occurs in the first few days after the soil is wetted. Hill et al. (1983) and Martin and Gilley (1993) caution that t must be limited for each wetting event so that total evaporation estimated over the t_d period is constrained by the depth of precipitation or irrigation. Daily precipitation totals that are less than about 0.3 ET_o can be ignored.

General Model for K_e A general model for K_e for estimating the evaporation from the surface layer of soil after rain or irrigation was introduced in FAO-56 (Allen et al. 1998) for use with the basal crop coefficient:

$$K_e = K_r(K_{c\,\max} - K_s K_{cb}) \quad \text{such that} \quad K_e \le f_{ew} K_{c\,\max} \tag{9-19}$$

where K_e is the soil evaporation coefficient, K_{cb} is the basal crop coefficient, $K_{c\,max}$ is the maximum value of K_c following rain or irrigation, K_s is a reduction coefficient to account for reduced transpiration under soil water shortage, K_r is a dimensionless evaporation reduction coefficient (0–1), and K_s is a dimensionless soil water stress factor (0–1). K_r can be expressed as a function of time [i.e., Eq. (9-18)] or in the FAO-56 dual K_c approach as a function of the cumulative depth of water depleted by evaporation from the soil. Parameter f_{ew} is the fraction of soil surface from which most of the evaporation occurs, which is generally taken as the fraction of soil surface that is both exposed to drying and is wetted during the wetting event. The FAO-56 application of Eq. (9-19) is intended to overcome problems that occur with Eq. (9-18) regarding the value for t during small wetting events. Its use of cumulative depth of evaporation to estimate K_r tends to stretch out drying periods when ET_{ref} is low and shorten them when ET_{ref} is high. A daily water balance of the effective surface evaporation layer is required. In Eq. (9-19), transpiration is preferred over evaporation from soil (i.e., $K_s K_{cb}$ is subtracted from $K_{c\,max}$ before calculating K_e). In some ET models, such as that by Ritchie (1972), evaporation from soil has priority over transpiration. $K_s\,K_{cb}$ is set to 0 when Eq. (9-19) is applied to completely bare soil.

In contrast to the SRT model where cumulative evaporation from bare soil is proportional to the increase in $\sqrt{t}$ after stage 2 evaporation begins (Philip 1957; Black et al. 1969; Ritchie 1971, 1972), the FAO-56 method uses a water balance of an effective evaporation layer to estimate the decreasing evaporation rate. The effective layer is typically the upper 0.1 to 0.15 m during the first three to four weeks of evaporation, potentially increasing to 0.20 to 0.25 m depth for longer time periods. For maximum accuracy, estimates of the upward flux of water into this layer from below may be required, especially for medium and fine-textured soils (Ventura et al. 2001). However, estimation of upward flux may require relatively complicated models and specific parameterization or soil hydraulic and thermal characteristics. Cahill and Parlange (1998, 2000) and Grifoll et al. (2005) apply sophisticated evaporation models that account for convective transport in both the gas and liquid water phases in addition to vapor dispersion and liquid sensible heat dispersion. Cahill and Parlange (1998, 2000) conclude that models and approaches for describing coupled heat and moisture transport in soils are able to explain most, but not all, measured changes in soil water profiles and flux rates. As demonstrated in the next subsection, for practical applications, a fixed potential depth of water depletion per drying event can generally be determined from field observation for specific soils and the decreasing evaporation rate estimated using the relatively simplified FAO-56 procedure. In the absence of field data, the total evaporable water can be estimated using an effective depth of the evaporation layer. Comparisons against simulations by the HYDRUS-1D one-dimensional finite element model shown in a later section tend to confirm this.

The FAO-56 Evaporation Model

The FAO-56 (Allen et al. 1998) evaporation procedure calculates a water balance for the effective evaporation layer of soil that tends to be approximately 0.1 to 0.15 m in depth. The method represents a compromise between complexity and general application by assuming that upward flux of water or vapor to the layer from below is considered negligible or that its effects are incorporated into the effective depth of the evaporating layer that dries to a threshold dryness point. In the case of the FAO procedure, the threshold point is taken as the mean soil water content halfway between air-dry and wilting point. This is an arbitrary dry point, but one that is relatively straightforward for field application and is reproducible. The maximum depletion depth for the layer provides a consistent stopping point for the evaporation cycle to ensure conservation of mass and can be customized for each application to fit observations.

