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Evapotranspiration Estimation Using Soil Water Balance, Weather and Crop Data

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1. Introduction

The rise in water demand for agriculture, industry, domestic, and environmental needs requires sagacious use of this limited resource. Since agriculture (mainly irrigation) is the major user of water, improving agricultural water management is essential. Efficient agricultural water management requires reliable estimation of crop water requirement (evapotranspiration). Evapotranspiration (ET) is the transfer of water from the soil surface (evaporation) and plants (transpiration) to the atmosphere. ET is a critical component of water balance at plot, field, farm, catchment, basin or global level. From an agricultural point of view, ET determines the amount of water to be applied through artificial means (irrigation). Reliable estimation of ET is important in that it determines the size of canals, pumps, and dams. The use of the terms 'reference evapotranspiration', 'potential evapotranspiration', 'crop evapotranspiration', 'actual evapotranspiration' in this chapter is based on FAO-56 (FAO Irrigation and Drainage publication No 56) (Allen et al., 1998).

There are different methods of determining evapotranspiration: direct measurement, indirect methods from weather data and soil water balance. These methods can be generally classified as empirical methods (eg. Thornthwaite, 1948; Blaney and Criddle, 1950) and physical based methods (eg. Penman, 1948; Montheith, 1981 and FAO Penman Montheith (Allen et al., (1998)). They vary in terms of data requirement and accuracy. At present, the FAO Penman Montheith approach is considered as a standard method for ET estimation in agriculture (Allen et al., 1998). A case study from a semiarid region of Australia will be used to demonstrate ET estimation for a canola (*Brassica napus* L.) crop using soil water balance and crop coefficient approaches. Daily rainfall data, soil moisture measurement data using neutron probe, and AquaCrop (Steduto et al., 2009) -estimated deep percolation below the crop root zone will be used to determine actual evapotranspiration of the crop using soil water balance. Reference evapotranspiration ET_o will be determined using FAO *ET_o calculator* (Raes, 2009). Crop canopy cover measured using a handheld *GreenSeeker™* and expressed as normalized difference vegetation index (NDVI) will be used to interpret evolution of evapotranspiration during the growing season (life cycle) of the canola crop.

2. Field experiment

2.1 Description of study area and field experiment

The study area is in Wagga Wagga, New South Wales (Australia). Wagga Wagga, referred to as 'the capital of Riverina', is located in the Riverina region of NSW. The Riverina extends from the foot hills of the Great Dividing Range in the east to the flat and dry inland plains in the west. Agriculture in the Riverina is significantly diversified with dry land farming of winter cereals and irrigation in Murrumbidgee and Colleambally irrigation areas. It has a Mediterranean type climate with a mixed farming system of winter cereal crops, summer crops, and pastures grazing lands. In addition to the major grain crops of rice, canola, wheat, and maize, the area also produces a quarter of NSW fruit and vegetable production (RDA, 2011). The Riverina region is characterized by the semiarid climate, with hot summers and cool winters (Stern et al., 2000). Seasonal temperature varies little across the region. More consistent rainfall occurs in winter months. Mean annual temperature is 15-18^{o}C. January is the hottest month of the year while July is the coolest. Mean annual rainfall varies from 238 mm in the west to 617 mm in the east. Long term and 2010 mean monthly rainfall, reference evapotranspiration, and temperature are presented in Fig. 1. Rainfall in 2010 was much higher than the long term average while evapotranspiration in 2010 was lower than the long term average.

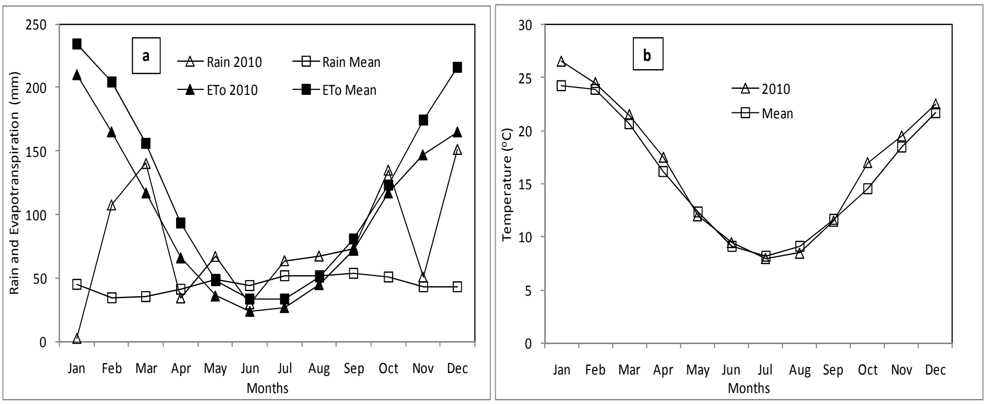

Fig. 1. (a) Rain and reference evapotranspiration ET_o (long term average and in 2010) (b) Monthly average temperature (long term average and in 2010) at Wagga Wagga, NSW (Australia).

A field experiment was carried out during the growing season of 2010 at canola field experimental site of Wagga Wagga Agricultural Research Institute located at Wagga Wagga (35^{o}03'N; 147^{o}21'E; 235 m asl), NSW (Australia). There was enough rainfall (930 mm) in contrast to long term average of 522 mm in 2010 to provode ideal growing conditions. A popular variety of canola (Hyola50) was sown on 30 April 2010. The experiment was conducted on a 24 m x 24 m area. There were 24 plots, 12 experimental plots and 12 buffer plots. The plots were 6 m long with 1 meter buffer on either end. Plot width was 1.8 m with a 0.5 m walking strip between plots for data collection.

About a month before the experimental season, neutron probe access tubes were installed to a depth of 1.5 m for soil moisture measurement. Two access tubes were installed at 2 m from either end of the plot and 2 m from each other. Soil moisture content was measured at 15, 30, 45, 60, 90, and 120 cm depths every two weeks. The probe was calibrated using gravimetric soil moisture measurements done when access tubes were installed on site.

2.2 Weather data

Daily weather data (rainfall, minimum and maximum temperature, solar radiation, relative humidity, and wind speed) were collected from the meteorological station of the Wagga Wagga Agricultural Institute located adjacent to the experimental site. Out of the total annual rainfall of 930 mm, the amount or proportion (in percentage) during the canola growing season (May to November) was 514 mm (53%) while the long term average was 333 mm (64% of the long term average of 522 mm). Monthly average maximum and minimum temperature was 26^{o}C and 3^{o}C respectively. Reference evapotranspiration ET_o was calculated using the procedure described in the FAO Irrigation and Drainage Paper 56 (Allen et al., 1998) with the help of the program FAO *ET_o Calculator* (Raes, 2009).

