Appendix 4. Consumptive Use and Evapotranspiration in the Farm Process

One of the fundamental parts of the Farm Process (FMP) is the calculation of consumptive water use according to land use. For MF-OWHM2, the consumptive use is defined as the consumption of water from any source to meet a land's use (or crop's) water consumption (evaporation and transpiration). The word "land use" in this report is synonymous with the word "crop" and may represent any simulated element that has a consumptive use. The term "crop" may represent a plant functional group that is either an aggregate of multiple crops or splits the same crop type into multiple plant functional groups, "crops," because the properties differ substantially. An example of aggregating is to lump different sets of berries, such as blackberries, blueberries, and raspberries, together as one crop and using one set of properties to define them. Plant functional groups may be location specific, however. For example, it may be necessary to split an FMP "crop"—such as strawberries—into two FMP "crops" because of spatial variability in the crop's properties such that coastal strawberries differ from inland strawberries.

The sections that follow describe how FMP calculates consumptive use, which becomes the demand component, and then attempts to satisfy it within water supply constraints. At a minimum, FMP requires specification for each crop includes a consumptive-use value, root length, soil capillary fringe, fraction of transpiration, and fraction of inefficient losses to surface water that comes from precipitation. If there are crops that receive applied water (irrigation), then irrigated crops additionally require an irrigation type flag, irrigation efficiency, fraction of evaporation from irrigation, and fraction of inefficient losses to surface water from irrigation. If the consumptive use is defined by a crop coefficient, then the user is required to specify a reference evapotranspiration. Published crop coefficients should cite the description of its associated reference evapotranspiration—typically, it is the evapotranspiration from well-watered grass of uniform height, actively growing, and completely shading the ground. For consistency in a simulation, it is required that all inputted crop coefficients refer to the same definition of reference evapotranspiration.

There are three methods available in the FMP to define how a land use's "root zone" interacts directly with groundwater and if the crop's potential consumptive use is reduced. The root-zone interaction with groundwater includes crop consumption of groundwater (called root groundwater uptake), crop anoxia reduction, and non-idealized soil stress reduction. The first method disables root groundwater update and consumptive-use reductions; the second is a linear root groundwater uptake and anoxia-limitation concept that takes into account the overlap between the groundwater capillary fringe and the root depth (*linear root response*); and the third is an analytical pseudo-steady state "reduced consumptive use" soil-moisture, soil-stress concept (*analytical root response*). If the *analytical root response* is used, then FMP requires the user to specify four stress-response root pressures, PSI, and the soil type in which the crop is grown—note PSI, or ψ, is in units of hydraulic head. Negative ranges of pressure heads reflect unsaturated conditions, whereas positive hydrostatic pressures reflect saturated conditions that act on the active roots zone and determine the extent to which the crop is under anoxic conditions, consumes groundwater, or wilts.

A fundamental assumption in FMP is that crops are grown in a unit-cropped area, which is partitioned into transpiratory-cropped area (leaf matter covered area) and evaporative-cropped area (exposed landscape). For most FMP simulations, the unit-cropped area is analogous to a single model cell's top-surface area. This assumption allows for the crop's consumptive use to be split into transpiration and evaporation components. These two components are further subdivided on the basis of consumption of water from groundwater, precipitation, and irrigation (applied water). This results in the consumptive use being split into six parts: transpiration from root groundwater uptake (T_{uptake}), transpiration from precipitation (T_p), transpiration from irrigation (T_{irr}), evaporation from irrigation (E_{irr}), evaporation from precipitation (E_p), and evaporation from groundwater (E_{gw}). The sum of these six terms is the final consumptive use (CU). Consumption of water is always calculated first, then any remaining water either becomes surface-water runoff or percolates through the root zone to groundwater as deep percolation. The priority order for satisfying consumption is always as follows:

1. Transpiration from root-groundwater uptake.
2. Transpiration from precipitation.
3. Transpiration from irrigation.
4. Evaporation from irrigation.
5. Evaporation from precipitation.
6. Evaporation from groundwater.

Although this appendix may seem complicated, with numerous variable definitions, the FMP minimum input is rather small. For a Crop that is not irrigated, FMP requires specification of the following for each unit-cropped area:

1. Spatial location of the crop.
2. Potential Consumptive Use specified as
   - the crop potential evapotranspiration or
   - a crop coefficient and reference evapotranspiration.
3. Root depth below land surface of the crop.
4. Fraction of transpiration (FTR, leaf covered area divided by unit-cropped area).
5. Precipitation runoff coefficient called fraction of inefficient losses from precipitation to surface water (FIESWP).

Although not directly related to the Crop, the following must be specified:

6. Soil capillary fringe length.
7. Precipitation rate (can be zero).

If the crop is irrigated, then the following, additionally, must be specified:

8. Sources of irrigation
   - Imported Water (Non-Routed Delivery, NRD).
   - Surface Water (Semi-Routed Delivery, SRD).
   - Groundwater well (FWEL).
9. Irrigation efficiency (OFE).
10. Irrigation runoff coefficient called fraction of inefficient losses from irrigation to surface water (FIESWI).
11. Fraction of Evaporation from Irrigation, which is the part of the unit-cropped area that is not covered by leaf matter but receives irrigation (FEI).

Equation Variable Definitions

This section provides a listing of variables and keywords used in this appendix and are presented in alphabetical order. The following name list is provided for convenience, and the names are formally defined in this appendix.

Area	is the unit-cropped area [L^2].
Anoxia	is level of anoxia, $0 \leq$ Anoxia [L^3/T].
BareArea	is the “bare soil” or fallow area—area not defined with an FMP land use type [L^2].
CIR	is the crop irrigation requirement assuming perfect efficiency [L^3/T].
CIR_{MAX}	is maximum quantity of irrigation with perfect irrigation efficiency that can be applied to a crop [L^3/T].
CU_{Bfinal}	is the final consumptive use for BareArea [L^3/T].
CU_{final}	is the final consumptive use for the unit-cropped area [L^3/T].
CU_{ini}	is the crop potential consumptive use [L/T].
$D_{irrigation}$	is the irrigation demand to satisfy the potential transpiration, $\tilde{T}_{pot}$ [L^3/T].
DP	is water that infiltrates to groundwater, deep percolation [L^3/T].
E_{act}	is the actual evaporation over the unit-cropped area [L^3/T].
E_{Bgw}	is the evaporation from groundwater for bare soil [L^3/T].
E_{Bgw_pot}	is the potential evaporation from groundwater [L^3/T].