The FAO procedure assumes that evaporation takes place in two stages following Ritchie (1971): the energy limiting stage 1 and the falling rate stage 2. When the soil is wet (in stage 1), the evaporation reduction coefficient, K_r, in Eq. (9-19) is assumed to be 1.0. When the water content in the effective evaporation layer begins to limit evaporation (in stage 2), K_r decreases to below 1.0. The value for K_r is set to zero when the total amount of water in the effective evaporation layer is depleted during the drying cycle. Assuming that the soil is at field capacity (θ_{fc}) shortly after rainfall or irrigation and that it can dry to halfway between 0 and the wilting point (θ_{wp}), the total amount of water that can be depleted by evaporation (TEW) from the effective evaporation layer during a drying cycle is estimated as

$$TEW = 1,000(\theta_{fc} - 0.5\theta_{wp})z_e \tag{9-20a}$$

where TEW is the total evaporable water in mm, θ_{fc} and θ_{wp} are in $m^3\,m^{-3}$, and z_e is the effective depth of the surface layer that is dried by evaporation in m. The value for θ_{fc} in Eq. (9-20a) may be set a few percentage points above normal values listed in Table 3-6 to compensate for extra soil water retained in the evaporation layer above θ_{fc} for one or two days after wetting. The cumulative depth of evaporation, D_e, at the end of stage 1 is the readily evaporable water (REW) that normally ranges from 5 to 12 mm depending on soil texture (Ritchie 1972).

Allen et al. (1998, 2005a) recommend downward adjustment of TEW during extended periods of low ET_{ref} (i.e., $ET_o < 5\,mm\,d^{-1}$) commonly experienced during nongrowing periods. During cool conditions, for example, during winter or other cool periods, less radiation energy is available for heating the soil surface layer and evaporating water, and total effective TEW representing a drying event will typically be smaller than during a warm period. Allen et al. (1998) suggest using ET_o as a surrogate for temperature and radiation conditions to reduce the value for TEW. When $ET_o < 5\,mm\,d^{-1}$, TEW is estimated as

$$TEW = 1,000(\theta_{fc} - 0.5\,\theta_{wp})z_e\sqrt{\frac{ET_o}{5}} \tag{9-20b}$$

where ET_o is an average representing the general estimation period in $mm\,d^{-1}$. A monthly average for ET_o is recommended. Varying ET_o in Eq. (9-20b) on a daily basis is not recommended because doing so will cause TEW to vary daily, which can cause numerical inconsistencies.

During the falling rate stage, where $D_e > REW$, the evaporation rate is estimated in proportion to the amount of water remaining in the surface soil layer, and K_r of Eq. (9-19) is calculated as

$$K_r = F_{\text{stage}\,1} + (1 - F_{\text{stage}1})\max\left[\min\left(\frac{TEW - D_{e(i-1)}}{TEW - REW}, 1.0\right), 0.0\right] \tag{9-21}$$

where $D_{e(i-1)}$ is the cumulative depth of evaporation at the end of time step (i–1), representing the previous time step, and $F_{\text{stage}\,1}$ is the fraction of the time step (day or hour) that resides in stage 1 evaporation. $1 - F_{\text{stage}1}$ of the time step resides in stage 2. The use of $F_{\text{stage}\,1}$ is an extension to the original FAO-56 model made by Allen et al. (2011a) to provide better definition of the transition from stage 1 to stage 2 drying during a time step and provide a more accurate, averaged value for K_r during that transition time step. The improved definition can be important when using daily calculation time steps, especially for coarse soils having small REW. The max function determines the greater of the two values in the brackets that are separated by the comma, and the min