2.3 Soil hydraulic characteristics

A 1.5m x 1.5m x 1.5m soil trench was dug for soil texture, field capacity (θ_{FC}), and wilting point (θ_{WP}) determination. Soil samples were retrieved from 0-30, 30-60, 60-90, and 90-120 cm depths for soil texture, θ_{FC}, and θ_{WP} determination using standard laboratory procedures hydrometer and pressure plate apparatus apparatus.

2.4 Crop parameters

The following crop phenological stages were recorded during the growing season: planting date, 90% emergence, beginning and end of flowering, senescence and maturity. The canopy cover was measured using *GreenSeeker^{TM}*, an Optical Sensor Unit (NTech Industries, Inc., USA). *GreenSeeker^{TM}*, is a handheld tool that determines Normalized Difference Vegetative Index (NDVI), is an integrated optical sensing and application system that measures green crop canopy cover.

3. Soil water balance method

Rain or irrigation reaching a unit area of soil surface, may infiltrate into the soil, or leave the area as surface runoff. The infiltrated water may (a) evaporate directly from the soil surface, (b) taken up by plants for growth or transpiration, (c) drain downward beyond the root zone as deep percolation, or (d) accumulate within the root zone. The water balance method is based on the conservation of mass which states that change in soil water content ΔS of a root zone of a crop is equal to the difference between the amount of water added to the root zone, Q_i, and the amount of water withdrawn from it, Q_o (Hillel, 1998) in a given time interval expressed as in Eq. (1).

$$\Delta S = Q_i - Q_o \tag{1}$$

Eq. (1) can be used to determine evapotranspiration of a given crop as follows

$$ET = P + I + U - R - D - \Delta S \tag{2}$$

where ΔS = change in root zone soil moisture storage, P = Precipitation, I = Irrigation, U = upward capillary rise into the root zone, R = Runoff, D = Deep percolation beyond the root

zone, ET = evapotranspiration. All quantities are expressed as volume of water per unit land area (depth units).
In order to use Eq. (2) to determine evapotranspiration (ET), other parameters must be measured or estimated. It is relatively easy to measure the amount of water added to the field by rain and irrigation. In agricultural fields, the amount of runoff is generally small so is often considered negligible. When the groundwater table is deep, capillary rise U is negligible. The most difficult parameter to measure is deep percolation D. If soil water potential and moisture content are monitored, D can be estimated using Darcy's Principle. In this study, deep percolation estimated using AquaCrop (Raes et al., 2009), was adopted. Runoff R was also estimated using AquaCrop following USDA curve number approach (Hawkins et al., 1985). The change in soil water storage ΔS is measured using specialized instruments such as neutron probe and time-domain reflectrometer.

4. Crop coefficient method

4.1 Introduction

The crop coefficient approach relates evapotranspiration from a reference crop surface (ET_o) to evapotranspiration from a given crop (ET_c) through a coefficient. Estimation of crop water requirement from weather and crop data is a simpler and cost effective method compared to other methods such as soil water balance method. In this method, potential evapotranspiration of a crop is presumed to be determined by the evaporative demand of the atmosphere and crop characteristics. Evaporative demand of the air is determined as the evapotranspiration from a reference crop. The reference crop is a hypothetical crop (grass or alfalfa) with specific characteristics such as crop height of 0.12 m and albedo of 0.23 (Allen et al., 1998). Penman (1956) defined reference evapotranspiration as "the amount of water transpired in unit time by a shorter green crop, completely shading the ground, of uniform height and never short of water." It is a useful standard of reference for the comparison of different regions and of different measured evapotranspiration values within a given region. As such, ET_o is a climatic parameter expressing the evaporation power of the atmosphere independent of crop type, crop development and management practices (Allen et al., 1998). FAO Penman Montheith approach is considered as the standard method. In this method, reference evapotranspiration ET_o is estimated from weather data as given in Eq. (3).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{3}$$

where ET_o = reference evapotranspiration (mm/day); Rn = net radiation at the crop surface (MJ/m² day); G = soil heat flux density (MG/m² day); T = air temperature at 2 m height (°C); u_2 = wind speed at 2 m height (m/s); e_s= saturation vapor pressure (kPa); e_a = actual vapor pressure (kPa); e_s-e_a = saturation vapor pressure deficit (kPa); Δ = slope vapor pressure curve (kPa/°C); γ = psychrometric constant (kPa/°C).
Reference evapotranspiration ET_o can be calculated using a spreadsheet or computer programs which are designed for various level of data availability eg. *CROPWAT* (Smith, 1992) and *ET_o Calculator* (Raes, 2009). In this study, the latter program was used. It is important to make clear distinction between reference evapotranspiration ET_o and potential crop evapotranspiration ET_c. The latter is also called maximum crop evapotranspiration.

Evapotranspiration from a given crop grown and managed under standard conditions is called potential crop evapotranspiration ET_c. Standard condition is a disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions. ET_o depends evapotranspiration (ET_c) represents the climatic "demand" for water by a given crop. Potential crop depends primarily on the evaporative demand of the air.

4.2 Single crop coefficient method

The single crop coefficient (K_c) method is used to determine soil evaporation and transpiration lumped over a number of days or weeks. The single "time-averaged" K_c curve incorporates averaged transpiration and soil wetting effects into a single K_c factor. The FAO-56 publication divides the crop growth stages into four phenological stages. Initial stage is from planting to 10% ground cover. Development stage is from 10% groundcover to maximum cover. Midseason stage is from the beginning of full cover to the start of senescence. The late season stage is from the start of senescence to full senescence or harvest. The evolution of crop coefficients during these stages is tabulated in FAO-56 for a number of crops including canola. Three coefficients are given for the initial, midseason, and end of season stages as $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$ respectively. $K_{c\ ini}$ is assumed to be constant and relatively small (<0.4). The K_c begins to increase during the crop development stage and reaches a maximum value $K_{c\ mid}$ which is relatively constant for most growing and cultural conditions. During the late season period, as leaves begin to age and senesce, the K_c begins to decrease until it reaches a lower value at the end of the growing period equal to $K_{c\ end}$. The K_c during the development is estimated using linear interpolation between $K_{c\ ini}$ and $K_{c\ mid}$. Similarly, K_c during the late season stage is determined using linear interpolation between $K_{c\ mid}$ and $K_{c\ end}$. The value of $K_{c\ ini}$ and $K_{c\ end}$ can vary considerably on a daily basis, depending on the frequency of wetting by irrigation and rainfall. The single crop coefficient method can be used for irrigation planning and design. It is accurate enough for systems with large interval such as surface and set sprinkler irrigation. It is also used for catchment level hydrologic water balance studies (Allen et al., 1998).