E_{Bp}	is the evaporation from precipitation on bare soil; it is always equal to E_{Bpot} [L^3/T].
E_{Bpot}	is the potential evaporation from bare-soil evaporation or reference evapotranspiration [L^3/T].
E_{CIR}	is the potential consumption of irrigation water necessary to fully satisfy evaporation [L^3/T].
E_{GW}	is the amount of evaporation from groundwater [L^3/T].
E_{GWpot}	is the potential evaporation from groundwater [L^3/T].
$E_{irrigation}$	is the actual consumption of irrigation water as evaporation, which may be limited by T_{CIR} [L^3/T].
E_p	is the quantity of precipitation that is consumed by evaporation [L^3/T].
E_{pot}	is the potential evaporation from groundwater and precipitation in the unit-cropped area [L^3/T].
ET_c	is the crop potential evapotranspiration [L/T].
ET_{CIR}	is potential consumption of irrigation water necessary to fully satisfy evapotranspiration [L^3/T].
ET_{ref}	is the reference evapotranspiration [L/T].
FEI	is the fraction of the unit-cropped area that has irrigated water applied to the exposed soil part of the unit-cropped area (that is, the area not covered by the crop's leaf matter), $0 \leq FEI \leq 1 - FTR$ [-].
FIESWI	is the fraction of inefficient losses from irrigation to surface water, $0 \leq FIESWI \leq 1$ [-].
FIESWP	is the fraction of inefficient losses from precipitation to surface water, $0 \leq FIESWP \leq 1$ [-].
FTR	is the fraction of transpiration, $0 \leq FTR = K_{cb}/K_c \leq 1$ [-].
FWEL	FMP supply well, a groundwater well supply source.
IRR	is the total applied irrigation to a unit-cropped area [L^3/T].
IRR_{Ex}	is the excess irrigation that becomes either runoff or deep percolation, $IRR_{Ex} = IRR - IRR \cdot OFE$ [L^3/T].
K_c	is the crop coefficient, $0 < K_c$ [-].
K_{cb}	is the basal (transpiration) crop coefficient, $0 < K_{cb} \leq K_c$ [-].
NRD	Non-Routed Delivery, an imported water supply (conveyance not simulated).
OFE	is the irrigation efficiency, called on-farm efficiency, $0 < OFE \leq 1$ [-].
P	is precipitation that falls over the unit-cropped area [L/T].
P_{eff}	is effective precipitation in the unit-cropped area [L/T].
P_{Bare}	is precipitation that falls over the BareArea [L/T].
P_{BEpot}	is the potential evaporation of precipitation from bare-soil area [L^3/T].
P_{Epot}	is the potential evaporation from precipitation from unit-cropped area [L^3/T]; if $E_{pot} > P_{Epot}$, then $P_{Epot} = E_{pot}$.
P_{Tpot}	is the potential transpiration from precipitation [L^3/T]; if $T_{pot} > P_{Tpot}$, then $P_{Tpot} = T_{pot}$.
$Precip_{Ex}$	is the excess precipitation that becomes either runoff or deep percolation [L^3/T].
SRD	Semi-Routed Delivery, a surface-water supply source (SFR stream reach).
SW_R	is surface-water runoff from excess precipitation and irrigation [L^3/T].
T_{act}	is the actual transpiration in the unit-cropped area [L^3/T].
T_{CIR}	is the potential consumption of irrigation water necessary to fully satisfy transpiration [L^3/T].
$T_{irrigation}$	is the actual consumption of irrigation water as transpiration, which may be limited by available irrigation supplies [L^3/T].
T_p	is the quantity of precipitation that is consumed by transpiration [L^3/T].
T_{pot}	is the potential transpiration in the unit-cropped area [L^3/T].
$\tilde{T}_{pot}$	is potential transpiration after any anoxia reduction [L^3/T].
T_{surf}	is potential transpiration demand to consume precipitation and irrigation [L^3/T].
T_{uptake}	is the transpiration satisfied from root groundwater uptake [L^3/T].

Consumptive Use, Crop Coefficients, and Crop Fractions

MF-OWHM2 attempts to satisfy the potential consumptive use (CU_{ini}) with water supplies that originate from root groundwater uptake, precipitation, or applied water (irrigation) from imported water, surface-water, and groundwater sources. An imported water source represents water available for consumption, but its conveyance and delivery are not directly simulated. Surface-water sources are simulated as a diversion for a stream network. Groundwater sources originate from pumping wells that extract water from the underlying aquifers. Applied water supplies are subject to efficiency losses that reduce the water supply available for consumption by the land use. The initial demand (DMD_{ini}) of the land use is the total water required by CU_{ini} plus any inefficient losses incurred during consumption. If the land use is a crop, then it may have its CU_{ini} lessened because of anoxia from a high water-table in the root zone. If the water supply, less inefficient losses, cannot meet the CU_{ini}, less by anoxia, then the final consumptive use (CU) is reduced to equal the water supply. The excess water from applied water efficiency losses and precipitation that is not consumed by a land use becomes either surface runoff or percolates through the root zone to groundwater (deep percolation).

Consumptive use in the Farm Process (FMP) is either a directly specified potential consumptive-use ($CU_{specified}$) or calculated from a crop coefficient (K_c) and reference evapotranspiration (ET_{ref}). A crop coefficient is a published crop property that can be multiplied by a reference evapotranspiration to obtain a potential evapotranspiration of the crop (ET_c). Reference evapotranspiration represents the evapotranspiration from a standardized vegetated surface. The specific vegetated surface is defined by the crop coefficient, which is commonly an extensive surface of well-watered grass of uniform height, actively growing, and completely shading the ground—from this definition, the grass used to define ET_{ref} has a $K_c = 1$. In FMP, ET_{ref} is specified spatially, aligned with the surface model grid, whereas crop coefficients are defined for each simulated crop.

Estimates of reference evapotranspiration can be derived from direct measurements, physically based equations, or empirically based equations. An example of a direct measurement system is the California Irrigation Management Information System (CIMIS) station system, developed in 1982. The most detailed approximation of reference evapotranspiration is the Penman-Monteith equation (Snyder and Eching, 2002), but requires the largest amount of input information and field observations, including daily mean temperature, wind speed, relative humidity and solar radiation. Samani (2000) determined that temperature and radiation explain at least 80 percent of reference evapotranspiration. The Priestley-Taylor equation was developed as a simplified substitute to the Penman-Monteith equation that calculates reference evapotranspiration using only solar radiation (irradiance) observations and replaces the Penman-Monteith aerodynamic term with a dimensionless empirical factor. Another method is the Hargreaves-Samani equation (Hargreaves and Samani, 1982, 1985; Hargreaves and others, 1985; Hargreaves and Allen, 2003), which estimates reference evapotranspiration using temperature and solar radiation data. Climate simulation models, such as the Basin Characterization Model (Flint and Flint, 2014; Flint and others, 2015), may also provide the spatial approximations of reference evapotranspiration that are necessary for crop coefficients.

Obtaining values of crop coefficients involves both researching published values and communicating with local water districts and agriculture organizations for their measured coefficients. The crop coefficient should not be confused with a basal crop coefficient (K_{cb}), which is multiplied by a reference evapotranspiration to obtain potential transpiration for the crop (T_{pot}) rather than the crop's potential evapotranspiration (ET_c). For FMP, the potential evapotranspiration is the crop's initial-potential consumptive use. The calculation of the consumptive use is as follows:

$$CU_{ini} = ET_c = K_c \cdot ET_{ref} \tag{4.1}$$

where

CU_{ini} is the crop potential consumptive use [L/T];
ET_c is the crop potential evapotranspiration [L/T];
K_c is the crop coefficient [-], $0 < K_c$; and
ET_{ref} is the reference evapotranspiration [L/T].

The FMP input defines a crop's initial-potential consumptive use either as a value, with the keyword **CONSUMPTIVE_USE**, or as a crop coefficient, with the keyword **CROP_COEFFICIENT**. If both are supplied, then their sum is used by FMP—that is, $CU_{ini} = CU_{user\text{-}specified} + K_c \cdot ET_{ref}$. To make the FMP input's CU_{ini} clearer, it is recommended to only specify for each crop either a consumptive use or a crop coefficient—that is, not both at the same time for the same crop. The option to include both allows for a mixing of input or to separate crop consumption into two input parts, but its use is not recommended. Demands that are not consumed by the crop may be specified as an added demand for irrigated water (keyword **ADDED_CROP_DEMAND**).

The FMP has multiple methods for calculating the actual consumption of water that depend on different combinations of crop properties and available water sources. In all cases, the final supply must equal the demanded water by either lowering excess supply to meet demand or curtailing demand to meet the insufficient supply. The curtailing of demand is contradictory to economic descriptions of demand, but remains in this report to be consistent with past FMP publications that are focused on water balances, such that final water supply is always equal to final water demand. The order of consumption of different water supplies is always root groundwater uptake, precipitation, and then applied water. The order of consumption of applied water is always imported water sources, surface-water sources, and then groundwater sources. In FMP, imported water sources are called Non-Routed Deliveries (NRD), surface-water sources are called Semi-Routed Deliveries (SRD), and groundwater sources are called FMP supply wells (FWEL).

