FROM LANDSCAPES

Equations (2) and (3) provide target estimates for K_L that can be used for planning and water management, where K_L can contain an explicit and intentional amount of managed stress for purposes of water conservation. The degree of implied managed stress is quantified in Eq. (2) by the K_{sm} term and provides a target K_L to accomplish the stress-induced reduction in ET. In practice, actual water management may result in a K_L where water stress is greater or less than the targeted managed stress. When conducting water balances for landscapes, determination of the actual water consumption is required. Under those situations, the managed stress coefficient K_{sm} in Eq. (2) or (3) needs to be replaced by an actual stress coefficient, K_s, where K_s is computed using Eq. (7) or (9) based on soil water depletion determined from a daily balance of root zone soil water, or is estimated from soil water measurments. Eq. (2) then takes the form

$$K_{L\,act} = K_v\, K_d\, K_s\, K_{mc} \tag{17}$$

where K_{sm} in Eq. (2) is replaced by an actual stress coefficient K_s and where $K_{L\,act}$ is the actual ET from the landscape under actual water availability. Eq. (3) that includes a separate estimate for evaporation from soil becomes

$$K_{Lact} = \big((1 - K_d)K_{soil} + K_v K_d K_s\big)K_{mc} \tag{18}$$

Actual ET from the landscape under actual watering conditions is

$$ET_{L\,act} = K_{L\,act}\, ET_o \tag{19}$$

K_s can be estimated from Eq. (7) or (9), where the depletion fraction p parameter, used to estimate *RAW*, is set to specific values determined for the species if these are available. Actual rates and timing of irrigation (I) and precipitation (P) are required. The effective depth of the root zone used to estimate *TAW* can be species or variety specific and therefore obtaining information specific to the variety is important.

Trees tend to develop lateral roots growing parallel to the surface of the soil. Factors affecting rooting depth, root density and spread of roots include soil texture and compaction, depth to a water table, fertility, and soil water content (Gilman 1990a) as well as extent and depth of mulching (Greenly and Rakow 1995). Some research has reported impacts of wetting amounts and frequency on rooting development, so that past irrigation history should be considered (Gilman 1990b). The vegetation coefficient K_v described in Table 1 represents the landscape K_L under a water supply that is sufficient to support full ET and having somewhat dense vegetation with near maximum ground cover and open environmental exposure.

The daily soil water balance required to calculate $K_{L\ act}$ with Eq. (17) or (18) can be scripted into software applications and even into future smart irrigation controllers that can make daily calculations for $K_{L\ act}$ and $ET_{L\ act}$ based on actual irrigation schedules and reported ET_o and P. Those estimates for $ET_{L\ act}$ can be compared with irrigation volumes or depths applied by the irrigation controllers to better inform water users on the operational performance of their watering systems.

Impact of Canopy Wetting and Irrigation Frequency on K_L

Wetting of landscape vegetation by irrigation or rainfall can substantially increase the potential ET from the landscape due to the combined influence of evaporation from exposed, wet soil and evaporation from water intercepted by vegetation during the wetting event, if by rainfall or sprinkler. The more frequent the wetting events, the greater the potential ET rate. Often, landscape irrigation is accomplished with automatic controllers that are easily set to irrigate frequently, even daily. Water that is intercepted and retained on the vegetation surfaces is freely evaporated during and following a wetting event, even if the underlying vegetation is experiencing some level of water stress and the soil is dry. Evaporation of intercepted water can occur even with nighttime irrigation, with evaporation from wet plant canopies and soil surface occurring the following day.

The impact of evaporation from exposed soil among vegetation when the density coefficient is $K_d < 1$

is accounted for using Eq. (3) and (18) with Figure 2, or when coupled with estimates for K_{soil} from a daily soil surface evaporation model such as provided in Allen et al. (1998) and ASCE (2016). Evaporation of intercepted water by plant canopies generally takes precedence over transpiration and evaporation from exposed soil, since intercepted water is a free water surface with little or no surface resistance. Generally, evaporation of intercepted water will raise the K_L to a maximum $K_{L\,max}$ that is limited by energy availability to convert liquid water to vapor. The potential increase in K_L from evaporation of intercepted water can be estimated as:

$$K_{Int} = \frac{S}{t_w ET_o} \tag{20}$$

where parameter S is the depth of intercepted water collecting on vegetation leaves from a precipitation or irrigation event in mm, and t_w is the time between wetting events in days. ET_o has units of mm d^{-1}. K_{Int} represents the additional amount of evaporation added to the normal landscape ET, in the form of a landscape coefficient component. An adjusted K_L that incorporates impacts of interception losses is calculated as:

$$K_L = K_{L\,Eq.2\ or\ 3} + K_{mc}\ \ min\left(K_d\, K_{Int}\ ,\ \left(K_{L\,max} - K_{L\,Eq.2\ or\ 3}\right)\right) \tag{21}$$

where $K_{L\,Eq.2\ or\ 3}$ represents the K_L estimated by Eq. (2) or (3) and $K_{L\,max}$ is the maximum limit imposed on K_L, estimated from Eq. (22). The K_d term accounts for only the vegetated portion of the surface having interception losses, with wetting of soil assumed to be accounted for in the K_{soil} factor of Eq. (3). The K_{mc} term increases or decreases the overall adjustment according to the local microclimate environment. Values for S are typically about 1 mm for trees and about 0.5 to 1 mm for turf (Hoffman et al. 1992; Breuer et al. 2003). These losses are relatively small compared to total ET_L when wetting events are relatively infrequent, but can become substantial when irrigation or precipitation intervals (t_w) are smaller than three or four days. For example, on an annual basis, these evaporative losses can be a significant factor in forest hydrology, ranging from 20% to 40% for conifer forests and 10% to 20% for hardwood forests (Zinke 1967). In the application of Eq. (21), the limits $K_L = K_v K_d K_{mc} K_{sm} \leq K_{L\,max}$ are applied. Eq. (21) can be similarly used to adjust the estimate for actual $K_{L\,act}$ in Eq. (17) or (18) for interception losses by substituting $K_{L\,act}$ for K_L in the right hand side of equation (21).

$K_{L\,max}$ used in Eq. (21) represents the maximum expected value for K_L following rain or irrigation, under conditions of either bare soil or some degree of vegetation cover. The value for $K_{L\,max}$ is governed by the amount of energy available for evaporation, and is generally greater than the energy converted to latent heat energy by a grass reference. Given energy availability constraints, and the definition of K_L as the ratio of ET_L to ET_o, the value for $K_{L\,max}$ is not generally expected to exceed 1.2 to 1.3. Following Allen et al. (1998), where the maximum K_L for the clipped grass reference basis is impacted by the height of the landscape vegetation and by average levels of wind speed and relative humidity:

$$K_{L\ \max} = 1.2 + [0.04\ (u_2 - 2) - 0.004\ (RH_{min})]\left(\frac{h}{3}\right)^{0.3} \tag{22}$$

where u_2 is average wind speed at 2 m during the month or period, RH_{min} is average daily minimum relative humidity during the month or period, h is the mean plant height (m) during the period of calculation. The 1.2 term in Eq. (22) is an expected landscape coefficient for tall, leafy vegetation, under moderate wind speed and RH, that has a wet leaf surface from intercepted irrigation or rain. The 1.2 value is similar to the crop coefficient value for crops used for tall agricultural crops such as alfalfa or maize (Allen et al., 1998) relative to the clipped grass reference. The estimate for $K_{L\,max}$ will increase under strong wind and/or low RH.

The min () argument in Eq. (21) limits the maximum value for K_L to K_{Lmax}. Eq. (21) is a good approximation for total K_L that considers leaf wetting by interception when Eq. (2) or (18) are used and where K_v includes averaged effects of evaporation from the soil surface. Using Eq. (21) with Eq. (3)

additionally includes impacts of evaporation from exposed soil that is influenced by wetting frequency.

The effect on K_L by evaporation of intercepted water from vegetation is illustrated in Table 6 where evaporation of intercepted water on vegetation from sprinklers and evaporation from wet soil in between plants are both considered. Eq. (21) is applied to a range of $K_vK_dK_{sm}K_{mc}$ using Eq. (3) under two levels of ET_o and for four irrigation intervals (1, 2, 3 and 7 days). Interception depth, S, was assumed to be 1 mm, K_{mc} = 1.0 and $K_{c\ max}$ = 1.2. Estimates for K_{soil} were taken from Fig. 2. The effect of evaporation of intercepted water on K_L is most pronounced for daily watering intervals and at lower values for K_d, impacting $K_vK_dK_{sm}K_{mc}$. Two entries are shown in Table 6 for $K_L = K_vK_dK_{sm}K_{mc} = 0.80$, where $K_d = 1.00$ and 0.8. These two values for K_d represent 1) full surface cover, as for turf grass, and 2) a landscape with approximately 20% exposed soil, for dense ornamentals, for example, and where K_v has a larger value than for turf. The effect of wet soil among vegetation without complete groundcover increased K_L slightly for a daily wetting frequency due to the high estimate for K_{soil}. Impacts of irrigation frequency, represented by t_w, are largest when the $K_vK_dK_{sm}K_{mc}$ is lowest, since there is more available energy for evaporating intercepted water and water from exposed soil. The impact of evaporation from soil is low when K_d is high, since transpiration dominates. The K_L estimated by Eq. (21) using Eq. (3) is similar under all wetting frequencies when $K_vK_dK_{sm}K_{mc}$ is high, for example equal to 1.1, since most available energy is already used by relatively high transpiration. The impact of irrigation frequency when increased from 7 days to 1 day was only 0.08 on K_L when the $K_vK_dK_{sm}K_{mc}$ was already 1.1.