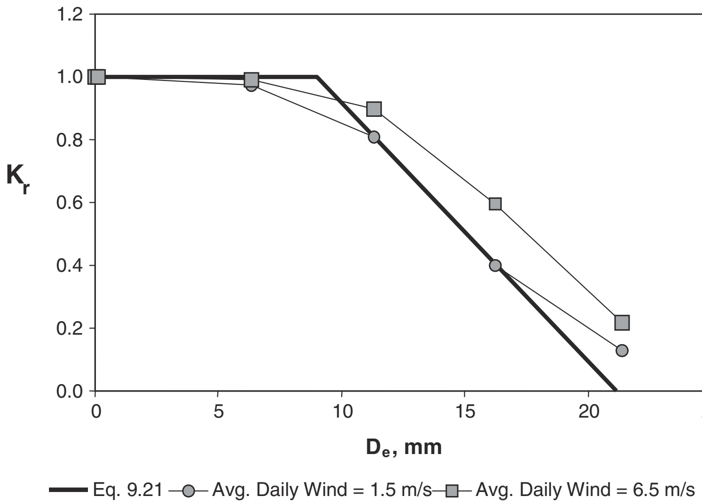

Fig. 9-3. Measured $\mathrm{K_r}$ *reported by Chanzy and Bruckler (1993) for a loam soil near Avignon, France, under two wind speed conditions, and* $\mathrm{K_r}$ *modeled by Burt et al. (2005) using Eq. (9-21) with REW = 9 mm and TEW = 21 mm based on* $\mathrm{z_e} = 0.1$ m, $\mathrm{F}_{stage\,1} = 0$, *and average* θ_{fc} *and* θ_{wp} *values for loam from Table 3-6*

function determines the lesser of the two values in the parentheses that are separated by the comma. These functions effectively limit the value for K_r to $0 \le K_r \le 1.0$. Setting $F_{\mathrm{stage\,1}}$ to 0 causes Eq. (9-21) to revert to the original FAO-56 form. Burt et al. (2005) find the linear proportionality of K_r to the depth of remaining evaporable water, as expressed by Eq. (9-21), to follow experimental data by Chanzy and Bruckler (1993) well for three soil types spanning clay, silty clay loam, and loam, as shown in Figure 9-3 for loam.

FAO-56 (example 31) presents a set of sample calculations for applying the FAO-56 K_e method (Allen et al. 1998). Setting the effective depth of evaporation, z_e, can be subjective, because the entire z_e layer will not uniformly approach air-dry conditions during a drying period, and an upward flux to this layer from below is not considered. The selection of z_e should be set to a value that causes the FAO-56 procedure to reproduce observed average total evaporation depth for the same or a similar soil after a long drying period and therefore include the effects of depletion of water from below the z_e layer (Allen et al. 2005a). Usually a value for z_e of 0.1 or 0.15 m is used. For evaporation periods extending beyond three or four weeks, a transition in z_e to a depth of 0.2 to 0.25 m may be required to better represent the soil depth contributing to total evaporation (Raes et al. 2009).

The fraction of calculation time step i that resides in stage 1, $F_{\text{stage}\,1}$, is approximated following Allen (2011) as

$$F_{\text{stage}\,1} = \frac{REW - D_{REW_{i-1}}}{K_{e\,\max} ET_{ref}}, \qquad 0 \le F_{\text{stage}\,1} \le 1.0 \tag{9-22}$$

where time step length can be one day, a tenth of a day, or one hour; $D_{REW_{i-1}}$ is the depletion of the upper "skin" soil surface layer that directly contributes to stage 1 drying, mm, at the end of time step $i-1$; and $K_{e\,max}$ is the value for K_e expected during stage 1 drying. The value for $K_{e\,max}$ is tied to the reference ET type, where $K_{e\,max} \sim 1.0$ is recommended when using the alfalfa reference, ET_r, and $K_{e\,max} \sim 1.2$ is recommended when using the clipped grass reference, ET_o. Typically, $K_{e\,max}$ can be set equal to $K_{c\,max}$, defined earlier. $F_{\text{stage}\,1}$ is limited to the range $0 \le F_{\text{stage}\,1} \le 1.0$. The water balance equation for determining D_{REW} is given later as Eq. (9-29). Figure 9-4 illustrates the three depths describing contributing portions of the soil profile, referred to as the skin layer; the total evaporation layer, z_e; and the root zone depth, z_r, in the case of presence of plants. Each depth is contained within the domain of the next deeper depth in the FAO-56 model, which is different from most layered soil water models. In other words, each layer is a subset of the next deeper layer.