Root groundwater uptake and anoxia reduction are calculated either using the *linear root response* or the *analytical root response*. Both methods determine consumption of groundwater by a crop based on the relative distances between the water table and the capillary fringe with the land surface elevation and root zone. The water table is calculated by the MF-OWHM2 flow package and the capillary fringe is specified as an FMP soil property keyword **CAPILLARY_FRINGE**. The root zone is the vertical space from the land surface elevation to a user-supplied root depth. The land surface elevation and root depth are defined as part of the FMP input with the keywords **SURFACE_ELEVATION** and **ROOT_DEPTH**, respectively.

In the *linear root response*, the crop's consumption of groundwater, through its roots, increases linearly with increasing overlap between the crop's root zone and the water table plus the capillary fringe. If there is no overlap, there is no uptake. When the water table reaches the bottom of the root depth, the full consumptive use is fulfilled by root groundwater uptake (there is maximum overlap between the capillary fringe and root zone). After that point, increases in the water table result in anoxic conditions and the crop's consumptive use decreases as the water table increases its overlap with the root zone. The *analytical root response* calculates the pressure head acting on the crop's root zone (ψ_{root}) using the water-table elevation, capillary fringe, and an analytical function (appendix 5). FMP combines ψ_{root} with a set of four user-supplied stress-response root zone pressures (ψ_1, ψ_2, ψ_3, ψ_4, keyword **ROOT_PRESSURE**) to quantify a crop's anoxia, groundwater consumption, and wilting. A soil saturation is anoxic to the crop's roots when ψ_{root} is greater than ψ_2 and is lethal to the crop when ψ_{root} is greater than ψ_1. A crop can consume groundwater directly when ψ_{root} is greater than ψ_4 and the consumption of groundwater is optimal (that is, consumptive use is fully satisfied with groundwater) when ψ_2 is greater than ψ_{root} is greater than ψ_3. Wilting (no consumption of groundwater from the roots) occurs when ψ_4 is greater than ψ_{root}. The four pressures can be split into three zones of stress response, which are anoxic conditions (ψ_{root} is greater than ψ_2), groundwater consumption (ψ_{root} is greater than ψ_4), and wilting (ψ_4 is greater than ψ_{root}).

FMP's calculation of actual consumption starts by splitting the initial consumptive use into a transpiration component and evaporation component (fig. 4.1). This split is determined by a user-supplied crop property called the fraction of transpiration (FTR, keyword **TRANSPIRATION_FRACTION**). The fraction of transpiration is the crop-covered area (area of transpiration) per unit-cropped area and the remaining area is non-vegetated "exposed soil" (area of evaporation). The exposed soil area is assumed to only have evaporation of water from groundwater, precipitation, or excess irrigation that is applied to the exposed soil. The unit-cropped area is the surface area of a model cell or user-specified fraction of the model cell's surface area (multi-crop per cell option). The formal definition of FTR is the ratio the basal crop coefficient to the crop coefficient:

$$\mathrm{FTR} = \frac{K_{cb}}{K_c} \tag{4.2}$$

where

- FTR is the fraction of transpiration [-], $0 \le \mathrm{FTR} \le 1$;
- K_c is the crop coefficient [-], $0 < K_c$; and
- K_{cb} is the basal (transpiration) crop coefficient [-], $0 < K_{cb} \le K_c$.

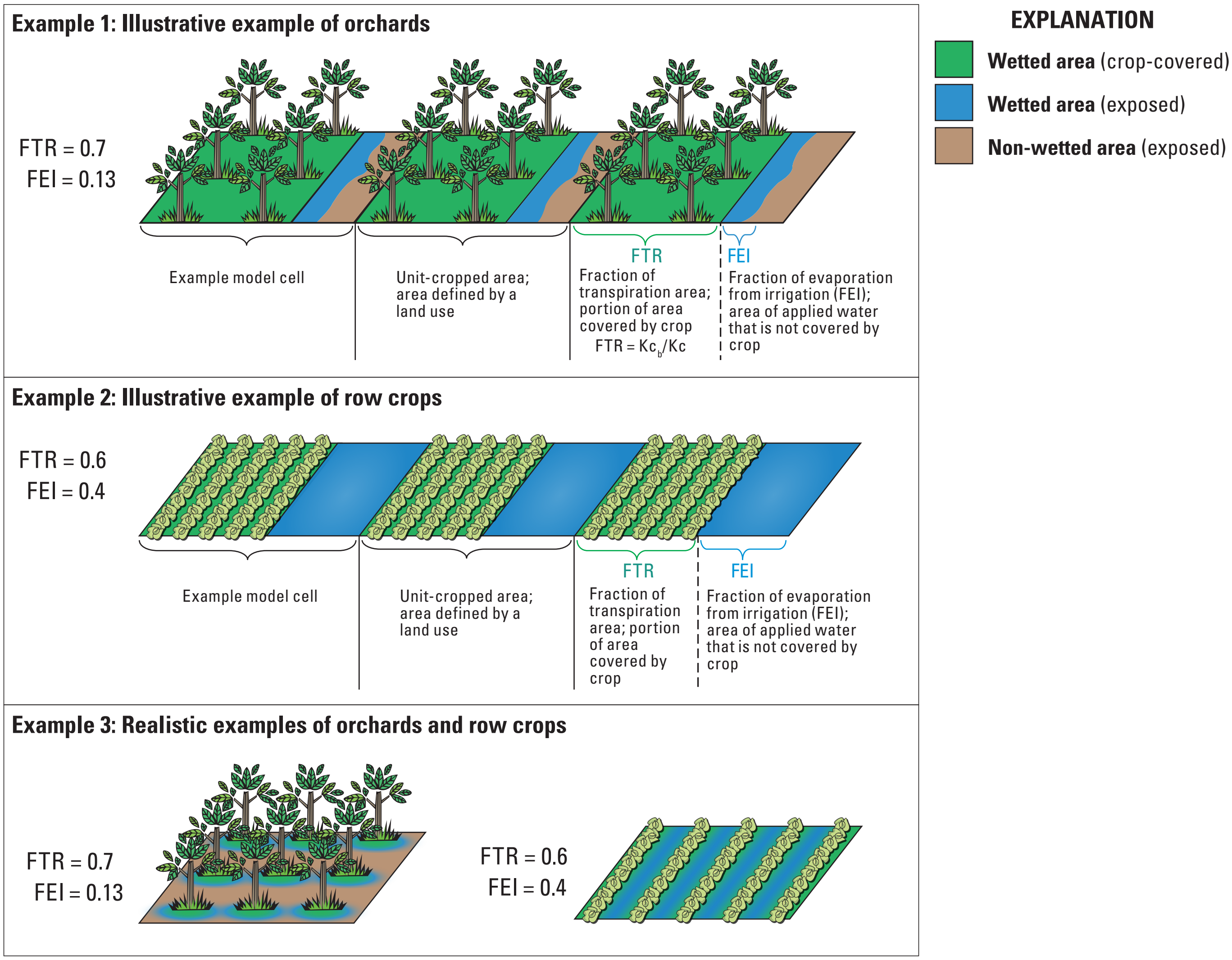

Figure 4.1. Spatial layout of the fraction of transpiration and the fraction of evaporation from irrigation for orchards and row crops (modified from Schmid and others, 2006).