TABLE 6. K_L Estimated from Eq. (21) using Eq. (3) for levels of $K_vK_dK_{sm}K_{mc}$; two levels of ET_o; and for irrigation intervals, t_w, of 1, 2, 3, and 7 days with K_{soil} from Fig. 2.

		ET_o = 4 mm d^{-1}				ET_o = 8 mm d^{-1}			
$K_vK_dK_{sm}K_{mc}$	t_w	1	2	3	7	1	2	3	7

	K_{soil}	1.1	0.9	0.7	0.35	0.85	0.8	0.55	0.3
	K_d	K_L				K_L			
1.1	1.00	1.20	1.20	1.18	1.14	1.20	1.16	1.14	1.12
1	1.00	1.20	1.13	1.08	1.04	1.13	1.06	1.04	1.02
0.8	1.00	1.05	0.93	0.88	0.84	0.93	0.86	0.84	0.82
	0.80	1.06	0.92	0.85	0.74	0.91	0.80	0.76	0.69
0.6	0.60	0.95	0.80	0.69	0.52	0.78	0.62	0.57	0.45
0.4	0.50	0.88	0.71	0.59	0.39	0.69	0.51	0.45	0.31

Note: For interception depth S = 1 mm and $K_{c\ max}$ = 1.2. K_{soil} was selected from the top graph of Fig. 2 using ET_O and t_w. t_w has units of days.

Example on applying Table 6 for Water Conservation in Turf

As an example of impacts of wetting frequency that considers both plant interception losses and soil water evaporation, Eq. 3 estimates daily watering to increase K_L to 1.05 as compared with K_L = 0.88 for watering every 3 days and K_L = 0.84 for weekly watering for typical turfgrass under moderately low ET_o = 4 mm d^{-1} and where K_d = 1.0 and K_{mc} = 1.0 and K_{sm} = 0.9 (mild imposed stress). In this case, $K_v K_d K_{sm} K_{mc}$ ~ 0.8, with K_L from Eq. (21) using $K_{L\ eq.\ 2\ or\ 3}$. This suggests a 25% increase in water consumption under these conditions when watering frequency is increased from weekly to daily. When ET_o is increased to 8 mm d^{-1}, the K_L increases from 0.82 to 0.93, or 13%, when shifting from weekly irrigation to daily irrigation. This is a smaller percentage increase than for ET_o = 4 mm d^{-1} because the amount of daily interception (1 mm) becomes smaller compared with the greater total daily ET rate.

The example values in Table 6 support increasing intervals between watering events to conserve water. However, one needs to recognize constraints on long time intervals between watering events imposed by maximum water dosage rates to limit surface runoff on low intake soils. In addition, such practices on lighter, fast draining soils can lead to percolation below the root zones of shallow rooted plants. Use of information from Table 6, with important constraints under certain soil and rooting conditions, should provide useful information for end-users and water managers.

Estimates of K_L during Wintertime and Nongrowing Seasons

Estimation of ET during winter or nongrowing periods can be important for annual water balances used in hydrologic studies and for estimation of accruals to soil water from precipitation during a nongrowing season. Nongrowing periods are defined as periods during which the landscape is dormant due to very cold or freezing conditions and most vegetation senesces to dead material, and deciduous trees drop leaves. In temperate climates, nongrowing periods include periods of frost and may represent continuously frozen conditions.

Types of Surface Conditions during Nongrowing Periods

The type and condition of the landscape surface during nongrowing periods dictate the range for ET_L. When the surface is bare soil, then K_L will be similar to the K_{soil} estimated from Fig. 2 or using Eq. (10-18) of ASCE (2016). When dead or dormant vegetation or some type of organic mulch or plant residue covers the surface evaporation rates generally decrease, and K_L will be lower than K_{soil}. When active weed growth or "volunteer" plants cover the surface, K_L will vary according to the leaf area or fraction of ground covered by the vegetation and by the vegetation vigor. In this case, K_L can be estimated by Eq. (3) using K_d from Eq. (4), and by the availability of soil water. When the surface is snow covered or frozen, then K_L is difficult to estimate and a low, constant value for ET_L may have to be assumed. Additional recommendations and estimating procedures are given in Chapter 10 of ASCE (2016).