Ritchie et al. (1989) suggest empirical equations to estimate potential values of REW based on soil texture:

$$REW = 20 - 0.15(Sa) \quad \text{for } Sa > 80 \tag{9-23a}$$

$$REW = 11 - 0.06(Cl) \quad \text{for } Cl > 50 \tag{9-23b}$$

$$REW = 8 + 0.08(Cl) \quad \text{for } Sa < 80 \quad \text{and} \quad Cl < 50 \tag{9-23c}$$

where Sa and Cl are percentage fractions of sand and clay in the soil. Units for REW are mm. Typical values of REW suggested by FAO-56 are summarized in Table 9-1. Limiting values for REW to less than TEW is important.

Experimental Values for z_e, *TEW*, and *REW* Because the typical soil water distribution after evaporation follows an exponential relationship as illustrated in Figure 9-2, the surface 0–0.05 m layer can be expected to approach air-dry approximated as 0.5 θ_{wp}. Below 0.05 to 0.1 m, the soil likely will not dry to less than θ_{wp} between irrigation or rainfall events. After 37 days of evaporation from a loam soil near Phoenix, Arizona, the soil water content below 0.04 m did not decrease to air-dry conditions and below 0.05 m was only approaching θ_{wp} (Jackson 1973). An alternate estimate of TEW assumes that only the 0–0.05 m layer would dry to 0.5 θ_{wp}, and below this depth the soil would dry only to θ_{wp}, or

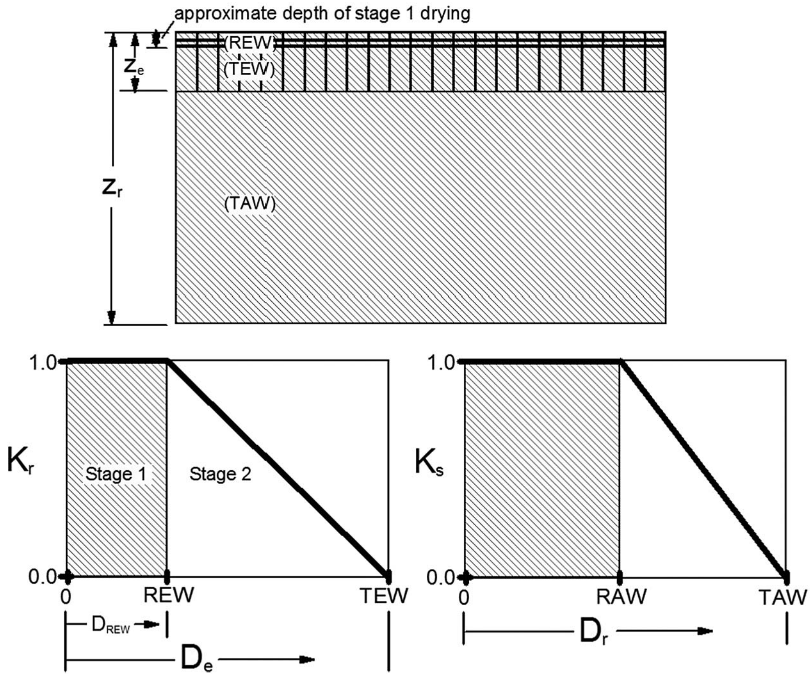

Fig. 9-4. Top: relative depths for the upper soil surface layer, referred to as the skin layer, contributing to stage 1 drying; the total evaporation layer, z_e*; and the root zone depth,* z_r*, in the case of presence of plants. Lower left: the shape of the* K_r *function vs.* D_e *and placement of REW and TEW defining stage 1 and stage 2 drying. Lower right: the shape of the* K_s *function vs.* D_r *and placement of readily available water,* RAW*, and total available water,* TAW

$TEW = 1,000 \quad [(0.05 - 0)(\theta_{fc} - 0.5\,\theta_{wp}) + (z_e - 0.05)(\theta_{fc} - \theta_{wp})]$. However, this adjustment is typically implicit in the establishment of the value for z_e and is generally not made.