The unit-cropped area is divided by the FTR to account for the crop transpiration of groundwater, precipitation, and applied water (irrigation), and the remaining unit-cropped area (1 – FTR) is assumed to contribute evaporation from groundwater and precipitation.

$$T_{pot} = CU_{ini} \cdot FTR \cdot Area \geq T_{act} \tag{4.3}$$

$$\begin{aligned} E_{pot} &= CU_{ini} \cdot (1 - FTR) \cdot Area + (T_{pot} - T_{act}) \\ &= CU_{ini} \cdot Area - T_{act} \end{aligned} \tag{4.4}$$

where

- Area is the unit-cropped area [L^2],
- T_{pot} is the potential transpiration in the unit-cropped area [L^3/T],
- T_{act} is the actual transpiration in the unit-cropped area [L^3/T], and
- E_{pot} is the potential evaporation from groundwater and precipitation in the unit-cropped area [L^3/T].

Determining potential and actual transpiration is discussed in detail in the “Satisfying the Potential Transpiration Component,” in the “Evaporation in a Unit-Cropped Area,” and in the “Evaporation in a Bare Soil Area” sections later in this appendix.

Precipitation is assumed to be distributed equally throughout the cropped area. The FTR provides a way of dividing rainfall available for potential consumption by the crop from rainfall that falls on the exposed soil (1 − FTR) and is available for potential evaporation. The following defines these relationships:

$$P_{Tpot} = P \cdot FTR \cdot Area \tag{4.5}$$

$$P_{Epot} = P \cdot (1 - FTR) \cdot Area \tag{4.6}$$

where

- P is precipitation that falls over the unit-cropped area [L/T];
- P_{Tpot} is the potential transpiration from precipitation [L^3/T], if $T_{pot} > P_{Tpot}$, then $P_{Tpot} = T_{pot}$; and
- P_{Epot} is the potential evaporation from precipitation [L^3/T], if $E_{pot} > P_{Epot}$, then $P_{Epot} = E_{pot}$.

The potential transpiration and evaporation from precipitation cannot exceed the respective total potentials defined in equation 3 and 4, respectively.

Irrigation water is primarily applied to the transpiratory-cropped area (crop covered, FTR), and some excess is applied to the evaporative-cropped area (exposed soil, 1 − FTR). To account for this, the fraction of evaporation from irrigation (FEI, keyword **EVAPORATION_IRRIGATION_FRACTION**) must be defined (fig. 4.1). FEI is the fraction of the unit-cropped area that is exposed soil and has irrigated water applied to it. FEI values depend on both the style of irrigation and the cultural agricultural practices. For example, drip irrigation has a small FEI, whereas flood irrigation has a large value (such as FEI = 1 − FTR). The limit of FEI is that its sum with FTR cannot be greater than one.

$$FTR + FEI \leq 1 \tag{4.7}$$

where

- FEI is the fraction of the unit-cropped area that has irrigated water applied to the exposed soil part of the unit-cropped area (that is, the area not covered by the crop’s leaf matter) [-], $0 \leq FEI \leq 1 - FTR$.

It should be noted that irrigation is the amount that can satisfy available potential transpiration and not the potential consumptive use (CU_{ini}). The available potential transpiration is the remaining portion of the potential transpiration after transpiratory consumption from groundwater and precipitation. If an irrigated crop does not consume any groundwater or precipitation (that is, $E_p = T_p = E_{GW} = T_{GW} = 0$), then the maximum quantity of irrigation with perfect irrigation efficiency (OFE = 1) is equal to equation 8.

$$CIR_{MAX} = CU_{ini} \cdot (FTR + FEI) \cdot Area \geq CIR \tag{4.8}$$

where

- CIR_{MAX} is maximum quantity of irrigation with perfect irrigation efficiency that can be applied to a crop [L^3/T], and
- CIR is the crop irrigation requirement assuming perfect efficiency [L^3/T].

The specific values of K_c and FTR depend on the type of crop grown and its growth stage, whereas FEI depends on irrigation practices. Crop coefficients may vary with time to represent different periods in the crop’s growth cycle throughout the year. If there are multiple crop yields within a year, then the annual time series of crop coefficients has a sawtooth shape. Typically, increases in K_c are also correlated with increasing K_{cb}, such that their ratio (FTR, eq. 4.2) stays relatively constant throughout the year. Annual variation in FTR should be much less than the variation in K_c. The FEI tends not to change unless the irrigation practices change or there is a violation of equation 7; that is, if the FTR plus FEI are greater than one, then the FTR and FEI are scaled so the sum equals one.

The largest area that a unit-cropped area can occupy is a single model cell's surface area. By default, crops are simulated on a cell-by-cell basis using each model cell's surface area as the unit-cropped area. If a unit-crop area is less than a model cell's surface area, then the remaining, non-cropped area is designated as "bare soil." If a model cell contains multiple crops (keyword **MULTIPLE_LAND_USE_PER_CELL**), then the "bare soil" area is equal to the model cell's surface area less the sum of the cell's crops' unit-crop areas. For example, if a model cell has a surface area of 100 m^2 and contained two crops that had unit-crop areas of 30 m^2 and 60 m^2, then the bare soil area is 10 m^2. Bare soil area only simulates evaporation from groundwater and precipitation, which is described in the "Evaporation in a Bare Soil Area" section. Bare soil calculations are included in case of incomplete datasets or to represent fallowed land, but it is recommended to fully described all crops such that there is no simulated bare soil. If a simulation contains bare soil (or multiple crops per model cell), then it is required to specify a potential bare-soil evaporation rate or the reference evapotranspiration (ET_{ref}) for FMP to calculate the bare soil evaporation from groundwater and precipitation. If both are specified, then the bare-soil evaporation rate is used. If the reference evapotranspiration is used to determine the potential bare soil evaporation, then it is assumed that the potential bare evaporation is half that of the reference evapotranspiration, which is the same as assuming a $K_c = 0.5$ (Allen and others, 1998). Instead of relying on bare soil calculations, it is recommended to define a "fallow crop" or "bare crop" type that contains a near-zero FTR and associated consumptive use.

Water from precipitation or irrigation not consumed by the crop either becomes surface runoff or infiltrates to groundwater (deep percolation). Excess precipitation is that precipitation not fully evaporated or consumed through transpiration. The irrigation efficiency (OFE) determines the excess irrigation required to meet demand after efficiency losses, which are referred to as inefficient losses. The fraction of inefficient losses from precipitation to surface water (FIESWP) and fraction of inefficient losses from irrigation to surface water (FIESWP) are used to determine the proportion of excess water that becomes surface-water runoff as follows:

$$IRR_{Ex} = IRR - IRR \cdot OFE \tag{4.9}$$

$$Precip_{Ex} = P - T_p - E_p \tag{4.10}$$

$$SW_R = Precip_{Ex} \cdot FIESWP + Irr_{Ex} \cdot FIESWI \tag{4.11}$$

$$DP = Precip_{Ex} \cdot \left(1 - FIESWP\right) + Irr_{Ex} \cdot \left(1 - FIESWI\right) \tag{4.12}$$

where

IRR_{Ex}	is excess irrigation that becomes either runoff or deep percolation [L^3/T];
IRR	is the total applied irrigation to a unit-cropped area [L^3/T];
T_p	is the quantity of precipitation that is consumed by transpiration [L^3/T];
E_p	is the quantity of precipitation that is consumed by evaporation [L^3/T],
$Precip_{Ex}$	is the excess precipitation that becomes either runoff or deep percolation [L^3/T];
OFE	is the irrigation efficiency, called on farm efficiency, $0 < OFE \leq 1$ [-];
SW_R	is surface-water runoff from excess precipitation and irrigation [L^3/T];
FIESWP	is the fraction of inefficient losses from precipitation to surface water [-], $0 \leq FIESWP \leq 1$;
DP	is water that infiltrates to groundwater, deep percolation [L^3/T];
Irr_{Ex}	is the excess irrigation not consumed by the crop [L^3/T]; and
FIESWI	is the fraction of inefficient losses from irrigation to surface water [-], $0 \leq FIESWI \leq 1$.