Bare Soil.

The frequency and amount of precipitation will strongly influence K_L when the ground is mostly bare following harvest or other removal of vegetation, and K_L can be calculated as $K_L = K_{soil}$ using Fig. 2 or using Eqs. (10-18) of ASCE (2016). The K_L varies with frequency of wetting events and magnitude of

ET_o. Martin and Gilley (1993) and Allen et al. (1998) have recommended this approach, and Snyder and Eching (2005) used a similar approach in the LIMP software to estimate a K_L during winter that was then melded with a K_L curve for the growing season. Where a daily soil water balance is applied, the user may elect to apply the dual or basal K_{cb} approach (Allen et al., 1998; ASCE 2016). During long dormant periods with little or no precipitation, the topsoil layer may dry to very low water contents. This provides the opportunity for $ET_L = 0$ during long periods of no rainfall.

Surface Covered with Dead Vegetation.

Dead plant residue and mulches reduce soil evaporation by providing a mechanical barrier to aerodynamic forces and shielding the soil surface from solar radiation. Mulches also reduce the connection between liquid or vapor in the soil and the air above (Burt et al. 2005). When the ground surface has a plant residue or other dead organic mulch cover, or where part of the unharvested crop remains suspended above the surface in a dead or senesced condition, then the surface will respond similarly to a surface covered by mulch. In this case, K_L can be set equal to K_{soil} as estimated from Fig. 2 or from Eq. (10-18) of ASCE (2016) with the value for K_{soil} reduced by about 5% for each 10% of soil surface that is effectively covered by organic mulch (Allen et al. 1998). Evaporation from dead, but wet, vegetation can be substantial for a few days following a precipitation event.

Surface Covered with Live Vegetation.

During frost-free periods following death or dormancy of landscape vegetation, weeds may germinate and grow. This vegetation extracts water from storage within the soil profile and from any rainfall. In addition, flower or garden seed lost during harvest may germinate following rainfall events and will add to the ground cover. The amount of ground surface covered by vegetation will depend on the severity of weed infestation, the density of the volunteer vegetation, the frequency and extent of soil tillage, the availability of soil water or rain, and any damage by frost. The value for K_v during the nongrowing period is estimated over time according to the amount of vegetation covering the surface using Eqs. (4) to (6) or from remote-sensing images by way of a vegetation index (Neale et al., 2005; Glenn et al., 2010).

The K_L for vegetation during the nongrowing period is limited by the amount of soil water available to supply evapotranspiration to satisfy the law of conservation of mass. Under all conditions, the integration of K_L ET_o over the course of the nongrowing period cannot exceed the sum of precipitation occurring during the period plus any residual soil water in the root zone at the end of the growing season that can be subsequently depleted by the vegetation plus any upward flow from a shallow saturated system. The root zone in this case is the root zone for the weeds or volunteer vegetation. A daily soil water balance may provide the best estimate of soil water–induced stress and associated reductions in K_L and ET_L.

*Frozen or Snow-Covered Surfaces***.**

When the ground surface is snow covered or frozen, any vegetation will be largely unresponsive and will not contribute directly to ET_L. In this situation, ET_L is closely related to the availability of free water at the surface and to the albedo of the surface. The albedo of snow-covered surfaces can range from 0.40 for old, dirty snow cover to 0.90 for fresh, dry snow (ASCE 2016). Therefore, the ET_L for snow cover will be less than ET_o, as 25-85% less shortwave energy is available. In addition, some energy must be used to melt the snow before evaporation, besides energy consumed in producing melted liquid that seeps into the snowpack.

Wright (1993), as summarized in ASCE (2016), measured ET_{act} averaging 1 mm d^{-1} over nongrowing season periods at Kimberly, Idaho, that were six months long (1 October to 30 March). The latitude of Kimberly is 42°N, and the elevation is about 1,200 m. Over the six-year study period, the ground was at least 50% covered by snow for 25% of the time from 1 October to 30 March. The ground, when exposed, was frozen about 50% of the time. The K_c averaged 0.25 during periods when the soil was not frozen but where frosts occurred (October and early November). When the ground had 50% or greater snow cover,

ET_c averaged only 0.4 mm d^{-1}. Wright found that over the six-month nongrowing period, total cumulative ET_c exceeded precipitation by about 50 mm, indicating a drying soil.