In the single crop coefficient method, potential crop evapotranspiration ET_c is estimated from a single crop coefficient (K_c) and reference evapotranspirations ET_o as in Eq. (4).

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

Eq. (4) gives the potential (maximum) evapotranspiration of the crop when the soil moisture is not limiting. Since localized K_c values are not always available in many parts of the world, the values of K_c as suggested by FAO (Allen et al., 1998) are being widely used to estimate evapotranspiration.

When rainfall amount and irrigation are not sufficient to keep the soil moisture high enough, the soil moisture content in the root zone is reduced to levels too low to sustain the potential crop evapotranspiration ET_c. This results in an evapotranspiration less than the potential, and the plants are said to be under water stress. This evapotranspiration is called actual evapotranspiration (ET_a). In general, the actual evapotranspiration ET_a from various crops will not be equal to the potential value ET_c. Actual evapotranspiration ET_a is generally a fraction of ET_c depending on soil moisture availability. Actual evapotranspiration ET_a from a well-watered crop might generally approach ET_c during the active growing stage, but may fall below during the early growth stage, prior to full canopy coverage, and again toward the end of the growing season as the matured plant starts to dry out (Hillel, 1997). The actual evapotranspiration ET_a is calculated by combining the effects of K_c and soil water stress coefficient (K_s) as shown in Eq. (5).

$$ET_a = ET_o K_c K_s \tag{5}$$

The stress reduction coefficient K_s [0-1] reduces K_c when the average soil water content of the root zone is not high enough to sustain full crop transpiration. The stress coefficient K_s is determined by the amount of moisture the crop depleted from the rootzone of a crop. The amount of water depleted from the rootzone is expressed by root zone depletion D_r, i.e. water storage relative to field capacity. Stress is presumed to initiate when D_r exceeds the readily available water (RAW), Fig. 2. When more than RAW is extracted from the rootzone (D_r >RAW), K_s is expressed (Allen et al., 1998) as

$$K_s = \frac{TAW - D_r}{TAW - RAW} = \frac{TAW - D_r}{(1-p)TAW} \tag{6}$$

Where TAW = total plant available soil water in the root zone (mm), and p = fraction of TAW that a crop can extract from the root zone without suffering water stress. When $D_r \leq$ RAW, K_s =1 indicating no water stress. The total available water in the root zone (TAW, mm) is estimated as the difference between the water content at the field capacity and wilting point

$$TAW = 1000(\theta_{FC} - \theta_{WP})Z_r \tag{7}$$

Where Z_r = effective rooting depth (m); θ_{FC} is soil moisture content at field capacity ($m^3\ m^{-3}$); θ_{WP} is soil moisture content at permanent wilting point ($m^3\ m^{-3}$).

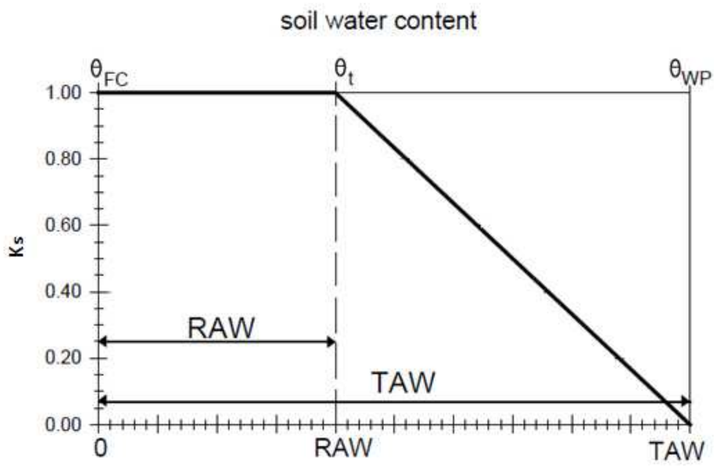

Fig. 2. Schematic of moisture stress coefficient (adapted from Allen et al., 1998).

Readily available water (RAW) is the amount of water which the crop can extract without experiencing stress. It is expressed as

$$RAW = pTAW \tag{8}$$

Soil moisture depletion fraction (p) is the fraction of soil water in the root zone that can be depleted before stress occurred. It varies from crop to crop and also varies at different growth stages of a given crop. Shallow rooted and sensitive crops such as vegetables have low p value while deep rooted and stress tolerant crops have a higher p value.

Canola crop coefficient values given in FAO 56 (Allen et al., 1998) are $K_{c\ ini}$ = 0.35, $K_{c\ mid}$ = 1.0-1.15, $K_{c\ end}$ = 0.35. These values represent K_c for a sub humid climate with RHmin = 45% and wind speed of 2 m/s. To take account for impacts of differences in aerodynamic roughness between crops and the grass reference with changing climate, the $K_{c\ mid}$ and $K_{c\ end}$ values larger than 0.45 must be adjusted using the following equation:

$$K_c = K_{c\ (\text{tab})} + \left[0.04\left(u_2 - 2\right) - 0.004\left(RH_{\min} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3} \tag{9}$$

Where K_c (tab) is the value of K_c taken from Table 12 of Allen et al. (1998); h is the mean plant height during the mid or late season stage (m); RHmin the mean value for daily minimum relative humidity during the mid or late season growth stages (%) for 20%≤RHmin≤ 80%; u_2 is the mean value for daily wind speed at 2 m during the mid season or late season stages (m/s) for 1m/s ≤ u_2 ≤ 6 m/s. In this study, $K_{c\ ini}$ = 0.35, $K_{c\ mid}$ = 1.10, and $K_{c\ end}$ = 0.35 were used. Accordingly, $K_{c\ mid}$ value was adjusted to 1.08 for RHmin = 48%, u_2 = 1.91 m/s, and plant height of 1.0 m during this stage. Since $K_{c\ end}$ was less than 0.4, it was not necessary to adjust it. Once the K_{cb} values for the initial stage, mid season stage, and end-of-season stage were determined, K_{cb} values for development and late season stages were determined using linear interpolation.