These two fractions are limited between 0 and 1 because they represent a split in the excess water between surface-water runoff and deep percolation.

For complex cropping, it may be necessary to aggregate multiple crop coefficients to make a composite coefficient that represents multiple crops within a time frame. Figure 4.2 presents the crop coefficient and fraction of transpiration used to describe deciduous orchard trees and raspberries, blackberries, and blueberries (Hanson and others, 2014d).

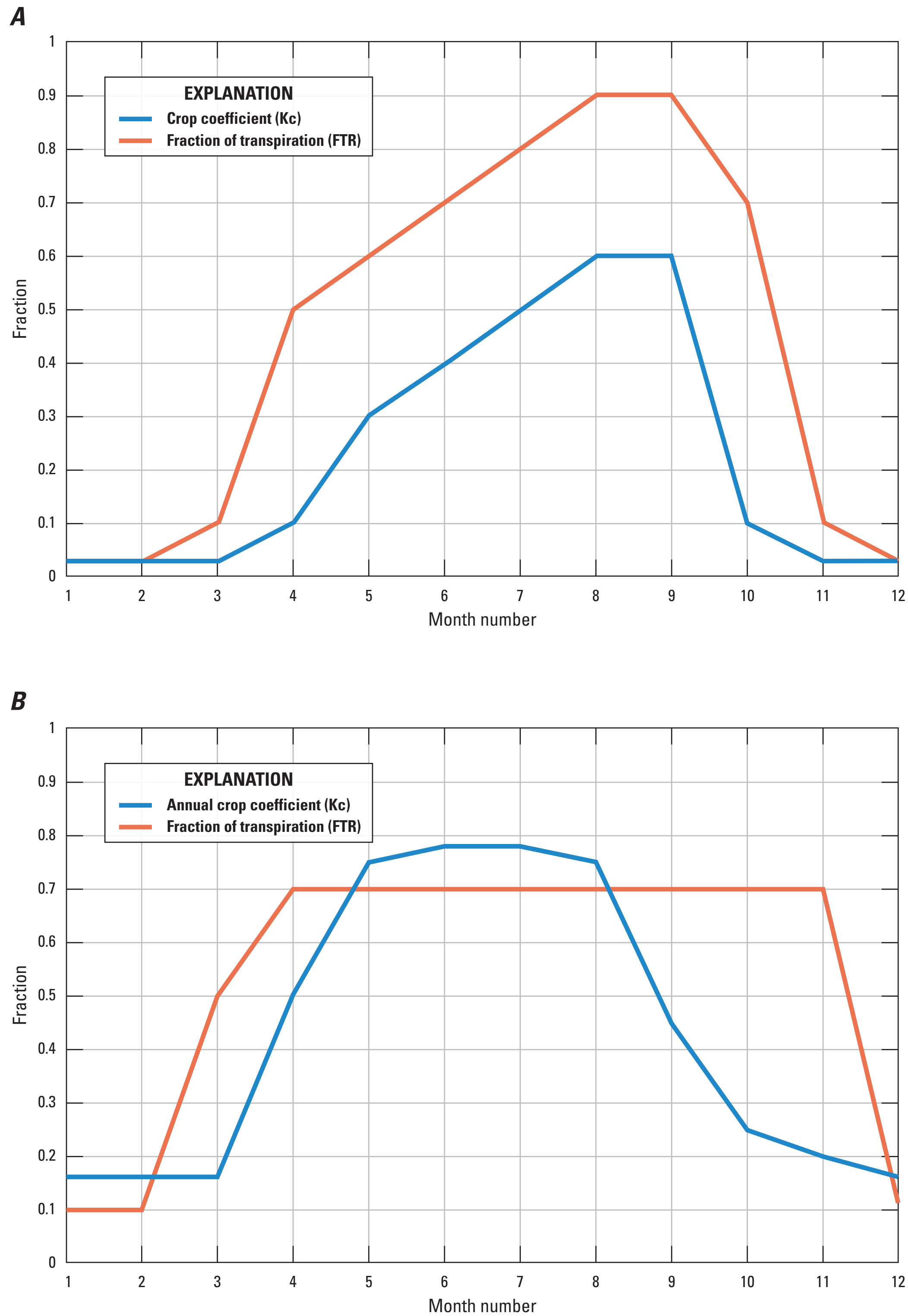

Figure 4.2. Monthly crop coefficients (K_c) and fractions of transpiration (FTR) used to represent the following crop types (modified from Hanson and others, 2014d): *A*, deciduous orchard trees; *B*, raspberries, blackberries, and blueberries.

Capillary Fringe, Root Depth, and Ponding

The FMP (farm process) determines transpiration and evaporation from crops and groundwater based on the overlap between the capillary fringe and crop root depth. The capillary fringe is the zone above the water table that contains water pulled upward by the porous medium's capillary forces (in FMP, this zone is a length added to the top of the water table). This is a property of the soil, and typical values span from 0.5 to 3 meters above the water table. Finer grained sediments typically have larger capillary fringe lengths compared to coarse material. Groundwater is assumed to evaporate when the water-table elevation plus the user-specified capillary fringe length is at or above the land surface. The root depth is a crop property that may change through time, depending on the growth stage of the crop. If the elevation represented by the water table added to the capillary-fringe length is greater than the land surface minus the root depth, then this crop takes up groundwater as part of its consumptive use. If the water-table elevation added to the capillary fringe overlaps too much of the root zone, the soil becomes anoxic (the crop starts to drown). If the water table reaches the land surface, plants may die. Some riparian vegetation and crops, such as rice, can sustain evapotranspiration under flooded conditions.

Three methods are available in FMP to prevent plant death and anoxia. The first is to remove root groundwater uptake and anoxia completely and require full consumptive use from precipitation and applied water. The second is to specify a ponding level for the *linear root response* groundwater uptake and anoxia concept. This alters the slope of the linear anoxia level to cause plant death to coincide with the land-surface elevation added to the ponding depth of the water. The third is to specify positive root zone pressures, PSI, for the *analytical root response* concept to indicate the water-table is above the cropped land surface. For crops that are semiaquatic, disconnected from the groundwater source, or are constantly ponded, it is recommended to remove root groundwater uptake and anoxia completely (by setting **GROUNDWATER_ROOT_INTERACTION** to 1 for the crop). An example crop that this works best for is rice, which grows in flooded areas or paddy fields.

Consumptive-Use Stress Factor

Typically, consumptive-use estimates and crop coefficients are based on idealized, unstressed conditions. MF-OWHM2 has two methods for accounting for stress on a crop. The first method uses the analytical pseudo-steady state soil-moisture, "reduced consumptive use" (*analytical root response*) concept for crops. This was developed as part of the original release of the FMP (Schmid and others, 2006). It requires the user to input a set of values for four stress-response root zone pressures, called PSI values, that indicate pressure ranges over which the crop optimally uptakes groundwater, wilts, or suffers from anoxia. The second input requirement is the soil type in which it grows, which can be one of four types: silt, silty clay, sandy loam, or sand. This feature results in a minor reduction in the consumptive use because the soil is not an ideal matrix. The FMP also may further reduce consumptive use as a result of anoxia (drowning of the roots due to high water table). It is not necessary to define all crops by PSI root pressures, but if one crop is defined with it, then it is required to define the soil type for the entire model. Any crops not defined with PSI values do not have consumptive use reduced because of non-idealized soil, but may have it reduced because of anoxia (note that setting all the PSI values to zero is the same as not specifying them).