THE ASABE S623 PROCEDURE

The IA decoupling procedure outlined above is a useful engineering framework for aggregated landscape water requirement estimates. In 2015, ASABE published the ANSI standard S623 "Determining Landscape Plant Water Requirements" which is a simplified procedure to estimate net plant water requirements for established landscape materials. S623 was developed by industry and academic experts and is applicable to peak growing season requirements for several broad plant types well established in the landscape. ASABE recognized the need for a broad summary of coefficients (e.g. K_L) readily useable by diverse landscape practitioners. The standard recommends plant factors (*PF*; equivalent to K_v) for turfgrasses, herbaceous perennials, annual flowers, woody plants, and desert plants as shown in Table 7 with the aim for the minimum water requirement needed to maintain acceptable landscape appearance and function.

In particular S623 serve the landscapes design community, water management agencies planning and enforcing conservation programs, and those managing landscapes with a simple and practical tool to estimate water requirements of landscapes with mixed turf and non turf plant types. As such, a landscape is portioned into hydrozones (Kjelgren et al., 2016) based on the design and controlled by a single solenoid valve connected to a time clock. The *PF* for a hydrozone is dictated by the plant type with the highest water requirements (Davis and Dukes, 2010). For example, a woody plant imbedded in a turfgrass hydrozone would be irrigated using a warm or cool season *PF*. Water requirement of the total landscape is an aggregate *PF* weighted by hydrozone area.

The S623 turf and perennial/ground cover *PF*s are functionally similar to the IA K_v values in Table 1 apart from warm season turf being somewhat lower, due its inherently more efficient C4 photosynthesis (Romero and Dukes, 2016). The greatest difference is in the woody PF values. Currently there isn't enough data, nor industry ability in practice, to separate water use and PF for trees from shrubs, but the literature does support distinguishing woody species based on stomatal response to dry air. Freestanding, well ventilated woody species typical of most landscapes have stomates closely coupled, and sensitive, to dry air (Jarvis and McNaughton, 1986). Increased crown ventilation means that woody plant stomates must exercise more direct control over transpiration than low, dense canopies (Goldberg and Bernhofer, 2008), and in high VPD environments plants partially close stomates to moderate transpiration (Choudhury and Monteith, 1986). High VPD environments are common in semi-arid to arid regions, such as much of the U.S. West, and hence PF values are lower for woody landscape species in those regions. Similarly, PF values for desert species are lower because they can meet landscape appearance and performance expectations through their evolutionary adaptation to limited water by uncoupling water use from the atmospheric factors that drive ET_o. For example, cacti with crassulacean acid metabolism species (Kluge and Ting, 2012) transpire at night, and other desert species transpire freely after rainfall, but tolerate high ET_o conditions through partial stomatal closure, desiccation tolerant leaves and deep-root water extraction.

The S623 equivalent to Eq. 2 is expressed as:

$$K_L = PF\ K_d \tag{23}$$

where K_{sm} and K_{mc} coefficients are factored into the PF value and K_d equals 1.0 when the fraction of ground cover, f_c, exceeds 0.80 (Kjelgren et al., 2016). Similar, but expanded values for PF for use in California have been proposed by the University of California (2020) via the SLIDE calculator (https://ucanr.edu/sites/UrbanHort/Water_Use_of_Turfgrass_and_Landscape_Plant_Materials/SLIDE__Simplified_Irrigation_Demand_Estimation/). The University of California values were adopted from S623 and Kjelgren et al. (2016) where the latter article provided an extensive list of values for PF for trees, shrubs, and other ground covers.

The ASABE S623 and IA procedures are complementary. Both utilize a vegetation type and density system as the basis for efficiently estimating scientifically accurate landscape water requirements. S623 *PF*s do not directly compare to the K_L values presented in Kjelgren et al. (2016) Table 6 because they depend on the mixture of plant types in a landscape. However, they do functionally align when K_L is between 0.80 for all turf landscapes, and for mixed woody plant-turf landscapes in a humid climate. A K_L of 0.6 aligns with water requirements of a mixed turf-woody landscape when estimated in an arid climate. In both cases, the lower K_L values have some degree of soil water stress explicitly addressed in the IA procedure as opposed to implicit stress in the S623 PF's.

Table 7. Annual average fraction of ET_o (i.e., K_L) from ASABE S623 for acceptable plant appearance.

Plant Type	Recommended Plant Factor
Turf, cool season	0.8
Turf, warm season	0.6
Annual flowers	0.8
Woody plants and herbaceous perennials, wet [1)]	0.7
Woody plants and herbaceous perennials, dry	0.5
Desert plants	0.3
[1)] Tropical plants: for tropical plants with precipitation the majority of months, a plant factor of 0.7 applies. Where monsoonal climates are present, 0.7 applies for the wet season, and 0.5 during the dry season.	

USE OF HIGH RESOLUTION AERIAL REMOTE SENSING DATA TO ESTIMATE K_L

The use of high resolution aerial remote sensing data can assist in K_v estimation, where K_v or K_L is approximated from vegetation indices that indicate the amount of vegetation present in a landscape. A common vegetation index is the normalized difference vegetation index (NDVI) that calculates a normalized difference between the red and near infrared reflectance from a surface.