4.3 Dual crop coefficient method

The single coefficient method does not separate evaporation and transpiration components of evapotranspiration. The dual crop coefficient approach calculates the actual increase in K_c for each day as a function of plant development and the wetness of the soil surface. It is best for high frequency irrigation such as microirrigation, centre pivots, and linear move systems (Suleiman et al., 2007). The effects of crop transpiration and soil evaporation are determined separately using two coefficients: the basal crop coefficient (K_{cb}) to describe plant transpiration and the soil water evaporation coefficient (K_e) to describe evaporation from the soil surface, Eq (10). AquaCrop determines crop transpiration (T_r) and soil evaporation (E) by multiplying ETo with their specific coefficients K_{cb} and K_e (Eq. 11) (Steduto et al., 2009).

$$K_c = K_{cb} + K_e, \text{ and} \tag{10}$$

$$ET_c = (K_{cb} + K_e)\ ET_o \tag{11}$$

The range of K_{cb} and K_e is [0-1.4]. When soil moisture is limiting, K_{cb} is multiplied by a coefficient K_s which is equal to 1 when D_r≤RAW and declines linearly to zero when all the available water in the rooting zone has been used. Evapotranspiration under such a condition is calculated using Eq. (12).

$$ET_a = (K_s K_{cb} + K_e)\ ET_o \tag{12}$$

Because the water stress coefficient impacts only crop transpiration, rather than evaporation from the soil, the application using Eq. (12) is generally more valid than is application using

Eq. (5) in the single crop coefficient approach. Allen et al. (1998) reported that in situations where evaporation from soil is not a large component of ET_c, use of Eq. (5) will provide reasonable results. The dual coefficient approach can be summarized into the following three steps: Calculate reference evapotranspiration (ET_o) from climatic data using Eq. (3), calculate individual crops potential evapotranspiration ET_c using Eq. (11), and when the soil moisture content is limited, K_{cb} coefficient is multiplied by stress factors K_s to calculate actual evapotranspiration ET_a using Eq. (12).

4.3.1 Basal crop coefficient

The basal crop coefficient K_{cb} is defined as the ratio of ET_c to ET_o when the soil surface layer is dry but where the average soil water content of the rootzone is adequate to sustain full plant transpiration (Bonder et al., 2007). The dual crop coefficient approach uses daily time step and is readily adapted to spreadsheet program. Some models such as AquaCrop (Steduto et al., 2009) determine crop water productivity from the "productive" component of evapotranspiration i.e. transpiration. AquaCrop requires regression of daily values of biomass and crop transpiration to determine crop water productivity. Therefore, transpiration should be measured or estimated.

FAO-56 has tabulated K_{cb} values for a number of crops, including canola, at the initial, mid season, and end of season stages. Since localized K_{cb} values were not available for the study area, the values of K_{cb} suggested by FAO-56 (Allen et al., 1998) were used. For canola these value were $K_{cb\ ini}$ = 0.15, $K_{cb\ mid}$ = 0.95-1.10, and $K_{cb\ end}$ = 0.25. In this study, K_{cb} of 0.15, 1, and 0.25, respectively, for the initial, mid-season, and end of season stages were selected. The growing season of canola vary from 5 months to 7 months in Australia i.e. 150 -210 days depending on the planting date and the weather conditions (rainfall and temperature) during the season. Initial, development, mid-season, and late season stage lengths for canola grown during the 2010 winter season in Wagga Wagga (Australia) were 10, 64, 84, 48 days respectively.

The values for K_{cb} in the FAO-56 table represent values for a sub humid climate with RH_{min} = 45% and wind speed of 2 m/s. To take account for impacts of differences in aerodynamic roughness between crops and the grass reference, the $K_{cb\ mid}$ and $K_{cb\ end}$ values larger than 0.45 must be adjusted using the following equation:

$$K_{cb} = K_{cb\ (\mathrm{tab})} + \left[0.04\left(\mathrm{u}_2 - 2\right) - 0.004\left(RH_{\min} - 45\right)\right]\left(\frac{h}{3}\right)^3 \tag{13}$$

Where K_{cb} (tab) is the value of $K_{cb\ mid}$ taken from Table 17 of Allen et al. (1998). The other parameters are as defined in Eq. (9). The K_{cb} values for the mid-season stage was adjusted using Eq. (13) to 0.98 for for RH_{min} = 48%, u_2 = 1.91 m/s, and plant height of 1.0 m. Once the K_{cb} values for the initial stage, mid season stage, and end-of-season stage were determined, K_{cb} values for development and late season stages were determined using linear interpolation.

The K_{cb} coefficient for any period (day) of the growing season can be derived by considering that during the initial and mid-season stages K_{cb} is constant and equal to the K_{cb} value of the growth stage under consideration. During the crop development and late season stage, K_{cb} varies linearly between the K_{cb} at the end of the initial stage ($K_{c\ ini}$) and the K_{cb} at the beginning of the midseason stage ($K_{cb\ mid}$). During the mid season stage K_{cb} is constant as $K_{cb\ mid}$. During late season stage, K_{cb} varies linearly between K_{cb} mid and K_{cb}

end. In the case of canola the end of season K_{cb} does not need adjustment since it is 0.25 which is less than 0.45.