Another method to account for stress is to include a climatic scale factor. A common practice for the U.S. Geological Survey MF-OWHM2 models is to use the cumulative departure from the mean (CDM) of precipitation to identify wet and dry periods of record (Faunt and others, 2009, 2015; Hanson and others, 2014a–c). The CDM takes a precipitation record (monthly or annual) and compares the mean precipitation ($\bar{P}$) for the entire record to a cumulative summation over the *m* individual departure records. If the change in the CDM is negative or follows a downward trend, the period is considered dry. Conversely, a positive change or upward trend is considered wet. The formal steps for calculating the CDM are as follows:

$$\begin{aligned} \bar{P} &= \frac{1}{m}\sum_{i=1}^{m} P_i \\ CDM_1 &= \left(P_1 - \bar{P}\right) \\ CDM_i &= \left(P_i - \bar{P}\right) + CDM_{i-1} \qquad \forall i = 2:m \end{aligned} \tag{4.13}$$

An example from the Pajaro Valley that has an annual period of record from 1880 to 2014 is presented in figure 4.3. At the start of the record, the change from the first year, 1880, to the second, 1881, is negative, so 1881 is considered a dry period. Conversely, the tenth data point, 1889, has a positive change to the next year, 1890, so the year of 1890 is considered a wet year.

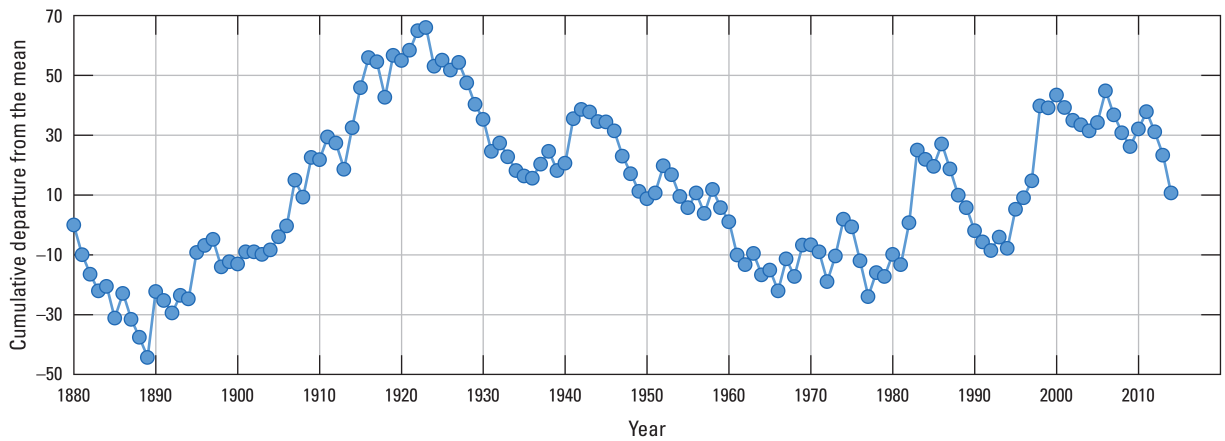

Figure 4.3. Example cumulative departure from the mean from an annual precipitation record for 1880 to 2014 from the integrated hydrologic model of Pajaro Valley (Hanson and others, 2014a).

The scale factors that incorporate climate stress are described by Allen and others (1998, 2005) as an additional stress factor that is used to scale the unstressed crop coefficients. They are commonly broken into a wet-seasonal group and dry-seasonal group of stress factors. This results in eight seasonal wet- and dry-year climatic scale factors: wet-fall, wet-winter, wet-spring, wet-summer, dry-fall, dry-winter, dry-spring, and dry-summer. These eight scale factors are applied to the consumptive use and the crop coefficients. To minimize the number of parameters, it is recommended to use one scale factor that multiplies all the different crop coefficients. For example, if there are NCROPs and the stress period is simulating January during a dry year, then the NCROP crop coefficients are all multiplied by the dry-winter scale factor. Previous publications (Hanson and others, 2014a–d) have scale factors greater than one (increase) for dry years and less than one (decrease) for wet years.

If the crops receive applied or irrigation water (non-zero irrigation flag), then there is an associated irrigation efficiency to account for efficiency losses. Irrigation efficiency is also multiplied by its own set of wet or dry seasonal scale factors. During dry periods, most agricultural practices tend to become more efficient as a result of the scarcity of water, so dry-year scale factors tend to be greater than one. Conversely, during wet periods, a common practice is to specify a lower efficiency, or wet-year scale factors less than one, because water is not scarce.

Satisfying the Potential Transpiration Component

The potential transpiration component (T_{pot}) is the maximum possible rate at which a crop may transpire for its given consumptive use. It is calculated from the fraction of transpiration (FTR), which is assumed to be independent of whether the potential transpiration component is satisfied by root groundwater uptake, precipitation, or applied water. This results in the following formulation:

$$T_{pot} = K_c \cdot ET_{ref} \cdot FTR \cdot Area = CU_{ini} \cdot FTR \cdot Area \geq T_{act} \quad (4.14)$$

The FMP attempts to satisfy the potential transpiration with the consumption of water from root groundwater uptake, precipitation, and applied water (irrigation). Based on the user-specified root-groundwater interaction level, anoxia and root groundwater uptake are calculated. If anoxia is included, it is determined by the water-table elevation and adjusts the potential transpiration as follows:

$$\tilde{T}_{pot} = T_{pot} - Anoxia \quad (4.15)$$

where

$\tilde{T}_{pot}$ is potential transpiration after any anoxia reduction [L^3/T], and

Anoxia is level of anoxia [L^3/T], $0 \leq Anoxia$.

Once the anoxia level is calculated, the root groundwater uptake, T_{uptake}, is determined by the root-groundwater interaction level.

The FMP is capable of simulating five root-groundwater interaction levels, which are outlined in figure 4.4. The different levels determine if a crop root is capable of consuming groundwater (root groundwater uptake = yes), if its consumptive use is reduced from anoxia (anoxia reduction = yes), and if its consumptive use is reduced as a result of soil-water-related stresses (soil stress reduction = yes). The default FMP approach, and the only option in previous releases, is level 5.

The first root-groundwater interaction level is to not have any interaction between the groundwater and the crop roots. With this option, defining the crop-root depth is optional and may be set to zero. The consumptive use is not lowered as a result of anoxia or stress conditions. It may be lowered, however, if there is not enough water supply to satisfy the transpiration demand, resulting in wilting conditions. This method is best for crops that are always disconnected from groundwater or do not suffer from anoxia, such as rice. The next level allows anoxia to reduce transpiration of the crop and consequently the consumptive use, but does not allow any root groundwater uptake, thus requiring all consumption of water to be from precipitation and irrigation. The third level is the opposite of the second, allowing for root groundwater uptake, but not reductions from anoxia or wilting. This may be best for native vegetation areas that do not suffer from anoxia and rely on root groundwater uptake as their main water source. Lastly, the fifth level is full interaction between the groundwater and the crop roots. Using the fifth level, if anoxia exists in the root zone, then the crop's reduced transpiration demand only consumes groundwater by root uptake. In previous releases of FMP, the fifth level was the only option, and with this release, it becomes the default if the root groundwater-interaction flag is not specified. If the water-table elevation plus the capillary fringe is lower than the land surface minus the root depth, then there is no root groundwater interaction, and all water consumption must come from surface sources (precipitation and irrigation).