Currently, a relatively high-resolution (1 m) aerial data set that covers the US and that is free of charge to use is the North American Imaging Program (NAIP) data set (https://www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-programs/naip-imagery/). The NAIP imagery is collected approximately every three years across the US during midsummer. A weakness of the NAIP data set is that it represents only a single snapshot of vegetation amount. A strength is that imagery collected during midsummer can be a good representative sample of landscapes. Another strength of NAIP is that the red and near infrared (NIR) bands can be used to calculate the NDVI. A requirement for its use, however, is that NAIP data, which is reported as 8-bit digital numbers that are scaled differently between the red and NIR bands must be calibrated into equivalent surface reflectances prior to computing NDVI so that NDVI values are consistent among the 6 km x 6 km NAIP scenes and can be related to values for K_L.

Kilic et al. (2017) developed a procedure for converting NAIP digital numbers (DN) to surface reflectance by calibrating against surface reflectance derived from Landsat and Sentinel 2 satellites. The surface reflectance was then used to estimate NDVI at 1 m scale for residential areas and to classify NAIP images into turf, trees, shadows, and impervious areas. The NDVI estimates were used to estimate K_L by a linear equation (http://appgearup.appspot.com/). Multiplication of K_L by ET_o produced maps of water consumption at the 1 m scale. An example of an aerial image and resulting map of landscape water consumption is shown in Figure 4.

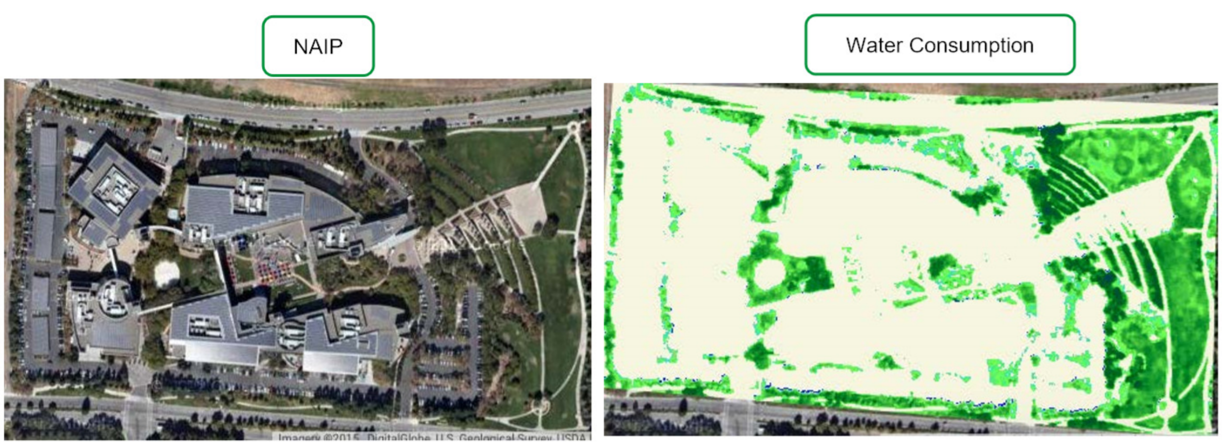

Figure 4. Areal photograph of the Googleplex building suite in Mountain View California (left) and a map of estimated water consumption (right) determined by the GEARUP application from calibrated NAIP imagery.

The GEARUP application, which operates on the Google Earth Engine, utilizes maps of water consumption to provide information to homeowners on managing residential water scheduling (Kilic et al., 2017).