4.3.2 Soil evaporation coefficient

Similar to K_{cb}, soil evaporation coefficient K_e needs to be calculated on a daily basis. K_e is a function of soil water characteristics, exposed and wetted soil fraction, and top layer soil water balance (Allen et al., 2005). In the initial stage of crop growth, the fraction of soil surface covered by the crop is small, and thus, soil evaporation losses are considerable. Following rain or irrigation, K_e can be as high as 1. When the soil surface is dry, K_e is small and even zero. K_e is determined using Eq. (14).

$$K_e = \min\{[K_r\left(Kc \text{ max - K}_{\text{cb}}\right)],[f_{ew} \text{ Kc max}]\} \tag{14}$$

Where K_c max = maximum value of crop coefficient K_c following rain or irrigation; K_r = evaporation reduction coefficient which depends on the cumulative depth of water depleted; and f_{ew} = fraction of the soil that is both wetted and exposed to solar radiation. K_c max represents an upper limit on evaporation and transpiration from the cropped surface. K_c max ranges [1.05-1.30] (Allen et al., 2005). Its value is calculated for initial, development, mid-season, or late season using Eq. 15.

$$K_{c \text{ max}} = \max\left(\left\{1.2 + \left[0.04\left(u_2 - 2\right) - 0.004\left(RH_{\min} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3}\right\},\left\{K_{cb} + 0.05\right\}\right) \tag{15}$$

Evaporation occurs predominantly from the exposed soil fraction. Hence, evaporation is restricted at any moment by the energy available at the exposed soil fraction, i.e. K_e cannot exceed f_{ew} x K_c max. The calculation of K_e consists in determining K_c max, K_r, and f_{ew}. K_c max for initial, development, midseason, and late season stages were calculated to be 1.196, 1.181, 1.187, and 1.195 respectively.

4.3.3 Evaporation reduction coefficient

The estimation of evaporation reduction coefficient K_r requires a daily water balance computation for the surface soil layer. Evaporation from exposed soil takes place in two stages: an energy limiting stage (Stage 1) and a falling rate stage (Stage 2) (Ritchie 1972) as indicated in Fig. 3. During stage 1, evaporation occurs at the maximum rate limited only by energy availability at the soil surface and therefore, K_r = 1. As the soil surface dries, the evaporation rate decreases below the potential evaporation rate (K_c max – K_{cb}). K_r becomes zero when no water is left for evaporation in the evaporation layer. Stage 1 holds until the cumulative depth of evaporation D_e is depleted which depends on the hydraulic properties of the upper soil. At the end of Stage 1 drying, D_e is equal to readily evaporable water (REW). REW ranges from 5 to 12 mm and highest for medium and fine textured soils (Table 1 of Allen et al., 2005). The evolution of K_r is presented in Fig. 3.

The second stage begins when D_e exceeds REW. Evaporation from the soil decreases in proportion to the amount of water remaining at the surface layer. Therefore reduction in evaporation during stage 2 is proportional to the cumulative evaporation from the surface soil layer as expressed in Eq. (16).

$$K_r = \frac{TEW - D_{e,j-1}}{TEW - REW} \text{ for } D_{e,j-1} > REW \quad (16)$$

where De, j-1 = cumulative depletion from the soil surface layer at the end of previous day (mm); The TEW and REW are in mm. The amount of water that can be removed by evaporation during a complete drying cycle is estimated as in Eq. (17).

$$TEW = 1000\left(\theta_{FC} - 0.5\theta_{WP}\right)Z_e \quad (17)$$

Where TEW =maximum depth of water that can be evaporated from the surface soil layer when the layer has been initially completely wetted (mm). θ_{FC} and θwp are in (m^3 m^{-3}) and Ze (m) = depth of the surface soil subject to evaporation. FAO-56 recommended values for Ze of 0.10-0.15m, with 0.10 m for coarse soils and 0.15 m for fine textured soils.

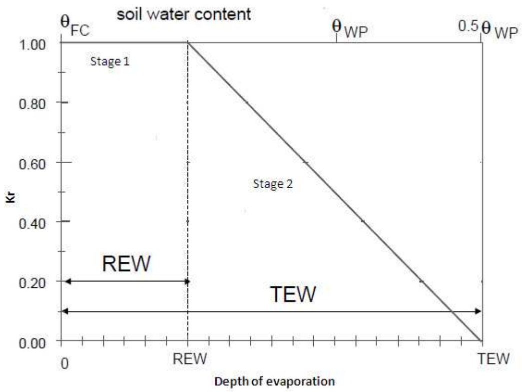

Fig. 3. Soil evaporation reduction coefficient K_r (adapted from Allen et al., 2005). REW stands for readily extractable water and TEW stands for total extractable water.

Calculation of K_e requires a daily water balance for the wetted and exposed fraction of the surface soil layer (f_{ew}). Eq. (18) is used to determine cumulative evaporation from the top soil layer (Allen et al., 2005).

$$D_{e,j} = D_{e,j-1} - \left(P_j - R_j\right) - \frac{I_j}{f_w} + \frac{E_j}{f_{ew}} + T_{ei,j} + D_{ei,j} \quad (18)$$

where $D_{e,j-1}$ and $D_{e,j}$ = cumulative depletion at the ends of days j-1 and j (mm); P_j and R_j = precipitation and runoff from the soil surface on day j (mm); I_j = irrigation on day j (mm); E_j = evaporation on day j (i.e., E_j = K_e x ET_o) (mm); $T_{ei,j}$ = depth of transpiration from exposed and wetted fraction of the soil surface layer (f_{ew}) on day j (mm); and $D_{ei,j}$ = deep percolation from the soil surface layer on day j (mm) if soil water content exceeds field capacity (mm). Assuming that the surface layer is at field capacity following heavy rain or irrigation, the minimum value of $D_{e,j}$ is zero and limits imposed are $0 \le D_{e,j} \le TEW$. T_{ei} can be ignored except for shallow rooted crops (0.5-0.6m).

Evaporation is greater between plants exposed to sunlight and with air ventilation. The fraction of the soil surface from which most evaporation occurs is f_{ew} = 1-f_c.

$$f_{ew} = \min(1-f_c, f_w) \quad (19)$$

Where $1-f_c$ = 1-CC; f_w is fraction of soil surface wetted by irrigation or rainfall; f_w is 1 for rainfall (Table 20 of Allen et al., 1998); f_c is fraction of soil surface covered by vegetation. In this study f_c is the canopy cover measured using *GreenSeeker™*. Values of parameters used in the dual coefficient approach are presented in Table 1.

Parameter	Value
Field capacity, θ_{FC} (m^3 m^{-3})	30.1
Permanent wilting point, θ_{WP} (m^3 m^{-3})	15.0
Effective rooting depth, Z_r (m)	1.00
Depth of the surface soil layer, Z_e (m)	0.15
Total evaporable water, TEW (mm)	33.7
Readily evaporable water, REW (mm)	9
Total available water, TAW (mm)	160
Readily available water, RAW (mm)	96
The ratio of RAW to TAW, p (fraction)	0.6
Wetting fraction, f_w (fraction)	1

Table 1. The parameters of the soil used in the determination of K_s, K_e, and K_r in the FAO dual coefficient method.