The selection of the value of z_e to use in the calculation of TEW should be based on experimental data, when possible. Hunsaker et al. (2003) find good accuracy in application of the FAO-56 approach for K_r using $z_e = 0.125$ m in Eq. (9-20) and $REW = 10$ mm for cotton on a clay loam soil in Arizona. Hunsaker et al. (2002) use $z_e = 0.15$ m, $TEW = 34$ mm, and $REW = 10$ mm for a loam soil under alfalfa based on lysimeter observations. Tolk and Howell (2001) and Howell et al. (2004) use $z_e = 0.15$ m, $TEW = 33$–38 mm, and $REW = 10$ mm for a clay loam soil and $z_e = 0.10$ m, $TEW = 20$ mm, and $REW = 9$ mm for a fine sandy loam near Amarillo, Texas. Allen et al. (2005c) use $z_e = 0.10$ m, $TEW = 25$ mm, and $REW = 10$ mm to fit lysimeter data on evaporation for a silt loam soil near Kimberly, Idaho. Allen et al. (2005a) find $z_e = 0.15$ m to fit observed evaporation data in Imperial Valley, California, for silty clay and silty clay loam and $z_e = 0.35$ m for sand. The larger value for z_e for sand accounts for upward flow of water to the surface. Mutziger et al. (2005) use $z_e = 0.10$ m for a sandy clay loam and 0.15 m for silt loam soils to fit experimental data using the two-stage FAO-56 model. They apply the extended three-stage model of Allen et al. (2005a, b) for three cracking soils to account for low-level diffusive evaporation from crack faces over long time periods. Burt et al. (2005) use $z_e = 0.10$ m and mean values from Table 3-6 for θ_{fc} and θ_{wp} in Eq. (9-20a) to model evaporation data reported by Chanzy and Bruckler (1993) for loam, silty clay loam, and clay soils. The average absolute value of percent differences between measured and FAO-56 modeled cumulative evaporation was 5%. The $\theta_{fc} = 0.35$ and $\theta_{wp} = 0.13\ \mathrm{m^3\,m^{-3}}$ presented by Jackson (1973) for the loam soil near Phoenix in Figure 9-1 and a value of $z_e = 0.1$ m produces $TEW = 30$ mm. Jackson (1973) observed maximum cumulative evaporation of 29 to 31 mm from the soil profile during his two test periods, which is in close agreement.

Stage 3 Evaporation for Cracking Soils Drying to depths as deep as 0.5 m or more is possible for severely cracking soils containing large amounts of montmorillinite clay where cracks can extend as deep as 0.6 m (Ritchie and Adams 1974) and 1 m (Pettry and Switzer 1996). An extension to the FAO evaporation model (Allen et al. 2005a) created a stage 3 where evaporation progresses in soils that crack substantially upon drying, thereby exposing progressively deeper depths to the drying process. The progressive drying tends to continue at low rates over extended periods of time and prolongs the time for K_r to decrease to zero, thereby creating a prolonged baseline evaporation rate.

In the extension for stage 3 drying, stage 2 transitions to stage 3 when K_r reduces to a threshold value labeled K_{r2}, as shown in Figure 9-5. For a three-stage drying system with the skin evaporation extension, Eq. (9-21) for K_r is replaced with Eq. (9-24) for the second stage when $REW < D_{e_{i-1}} < TEW_2$:

$$K_r = K_{r2} + (1 - K_{r2}) \times \left\{ F_{\text{stage}\,1} + (1 - F_{\text{stage}\,1}) \max\left[\min\left(\frac{TEW_2 - D_{e,i-1}}{TEW_2 - REW}, 1.0\right), 0.0\right]\right\} \tag{9-24}$$

and K_r during stage 3 when $TEW_2 \le D_{e,i-1} \le TEW_3$ is

$$K_r = F_{\text{stage}\,1} + (1 - F_{\text{stage}\,1}) K_{r2} \max\left[\min\left(\frac{TEW_3 - D_{e,i-1}}{TEW_3 - TEW_2}, 1.0\right), 0.0\right] \tag{9-25}$$