If there is root-groundwater interaction in the form of groundwater uptake or anoxia, two concepts determine the amount of uptake and anoxia. The first is the *linear root response,* which is described in detail in appendix 5 as an "implicit stress assumption" or "non-reduced consumptive use" concept that relies on a piecewise linear approximation of root groundwater uptake and anoxia. This assumes that there is a linear increase in root groundwater uptake when the water table added to the capillary fringe intersects the crop's roots, and the full potential transpiration is taken up until the water table reaches the bottom of the roots. If the water table intersects the root depth, then the crop's transpiration decreases as a result of anoxia; transpiration progressively decreases as the water-table rise continues until the water table reaches the land surface (plus a ponding depth if specified). Once the water table is at the land surface, the crop is assumed to have drowned and no longer transpires water.

The second is the *analytical root response,* which is described in detail in appendix 5 as an analytical pseudo-steady state soil-moisture, "reduced consumptive use" soil-stress concept or so-called "explicit stress response." First, the user must supply the soil type in which the crop is grown. This can be defined as *silt, silty clay, sandy loam,* or *sand*; these soil types are used to determine any water-stress related reduction in transpiration. The user must also supply four root-zone pressures, PSI, that represent the upper pressure head limit at which the root uptake becomes zero because of anoxia, then two pressure heads that represent the range of optimal root uptake, and then finally a lower pressure head limit that results in wilting or zero root uptake.

Level	Root groundwater uptake	Anoxia reduction	Water-stress reduction
0	—	—	—
1	No	No	No
2	No	Yes	Yes
3	Yes	No	No
4	Yes	No	Yes
5	Yes	Yes	Yes

Figure 4.4. Farm Process (FMP) crop root-groundwater interaction level's effect on the calculation of potential evapotranspiration (ET_c). Level zero sets the crop's potential evapotranspiration to zero. [— indicates the crop evapotranspiration process is not simulated, so it is neither yes or no. Root groundwater uptake is the process that a crop's roots can consume water directly from saturated groundwater. Anoxia reduction can reduce ET_c because the water table overlaps with the crop's roots. Water-stress reduction can reduce ET_c resulting from non-idealized soil effects.]

Using an iterative, empirical formulation, the soil-water pressure in the root zone is calculated according to the soil type, PSI root pressures, and the water-table elevation plus capillary fringe (see appendix 5). This root-zone pressure then determines water-stress and anoxia transpiration reduction and root groundwater uptake.

After the level of anoxia and transpiratory direct uptake from groundwater, $T_{uptake,}$ is determined, any remaining transpiration demand is supplied by surface supplies (precipitation and irrigation). The following is the demand for surface-supplied transpiration:

$$T_{surf} = \tilde{T}_{pot} - T_{uptake} \tag{4.16}$$

where

T_{surf} is potential transpiration demand to consume precipitation and irrigation [L^3/T].

The demand for surface-supplied transpiration first uses any available precipitation for transpiration, P_{Tpot}, to yield the final contribution of precipitation to transpiration, T_p. If any unmet transpiration demand remains, then it must be satisfied with irrigation water.

$$T_{CIR} = \tilde{T}_{pot} - T_{uptake} - T_p \geq T_{irrigation} \tag{4.17}$$

where

T_{CIR} is the potential consumption of irrigation water necessary to fully satisfy transpiration [L^3/T], and
$T_{irrigation}$ is the actual consumption of irrigation water as transpiration, which may be limited by available irrigation supplies [L^3/T].

If the crop is not irrigated ($T_{irrigation} = 0$), then its transpiration is reduced as a result of wilting conditions; consequently, its consumptive use is reduced. If the crop is irrigated, then FMP attempts to fulfil T_{CIR} using imported water, surface water, and groundwater pumping.

If the irrigation supplies are enough to fulfill the potential transpiration demand from irrigation, then $T_{irrigation} = T_{CIR}$. The total irrigation water required to satisfy the potential transpiration (T_{CIR}) and evaporation demand (E_{CIR}) for irrigation is the crop irrigation requirement (CIR). FMP assumes that evaporation from irrigation varies linearly with the transpiration from irrigation. With this assumption, the total evapotranspiration from irrigation and CIR can be calculated as follows:

$$\frac{E_{CIR}}{T_{CIR}} = \frac{FEI}{FTR} = \frac{E_{irrigation}}{T_{irrigation}} \tag{4.18}$$

$$CIR = ET_{CIR} = \left(FEI / FTR\right) \cdot T_{CIR} + T_{CIR} \tag{4.19}$$

$$D_{irrigation} = CIR / OFE \tag{4.20}$$

where

T_{CIR} the potential consumption of irrigation water necessary to fully satisfy transpiration [L^3/T];
E_{CIR} is the potential consumption of irrigation water necessary to fully satisfy evaporation [L^3/T];
$E_{irrigation}$ is the actual consumption of irrigation water as evaporation, which may be limited by T_{CIR} [L^3/T];
ET_{CIR} is potential consumption of irrigation water necessary to fully satisfy evapotranspiration [L^3/T];
CIR is the crop irrigation requirement assuming perfect efficiency [L^3/T];
OFE is the irrigation efficiency, called on-farm efficiency, $0 < OFE \leq 1$ [-]; and
$D_{irrigation}$ is the irrigation demand to satisfy the potential transpiration, $\tilde{T}_{pot}$ [L^3/T].

To meet the irrigation demand ($D_{irrigation}$, eq. 4.20), imported water is applied first, then surface water, then any remaining irrigation required is supplied by groundwater pumping up to the maximum capacity of the wells.

If groundwater pumping is not enough to satisfy the $D_{irrigation}$, there are two potential scenarios. With the first, “deficit irrigation,” the crop suffers from wilting from a lack of water and its actual transpiration is decreased to meet the water supplies. To calculate the actual transpiration from irrigation under a deficit irrigation scenario, equations 19 and 20 can be reformulated as follows:

$$T_{irrigation} = \frac{IRR \cdot OFE}{1 + FEI / FTR} \quad (4.21)$$

where

IRR is the total applied irrigation to a unit-cropped area [L^3/T].

The second scenario is called the “external water scenario.” Under this situation, it is assumed that the crop receives additional water from unknown sources to meet the demanded irrigation, $D_{irrigation}$. If the external water is applied, then the transpiration from irrigation is fully met ($T_{irrigation} = T_{CIR}$).

The final transpiration is the sum of its three transpiration components:

$$T_{act} = T_{uptake} + T_p + T_{irrigation} \quad (4.22)$$

Evaporation in a Unit-Cropped Area

The total evaporation from a unit-cropped area is subdivided into three sources: irrigation, precipitation, and groundwater. FMP first calculates the evaporation from irrigation ($E_{irrigation}$), then evaporation from precipitation (E_p), then evaporation from groundwater (E_{GW}).

Evaporation from Irrigation

The evaporation from irrigation depends on the amount of water applied to the crop and is correlated to the transpiration from irrigation. Conversely, precipitation and groundwater evaporation have a maximum rate equal to the potential evaporation rate from groundwater and precipitation, E_{pot}, which is determined by the fraction of transpiration (FTR) with equation 4.

The evaporation from irrigation is assumed to vary linearly with transpiration from irrigation and follows the relationship defined in equation 18. This relationship necessitates first evaluating the transpiration demanded from irrigation and the corresponding amount of applied water. For a given amount of applied water, irrigation efficiency, and fractions of transpiration and evaporation supplied by irrigation, the final evaporation loss from irrigation water is calculated as follows:

$$E_{irrigation} = \left(FEI / FTR\right) \cdot T_{irrigation} \quad (4.23)$$

Evaporation from Precipitation

After the evaporation from irrigation is established, then evaporation from precipitation is calculated. By default, FMP assumes that evaporative consumption of precipitation (E_p) is equal to the calculated potential evaporation rate such that $E_p = P_{Epot}$ (eq. 4.6). This assumption works well for arid and semi-arid simulation domains, but can lead to an overconsumption of precipitation if there is frequent high intensity, short duration rainfall a simulated time step. To prevent overconsumption, FMP supports specifying an upper limit for consumption of precipitation, which is discussed in the “Limiting Precipitation Consumption” section.