The top soil layer (0-0.15 m) of the soil in this study is sandy clay loam. Readily extractable water (REW) is 9 mm for this soil texture (Table 1 of Allen et al., 2005). Field capacity and wilting point of this soil were determined as part of soil hydraulic properties characterization. Canola effective rooting depth was determined as part of National Brasicca Germaplasm Improvement Program (David Luckett, personal communication). Soil moisture content was monitored using on-site calibrated neutron probe. Soil moisture depletion fraction (p) of 0.6 m was taken from FAO-56 publication (Allen et al., 1998). Since the only source of water was rainfall, wetting fraction f_w of 1 was used.

4.4 AquaCrop approach of determining dual evapotranspiration coefficients

Eq. (11) gives evapotranspiration when the soil water is not limiting. When the soil evaporation and transpiration drops below their respective maximum rates, AquaCrop simulates ET_a by multiplying the crop transpiration coefficient with the water stress coefficient for stomatal closure (Ks_{sto}), and the soil water evaporation coefficient with a reduction K_r [0-1] (Steduto et al., 2009) as

$$ET_a = (Ks_{sto}K_{cb} + K_rK_e)\ ET_o \tag{20}$$

AquaCrop calculates basal crop coefficient at any stage as a product of basal crop coefficient at mid-season stage $K_{cb(x)}$ and green canopy cover (CC). For canola $K_{cb(x)}$ = 0.95 was used.

$$K_{cb} = K_{cb(x)} \text{ x CC} \tag{21}$$

$$K_e = K_{e(x)} \text{ x (1-CC)} \tag{22}$$

Evaporation from a fully wet soil surface is inversely proportional to the effective canopy cover. The proportional factor is the soil evaporation coefficient for fully wet and unshaded

soil surface ($K_{e(x)}$) which is a program parameter with a default value of $K_{e(x)}$ = 1.1 (Raes et al., 2009).
During the energy limiting (non-water limiting) stage of evaporation, maximum evaporation (E_x) is given by

$$E_x = K_e\, ET_o = [(1\text{-}CC)K_{ex}]ET_o \tag{23}$$

Where CC is green canopy cover; K_{ex} is soil evaporation coefficient for fully wet and non shaded soil surface (Steduto et al., 2009). In AquaCrop, K_{ex} is a program parameter with a default value of 1.10 (Allen et al., 1998). When the soil water is limiting, actual evaporation rate is given by

$$E_a = K_r E_x \tag{24}$$

Maximum crop transpiration (T_{rx}) for a well-watered crop is calculated as

$$T_{rx} = K_{cb}\, ET_o = [CC\, K_{cbx}]ET_o \tag{25}$$

K_{cbx} is the basal crop coefficient for well-watered soil and complete canopy cover.

5. Results and discussion

5.1 Soil water balance

The actual evapotranspiration determined using soil water balance method is presented in Table 2. Evapotranspiration was determined using Eq. (2) from measurement of 12 neutron probes several times during the season. Deep percolation and runoff were not measured. Therefore, values estimated by AquaCrop (Steduto et al., 2009; Raes et al., 2009) during the canola water productivity simulation were adopted.

DAP*	Rainfall (mm)	Deep percolation (mm)	Runoff (mm)	Change in storage (mm)	Evapotranspiration ET_a using water balance (mm)
0-13	6.5	0	0	-2.1	8.6
14-21	0	0	0	-1.8	1.8
22-28	36.9	4.6	0.5	13.4	18.4
29-35	23.4	24.6	1.4	-10	7.4
36-42	1.8	1.8	0	-3.1	3.1
43-49	6	2.2	0	-1.1	4.9
50-63	21.8	6.7	0	4.6	10.5
64-77	60	20.2	4.1	17.7	18
78-94	3.2	18.9	0	-25.6	9.9
95-118	58.7	21.2	1.6	6.7	29.2
119-143	81	34.3	3.8	-20.8	63.7
144-159	0	1.5	0	-39.6	38.1
160-173	103.9	8.6	14	30.3	51
174-196	31.6	3.8	0	-20.7	48.5
*DAP stands for days after planting				Seasonal	313

Table 2. Evapotranspiration determined using soil water balance method for canola planted on 30 April 2010 at Wagga Wagga (Australia).

The runoff estimated using AquaCrop was low, supporting the consensus that runoff from agricultural land is low. However, deep percolation past the 1.2 m was significant. The actual annual crop evapotranspiration estimated using this method was 313 mm. It can be observed that evapotranspiration was higher during the mid season and highly evaporative months.

5.2 Evapotranspiration coefficient

Single and dual evapotranspiration coefficients and crop canopy cover data are presented in Fig. 4. The K_c and K_{cb} values adopted from FAO-56 publication and adjusted for the local condition are shown in the Figure. The K_c and K_{cb} curves follow similar trend as the measured canopy cover curve. The canopy cover values were higher than the K_c and K_{cb} curves towards the end of the season. This is due to the fact that as an indeterminate crop, canola still had green canopy due to the ample rainfall during this late season stage of the crop. The soil evaporation coefficient K_e was correctly simulated using the top-layer soil water balance model. It can be seen that K_e is high during the initial and late season stages. It remained low and steady during the midseason stage. The higher number of K_e spikes are