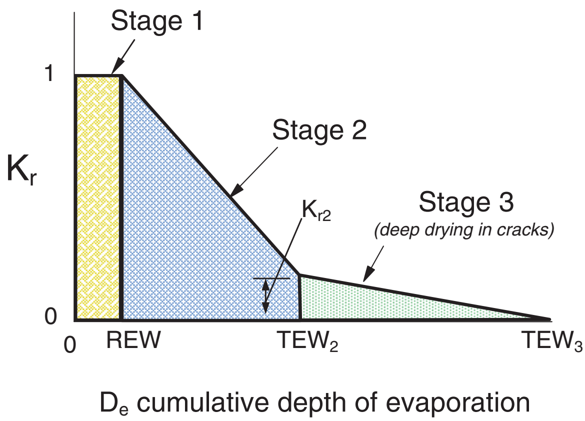

Fig. 9-5. General schematic showing the transition of the K_r *function [Eqs. (9-24) and (9-25)] for a cracking soil having stage 3 evaporation as a function of cumulative depth of evaporation depletion,* D_e
Source: Allen et al. (2005a); copyright ASCE

where TEW_2 is the D_e when $K_r = K_{r2}$ (point at which evaporation transitions from stage 2 to stage 3 drying, mm), and K_{r2} is the value for K_r at the junction of stage 2 and stage 3 drying. TEW_3 is maximum cumulative depth of evaporation (depletion) from the soil surface layer when the soil is dry and no further evaporation occurs ($K_r = 0$), mm. The value TEW_3 includes REW and TEW_2. K_r is 0 when $D_{e,i-1} \geq TEW_3$. In all cases, for Eq. (9-24) and (9-25), K_r is limited to $0 \leq K_r \leq 1.0$. TEW_2 is typically set to TEW computed from Eq. (9-20a, b) using $z_e = 0.1$ or 0.15 m, and TEW_3 is estimated from Eq. (9-20a, b) using a value for z_e greater than the z_e used to estimate TEW_2. Comparisons against observed data are recommended to determine best parameter values.

Generally, the value for K_{r2} ranges between about 0.05 and 0.4, depending on the nature and degree of cracking as the soil dries. Allen et al. (1998, 2005a) recommend $K_{r2} \sim 0.2$ for cracking soils. Mutziger et al. (2005) find best fit values for K_{r2} for two cracking soils in Texas to be 0.3 and 0.2 when comparing against lysimeter measurements of evaporation for a black clay and clay loam. Stage 3 drying in the FAO-style model has been applied to cracking heavy clay soils in the Imperial Irrigation District of California (Allen et al. 2005a) and to two cracking or partially cracking soils in Texas (Mutziger et al. 2005). Values for the Imperial soils were $REW = 8$ mm, $TEW_2 = 50$ mm, $TEW_3 = 100$ mm, and $K_{r2} = 0.2$. Best fit values to lysimeter evaporation measurements for the Houston black clay and Pullman clay loam soils of Mutziger et al. (2005) were $REW = 7$ mm, $TEW_2 = 30$ and 22 mm, and $TEW_3 = 50$ and 45 mm. The stage 3 option for the FAO-56 method can also be used to simulate effects of upward flow from deeper soil layers for noncracking soils as illustrated later in comparisons against the HYDRUS model.

Application within the Dual K_c Context In the FAO-56 dual K_c model, described in Chapter 10, f_w, the fraction of the surface wetted by irrigation and/or precipitation, is used to limit the potential spatial extent of evaporation. Common values for f_w are listed in Table 9-2. When the soil surface is completely wetted, as by precipitation or sprinkler, the fraction of exposed wetted soil, f_{ew}, is set equal to $(1 - f_c)$, where f_c is the fraction of soil surface effectively covered by vegetation. For irrigation systems where only a fraction of the ground surface (f_w) is wetted, f_{ew} is limited to f_w:

$$f_{ew} = \min(1 - f_c, f_w) \tag{9-26}$$

Both $(1 - f_c)$ and f_w, for numerical stability, have limits of 0.01–1. In the case of drip irrigation, Allen et al. (1998) suggest that where most soil wetted by irrigation is beneath the crop canopy and is shaded f_w be reduced to about one-half to one-third of that given in Table 9-2. Their general recommendation for drip irrigation is to multiply f_w by $[1 - (2/3)\ f_c]$. Pruitt et al. (1984) and Bonachela et al. (2001) describe evaporation patterns and extent under drip irrigation.