COMPARISON OF DECOUPLED K_L TO EXPERIMENTAL DATA

The following comparisons provide examples of using Eq. (2) and (3) to reproduce measurements of K_L from landscape experiments. Values for K_v are taken from Table 1, and K_d and K_{mc} are set to 1.0 representing full cover conditions and an assumed neutral microclimate. The stress coefficient K_{sm} of Eq. (2) is set to a value that approximately reproduces the measured K_L.= 0.90. As a first example, Brown et al. (2001) reported K_L for Tiffany bermudagrass, a warm-season grass, in Tucson, Arizona, with daily to three-day watering ranging from 0.78 during high ET_o periods (June and July) to 0.83 during low ET_o periods (September). Using a K_v = 0.90 for warm-season grass from Table 1, K_d = 1 and K_{mc} = 1 and mild stress so that K_{sm} = 0.90, the estimated K_L from Eq. (2) = $K_vK_dK_{sm}K_{mc} \approx 0.80$, which reproduces the experimental data. Using Eq. (21) or Table 6 to add effects of evaporation from soil, the K_L associated with these values for a three-day wetting frequency is 0.84 during high ET_o periods (ET_o = 8 mm d^{-1}) and 0.88 under low ET_o periods (ET_o = 4 mm d^{-1}). These values are about 10% greater than reported by Brown et al (2001). The twice-weekly mowing height reported by Brown et al. (2001) was 22 to 25 mm, which is relatively short and may explain the differences between K_L estimated by Eq. (21) and reported K_L. If no water stress is assumed in the Brown, then K_{sm} = 1.0 and $K_{Lo} = K_vK_dK_{sm}K_{mc} \approx 0.9$, and, from Eq. (24) or Table 7 (interpolated), for daily watering, K_L = 0.96 under ET_o = 4 mm $d^{-1}$and K_L = 0.93 under ET_o = 8 mm d^{-1}. These values are about 15% greater than reported by Brown et al. (2001) and may be due to the short and frequent cutting heights in their study. Brown et al. (2001) reported K_L values for bermudagrass from the literature ranging from 0.57 to 0.83. These values include some amount of managed water stress.

Brown et al. (2001) reported K_L for Froghair intermediate ryegrass, a cool-season grass, over-seeded into bermudagrass in Tucson, Arizona, ranging from 0.85 to 0.90 during high ET_o periods (May and June) to 0.78 to 0.82 during low ET_o periods with short day lengths (December to February). Those values can be approximately reproduced using K_v = 0.90 for cool-season grass from Table 1, K_d = 1.00 and K_{mc} = 1.00 and mild stress K_{sm} = 0.90, and 3 day watering interval. The resulting K_L estimated from Eq. (21) or Table 6 during high ET_o periods is ~ 0.84 where ET_o = 8 mm d^{-1} and 0.88 under low ET_o periods where ET_o = 4 mm d^{-1}. These values are about 5% lower than reported by Brown et al for the high ET_o periods and about 10% greater than by Brown et al. for the low ET_o periods. Brown et al. (2001) reported K_L values for cool-season turf grasses from the literature ranging from 0.60 to 1.04.

Figs. 4 and 5 compare monthly K_L for warm season grasses and cool season grasses derived using Eq. (3) and Tables 1–3 with measurements by eddy covariance from Florida (Jia et al., 2007) and by time domain reflectometry measurements of soil water in Georgia (Carrow 1995). The K_L values reported for the warm season Bahiagrass measured by Jia et al., (2007) include some water-stressed time periods, as do those by Carrow, where both wet and stressed periods are included in the two-year data sets. Eq. (3) with K_v = 0.90 for both warm and cool season grasses from Table 1 for the growing season, and with K_d =1.00, K_{mc} = 1.00, and K_{sm} = 0.80 for warm season and K_{sm} = 0.90 for cool season curves produces K_L of 0.72 for warm season grass and 0.81 for cool season grass. The K_{sm} = 0.80 and K_{sm} = 0.90 are recommended for low amounts of stress, on average, for the two grass types. A value of K_{soil} = 0.20 was used during the offseason, with K_d = 0.0, to reflect background evaporation from dormant turf. It was assumed that no over-seeding of cool season grass occurred during winter.

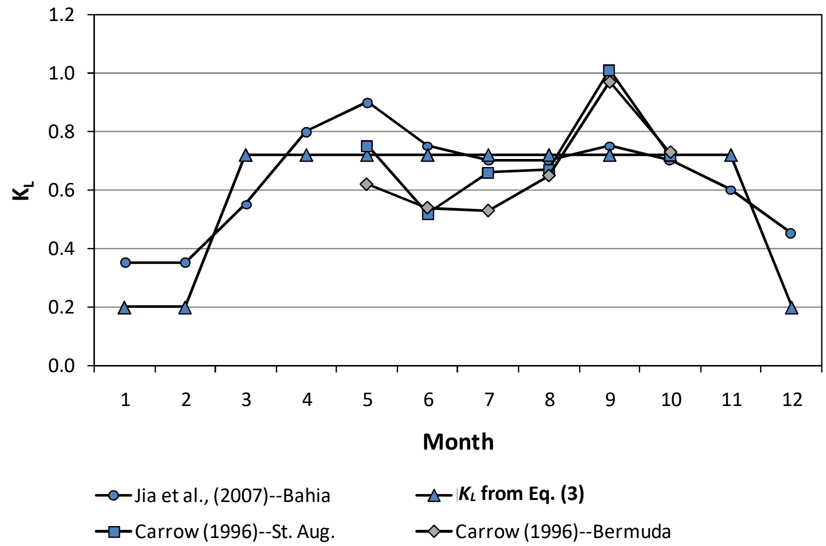

Figure 4. Measured monthly K_L for Bahia grass in Florida by Jia et al. (2009) and for St. Augustine and Bermuda grasses in Georgia by Carrow (1996) compared with a steady target K_L from Eq. (3) and Tables 1-3 for a warm-season grass. Source: Data from Jia et al. (2009) and Carrow (1995, 1996).