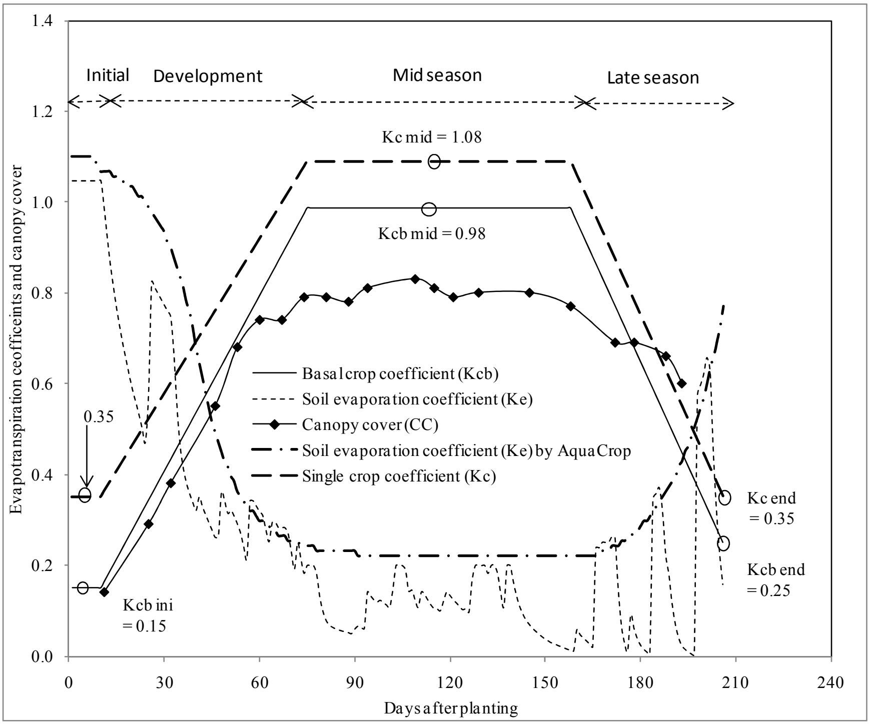

Fig. 4. Single crop coefficient (K_c), basal coefficient (K_{cb}), soil evaporation coefficient (K_e), crop canopy cover (CC) curves for canola having growth stage lengths of 10, 64, 84, and 48 days during initial, development, midseason, and late season stages. Indicated on curve are also single and basal crop coefficient (K_c and K_{cb}) at initial, midseason, and end of season stages. Day of planting is 30 April 2010.

due to frequent rainfall during the season. The K_e value estimated using AquaCrop followed similar trend to the manually calculated using Eq. (14). However, AquaCrop did not simulate response to individual rainfall events.

In the development stage, the soil surface covered by the crop gradually increases and the K_e value decreases. In the midseason stage, the soil surface covered by the crop reaches maximum and water loss is mainly by crop transpiration and K_e is as low as 0.05. In the late season stage, the K_e values are greater than that in the mid-season stage because of the senescence.

Evaporation and transpiration estimated using the dual coefficient approach (Fig. 5) are correctly simulated, with high evaporation during the initial and late stages, and low during the developmental and mid season stages. The fluctuation in the evaporation component is high at these stages and low and steady during the mid season stage except minor spikes after rainfall events. Evaporation during the late stage (late spring months) was high compared with the initial stage which is a winter period. The transpiration component was steady increasing during the crop development stage before reaching a maximum in late mid season stage and declined during the late season stage due to senescence. The trends in evaporation and transpiration were in perfect phase with the weather and crop phenology.

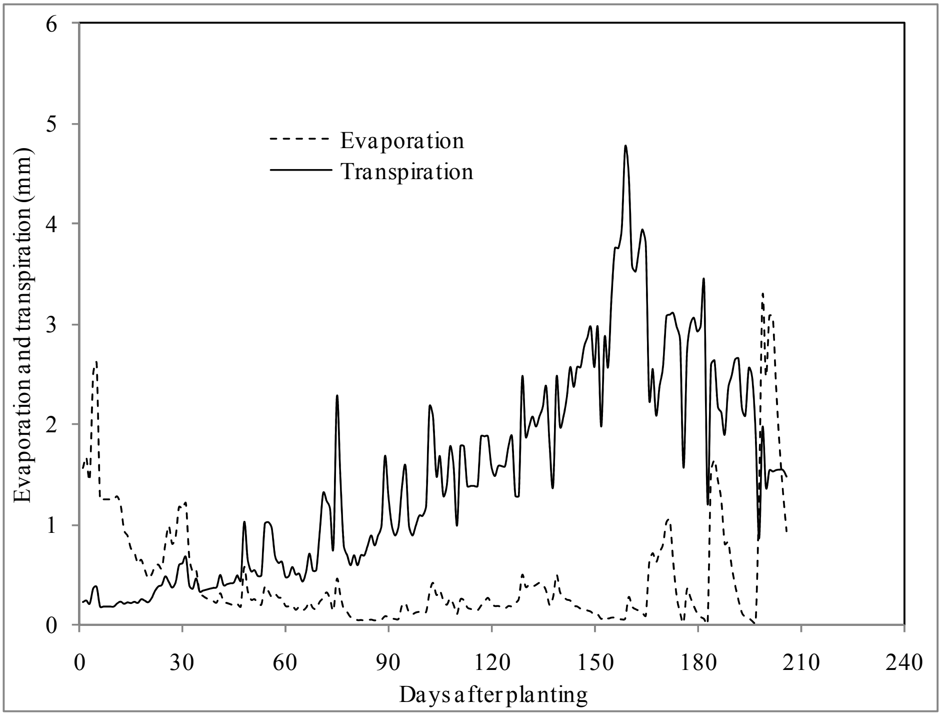

Fig. 5. Daily soil evaporation and transpiration estimated using dual coefficient method for canola planted on 30 April 2010 at Wagga Wagga, NSW (Australia).

Evapotranspiration varies during the growing period of a crop due to variation in crop canopy and climatic conditions (Allen et al., 1998). Variation in crop canopy changes the proportion of evaporation and transpiration components of evapotranspiration. The spikes in basal crop coefficient were high during the initial and crop development phases and decreases as the soil dries (Fig. 4). The spikes decrease as the canopy closes and much of ET is by transpiration. During the late season stage, there were fewer spikes because soil evaporation was low and almost constant. The largest difference between K_c and K_{cb} is found in the initial growth stage where evapotranspiration is predominantly in the form of soil evaporation and crop transpiration. Because crop canopies are near or at full ground cover during the mid-season stage, soil evaporation beneath the canopy has less effect on crop transpiration and the value of K_{cb} in the mid season stage is very close to K_c. Depending on the ground cover, the basal crop coefficient during the mid season stage may be only 0.05-0.10 lower than the K_c value. In this study $K_{cb\ mid}$ is 0.10 lower than $K_{c\ mid}$.

Some studies, carried out in different regions of the world, have compared the results obtained using the approach described by Allen et al. (1998) with those resulting from other methodologies. From this comparison, some limitations should be expected in the application of the dual crop coefficient FAO-56 approach. Dragoni et al. (2004), which measured actual transpiration in an apple orchard in cool, humid climate (New York, USA), showed a significant overestimation (over 15%) of basal crop coefficients by the FAO 56 method compared to measurements (sap flow). This suggests that dual crop coefficient method is more appropriate if there is substantial evaporation during the season and for incomplete cover and drip irrigation.