Using a three-dimensional crop energy balance model, Luquet et al. (2005) suggest that plant transpiration in a cotton canopy can increase by 10% when shifting from furrow irrigation to drip irrigation due to transfer of heat from dry soil to adjacent vegetation. This implies that the K_{cb} might increase by a small amount when irrigated by drip or other irrigation

Table 9-2. Common Values for the Fraction of Soil Surface Wetted by Irrigation or Precipitation

Wetting Event	f_w
Precipitation	1.0
Sprinkler irrigation, field crops	1.0
Sprinkler irrigation, orchards	0.7 ... 1.0
Basin irrigation	1.0
Border irrigation	1.0
Furrow irrigation (every furrow), narrow bed	0.6 ... 1.0
Furrow irrigation (every furrow), wide bed	0.4 ... 0.6
Furrow irrigation (alternate furrows)	0.3 ... 0.5
Microspray irrigation, orchards	0.3 ... 0.8
Trickle (drip) irrigation	0.3 ... 0.4

Source: Data from FAO-56, Allen et al. (1998)

method where only a small fraction of the surface is wetted. However, the increase is a function of the fraction of time that the soil surface is wet. Typically drip irrigation wets the surface more frequently than a surface irrigation method so that some of the reduced evaporation from smaller f_w and perhaps increased transpiration by heat transfer is compensated by more frequent wetting events as opposed to surface or sprinkle irrigation (Burt et al. 2005). A schematic illustrating common extent and location of f_w and $1 - f_c$ is shown in Figure 9-6.

Visual observation generally determines the value for f_c. For purposes of estimating f_{ew}, f_c can be estimated using a general relationship between f_c and K_{cb} from FAO-56:

$$f_c = \left(\frac{K_{cb} - K_{c\ \min}}{K_{c\ \max} - K_{c\ \min}} \right)^{(1+0.5h)} \tag{9-27}$$

where $K_{c\ min}$ is the minimum (basal) K_c for dry bare soil with no ground cover, and h is the height of the crop in m. The differences $K_{cb} - K_{c\ min}$ and $K_{c\,max} - K_{c\ min}$ are limited to ≥ 0.01 for numerical stability. The value for f_c will change daily as K_{cb} changes. $K_{c\ min}$ ordinarily has the same value as K_{cb} during the initial growth period for annual crops, $K_{cb\,ini}$, which represents nearly bare soil conditions (i.e., $K_{c\ min} \sim 0.10$ to 0.15). However, $K_{c\ min}$ is set to 0 or nearly zero under conditions with long time periods between wetting events, for example, in applications with natural vegetation in deserts. The value for f_c decreases during the late season period in proportion to K_{cb} to account for local transport of sensible heat from senescing leaves to the soil surface. K_{cb}, $K_{c\ min}$, and estimation of $K_{c\,max}$ are discussed in more detail in Chapter 10. The FAO-56 dual K_c model can be applied using ET_o and ET_r references, provided the K_{cb} values used in the procedure are associated with the specific reference.

9.7 RELATIONSHIPS BETWEEN EVAPORATION AND TRANSPIRATION

For partial or full plant cover, the rate of stage 1 evaporation under a crop canopy relative to reference ET is strongly linked to the LAI, or plant cover, that affects net radiation at the soil surface. Allen et al. (1964) illustrate how crop canopies intercept radiation, thus reducing energy for evaporation at the surface. Measurements of evaporation under corn, cotton, and maize canopies in Spain by Villalobos and Fereres (1990) indicate that E/ET_o decreases as LAI increases (Figure 9-7) in a manner similar to the decrease in the ratio reported by Ritchie (1972). Ritchie and Burnett (1971) show the ratio of net radiation at the soil surface (R_{ns}) to total