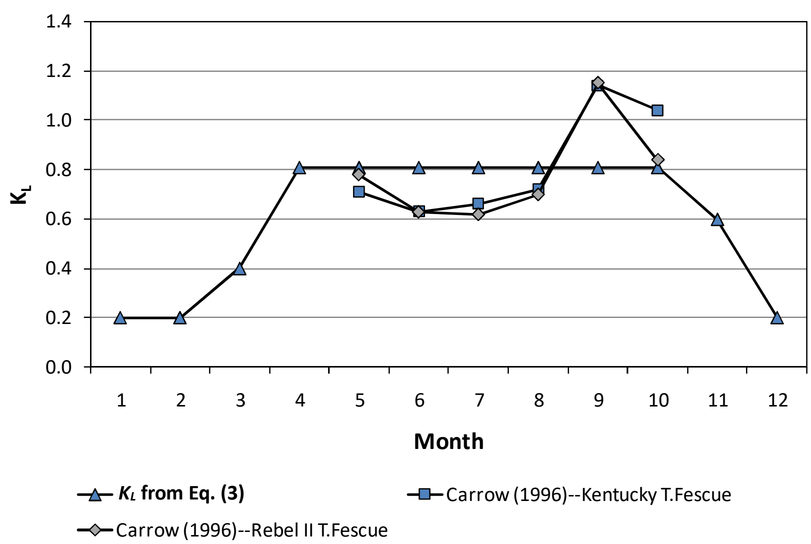

Figure 5. Measured monthly K_L for two types of Tall Fescue grass in Georgia by Carrow (1996) compared with a steady target K_L from Eq. (3) and Tables 1-3 for a cool-season grass. Source: Data from Carrow (1995, 1996).

Estimated K_L compares favorably with measured K_L, that includes periods of both stress and no stress. The K_L curve measured for Bahiagrass in central Florida is greater than the straight-line "target" curve during April and May when the climate was generally wet and then steadily follows the target curve during June-September when some stress occurred due to longer times between wetting events (Jia et al. 2007). The data of Carrow (1995) fall below the target curve during June-August when substantial stress occurred and rise above the target curve during the wetter period of September. The trends observed by Carrow (1995) for cool season tall fescue grasses are similar for the same reasons. On average, the observed data follow the steady target K_L values within uncertainties common to water measurement and management and variation in weather.

CONCLUSIONS

The multi-component decoupling method, $K_L = K_v K_d K_{sm} K_{mc}$, for the landscape coefficient accounts for variation in vegetation type, density, local climate, and soil water management. The method can help to accomplish objectives for water management of landscapes that are increasingly targeted toward water conservation, but, at the same time, retaining general greenness and health. The multi-component method is somewhat complicated in order to estimate water requirements of landscapes that can be highly variable. However, the methodology can be programmed into software applications where component coefficients are selected from tables or are computed from other parameters. The upper bounds of 1.00 for the modifying coefficients K_d, K_{mc} and K_{sm} simplify their estimation and reduce uncertainties. Each coefficient can be estimated using readily observable descriptions of a landscaped area, coupled with management objectives. The incorporation of evaporation from soil and intercepted water on foliage in Eq. (3) and (21) provide an opportunity to assess the effects of wetting frequency on total water consumption. Effects of soil wetting diminish as vegetation density increases and relative effects of interception from frequent irrigation reduce as the reference ET rate increases.

Target K_L estimates are useful for planning and for recommending guidelines for water conservation programs. Actual K_L estimates are useful for assessing results of actual water management practices and for use in hydrologically-based water balances. The ASABE S623 procedure for estimating recommended target water requirements represents a more simplified and reduced form from the multi-component IA procedure and is complementary to that procedure.

ACKNOWLEDGEMENTS

Substantial first efforts at formulating a multi-component procedure were by the WUCOLS program of California. These efforts pointed the way to evolving the IA method described here. The authors acknowledge funding support by the Idaho Agricultural Experiment Station, University of Florida Institute of Agricultural Sciences, Utah Agricultural Experiment Station, University of California Cooperative Extension, and Nebraska Agricultural Experiment Station and guidance support by the Irrigation Association and by the American Society of Agricultural and Biological Engineers and American Society of Civil Engineers. Valuable recommendations by the anonymous reviewers are also acknowledged and appreciated.

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