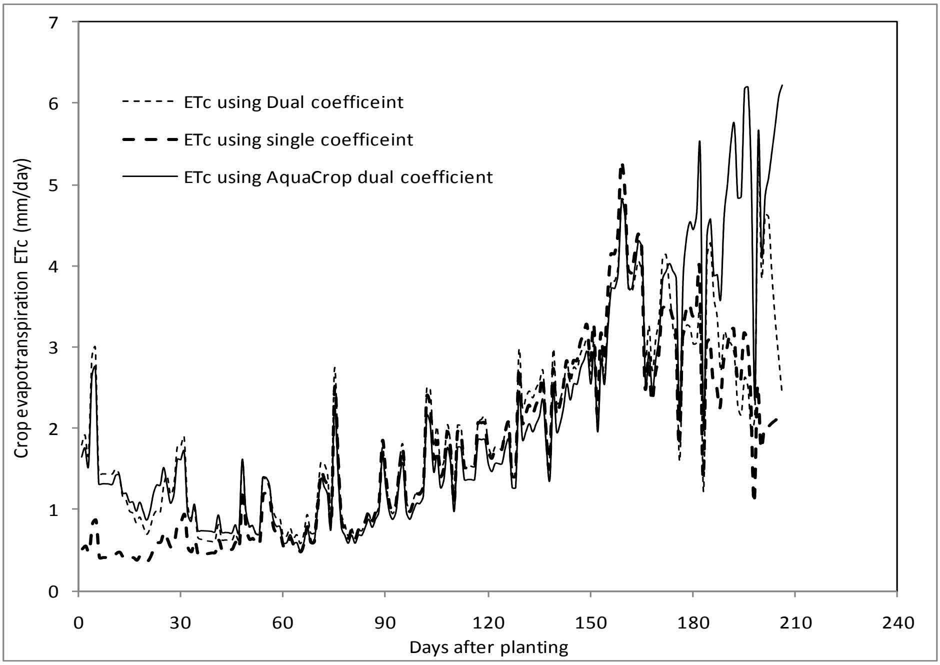

Fig. 6. Crop evapotranspiration determined using single and dual coefficient approaches of FAO 56 for a canola planted on 30 April 2010 at Wagga Wagga, NSW (Australia). ET_c estimated using AquaCrop (dual coefficient) is also presented.

Crop evapotranspiration estimated using single and double coefficients is presented in Fig. 6. ET_c estimated using AquaCrop is also presented in the Figure. It can be observed that ET_c estimated using the three approaches is similar except in the initial and late season stages. During the initial stage, the ET_c estimated using Eq. (14) and AquaCrop (Eqs. 21 and 22) are very close. However, the single coefficient method underestimated ET_c at this stage. During the initial stage when most of the soil is bare, evaporation is high especially if the soil is wet due to irrigation or rainfall. The single crop coefficient approach does not sufficiently take this into account. A similar pattern was observed during the late season stage. However, AquaCrop overestimated ET_c during this stage compared to the other two methods. The annual evapotranspiration estimated using different approaches was as follows: soil water balance (ET_a = 313 mm), single crop coefficient (ET_c = 332 mm), dual coefficient approach (ET_c = 366 mm with E of 79 mm and T of 288 mm), AquaCrop (ET_c = 382 mm with E of 139 mm and T of 243 mm). The evapotranspiration determined using soil water balance method is the "actual" evapotranspiration while the other methods measure potential evapotranspiration ET_c. Soil water depletion (Dr) in Eq. (6) was determined using soil moisture content measured during the season and it was found that $Dr<RAW$ throughout the season indicating that there was no soil moisture stress (K_s = 1). That might be why the ET_c estimated using single coefficient method is close to the ET_c determined using soil water balance method. Approaches using dual coefficient (Eq. 14) and Eqs. (21 and 22) resulted in higher ET_c values. This might be due to the fact that in these approaches, the evaporation during the initial and late season stages was well simulated.

6. Conclusion

Two approaches of estimating crop evapotranspiration were demonstrated using a field crop grown in a semiarid environment of Australia. These approaches were the rootzone soil water balance and the crop coefficient methods. The components of rootzone water balance, except evapotranspiration, were measured/estimated. Evapotranspiration was calculated as an independent parameter in the soil water balance equation. Single crop coefficient and dual coefficient approaches were based on adjustment of the FAO 56 coefficients for local condition. AquaCrop was also used to estimate crop evapotranspiration using the dual coefficient approach. It was found that the dual coefficients, basal or transpiration coefficient K_{cb} and evaporation coefficient K_e, correctly depict the actual process. The effects of weather (rainfall and radiation) and crop phenology were correctly simulated in this method. However, single coefficient does not show the high evaporation component during the initial and late season stages. Generally, there is a strong agreement among different estimation methods except that the dual coefficient approach had better estimate during the initial and late season stages. The evapotranspiration estimated using different approaches was as follows: soil water balance (ET_a = 313 mm), single crop coefficient (ET_c = 332 mm), dual coefficient approach (ET_c = 366 mm with E of 79 mm and T of 288 mm), AquaCrop (ET_c = 382 mm with E of 139 mm and T of 243 mm). Evapotranspiration estimated using soil water balance method is actual evapotranspiration ET_a, while other methods estimate potential (maximum) evapotranspiration. Accordingly, ET estimated using rootzone water balance is lower than the ET estimated using the other methods. The single coefficient approach resulted in the lowest ET_c as it is not taking into account the evaporation spikes after rainfall during the initial and late season stages.

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This edition of Evapotranspiration - Remote Sensing and Modeling contains 23 chapters related to the modeling and simulation of evapotranspiration (ET) and remote sensing-based energy balance determination of ET. These areas are at the forefront of technologies that quantify the highly spatial ET from the Earth's surface. The topics describe mechanics of ET simulation from partially vegetated surfaces and stomatal conductance behavior of natural and agricultural ecosystems. Estimation methods that use weather based methods, soil water balance, the Complementary Relationship, the Hargreaves and other temperature-radiation based methods, and Fuzzy-Probabilistic calculations are described. A critical review describes methods used in hydrological models. Applications describe ET patterns in alpine catchments, under water shortage, for irrigated systems, under climate change, and for grasslands and pastures. Remote sensing based approaches include Landsat and MODIS satellite-based energy balance, and the common process models SEBAL, METRIC and S-SEBS. Recommended guidelines for applying operational satellite-based energy balance models and for overcoming common challenges are made.