Evaporation from Groundwater

This changes the potential evaporation for groundwater as follows:

$$E_{GWpot} = E_{pot} - E_p - E_{irrigation} \tag{4.24}$$

where

E_{GWpot} is the potential evaporation from groundwater [L^3/T].

Groundwater only evaporates when the water-table elevation added to the user-specified capillary fringe depth is above the land-surface elevation. When this occurs, there is a linear increase in evaporation from groundwater as the water table rises to reach its maximum, E_{GWpot}, when the water table is above the land surface.

The actual evaporation over the total cropped area (crop covered area and exposed area) is then the sum of the three evaporative components:

$$E_{act} = E_p + E_{GW} + E_{irrigation} \tag{4.25}$$

where

E_{act} is the actual evaporation over the unit-cropped area [L^3/T],
E_p is the quantity of precipitation that is consumed by evaporation [L^3/T], and
E_{GW} is the amount of evaporation from groundwater [L^3/T].

Evaporation in a Bare Soil Area

The bare-soil evaporation represents any area that is not specified with a crop (undefined area). Bare soil is not the same as "exposed soil," which is the area not covered by leaf matter (1 − FTR). Bare soil does not include transpiration (FTR = 0) and follows the same calculation process described the "Evaporation in a Unit-Cropped Area" section (E_{pot}), except the potential evaporation (E_{Bpot}) is different and there is no irrigated evaporative component. If there are bare soil cells in the model, then the user is required to specify either a potential bare-soil evaporation rate (E_{Bpot}) or the reference evapotranspiration rate (ET_{ref}), which represents the upper limit of bare soil evaporation. If both rates are specified, then the bare-soil evaporation rate is used. As with satisfying evaporation from crops, precipitation evaporates first, and its rate is calculated as follows:

$$P_{BEpot} = P_{Bare} \cdot \text{BareArea} \tag{4.26}$$

where

P_{BEpot} is the potential evaporation of precipitation [L^3/T],
BareArea is the bare-soil area [L^2], and
P_{Bare} is precipitation that falls over the BareArea [L/T].

This allows for the potential evaporation from groundwater to be this:

$$E_{Bgw\_pot} = E_{Bpot} - P_{BEpot} \tag{4.27}$$

where

E_{Bgw_pot} is the potential evaporation from groundwater [L^3/T], and
E_{Bpot} is the potential evaporation from bare-soil evaporation or reference evapotranspiration [L^3/T].

Groundwater under bare soil only evaporates when the water-table elevation plus the user-specified capillary fringe depth is greater than the land-surface elevation. When this occurs, there is a linear increase in evaporation from groundwater under bare soil, E_{Bgw}, as the water table rises, and it reaches its maximum, E_{Bgw_pot}, when the water table is above the land surface.

Limiting Precipitation Consumption

In FMP, precipitation that falls over a landscape is either consumed as evapotranspiration (as part of CU_{final}), flows away over the land surface as runoff, or percolates below the root zone of the Crop (deep percolation). In FMP, effective precipitation (P_{eff}) is the portion of precipitation that is potentially consumable by the crop. The FMP assumes that the difference between precipitation and effective precipitation ($P - P_{eff}$) represents the quantity of water that always becomes runoff. It should be noted that if a Crop does not consume all of P_{eff}, then the unconsumed portion ($P_{eff} - CU_{final}$, given that P_{eff} is greater than CU_{final}) becomes deep percolation and additional runoff. Factors that influence P_{eff} include the climate, soil texture, soil structure, and the depth of the root zone.

By default, FMP assumes that the potential consumption of precipitation is limited to a Crop's consumptive use less any groundwater consumption, which is analogous to $P = P_{eff}$. This assumption works well for arid and semi-arid simulation domains. If a simulation's stress period contains frequent, high-intensity, short duration rainfall, then the equivalent stress period precipitation can result in an overconsumption of precipitation. To prevent overconsumption, the FMP allows specifying effective precipitation, which serves as an upper limit for consumption of precipitation. If effective precipitation is specified as part of the simulation, then FMP replaces equations 6, 7, and 11 with equations 28, 29, and 30.

$$\begin{aligned} &\text{if } P > P_{eff} \\ &\qquad P_{Tpot} = P_{eff} \cdot FTR \cdot Area \\ &\text{else} \\ &\qquad P_{Tpot} = P \cdot FTR \cdot Area \end{aligned} \tag{4.28}$$

$$\begin{aligned} &\text{if } P > P_{eff} \\ &\qquad P_{Epot} = P_{eff} \cdot \left(1 - FTR\right) \cdot Area \\ &\text{else} \\ &\qquad P_{Epot} = P \cdot \left(1 - FTR\right) \cdot Area \end{aligned} \tag{4.29}$$

$$\begin{aligned} &\text{if } P > P_{eff} \\ &\qquad SW_R = Precip_{Ex} \cdot FIESWP + Irr_{Ex} \cdot FIESWI + \left(P - P_{eff}\right) \\ &\text{else} \\ &\qquad SW_R = Precip_{Ex} \cdot FIESWP + Irr_{Ex} \cdot FIESWI \end{aligned} \tag{4.30}$$

where

P_{eff} is effective precipitation in the unit-cropped area [L/T].

Final Consumptive Use

The final consumptive use is the summation of the transpiration from the crop, evaporation from the crop, and evaporation from bare soil. Typically, a model cell has been defined as to crop or is simulated as bare soil. This results in a total summation as follows:

$$\begin{aligned} CU_{final} &= T_{uptake} + T_p + T_{irrigation} + E_p + E_{GW} + E_{irrigation} \\ CU_{Bfinal} &= E_{Bp} + E_{Bgw} \end{aligned} \tag{4.31}$$

where

CU_{final} is the final consumptive use for the unit-cropped area $[L^3/T]$;

CU_{Bfinal} is the final consumptive use for the BareArea (L^3/T);

T_{uptake} is the transpiration satisfied from root groundwater uptake $[L^3/T]$;

T_p is the quantity of precipitation that is consumed by transpiration $[L^3/T]$;

$T_{irrigation}$ is the transpiration satisfied from irrigation $[L^3/T]$;

E_p is the quantity of precipitation that is consumed by evaporation $[L^3/T]$;

E_{GW} is the evaporation from groundwater $[L^3/T]$;

$E_{irrigation}$ is the evaporation from applied water (irrigation) $[L^3/T]$;

E_{Bp} is the evaporation from precipitation on bare soil, which is always equal to E_{Bpot} $[L^3/T]$; and

E_{Bgw} is the evaporation from groundwater for bare soil $[L^3/T]$.

The final consumptive use is in units of volume per time, even though the initial input was in units of length per time. To express the final consumptive use in units of length, it must be divided by the cropped area (Area) or bare-soil area (BareArea).

Flow Chart of Evapotranspiration Calculation and Data Requirement Options

The diagrams that follow provide an overview of the final consumptive-use calculation and the data required. The consumptive-use estimation assumes that a crop may be irrigated, so irrigation options are included as required input. Figure 4.5 shows that the workflow path of consumptive-use estimation for an individual crop requires specification of a sequence of attributes that are conditioned by the set of options specified by the user, starting with the consumptive-use concept and then branching through the respective options for the two concepts.

The other component of consumption is bare-soil evaporation. Figure 4.6 shows the estimation sequence for the evaporation component (E) of evapotranspiration for the remainder of the area in a model cell (exposed soil) that is not contributing to consumptive use through the canopy and transpiration.

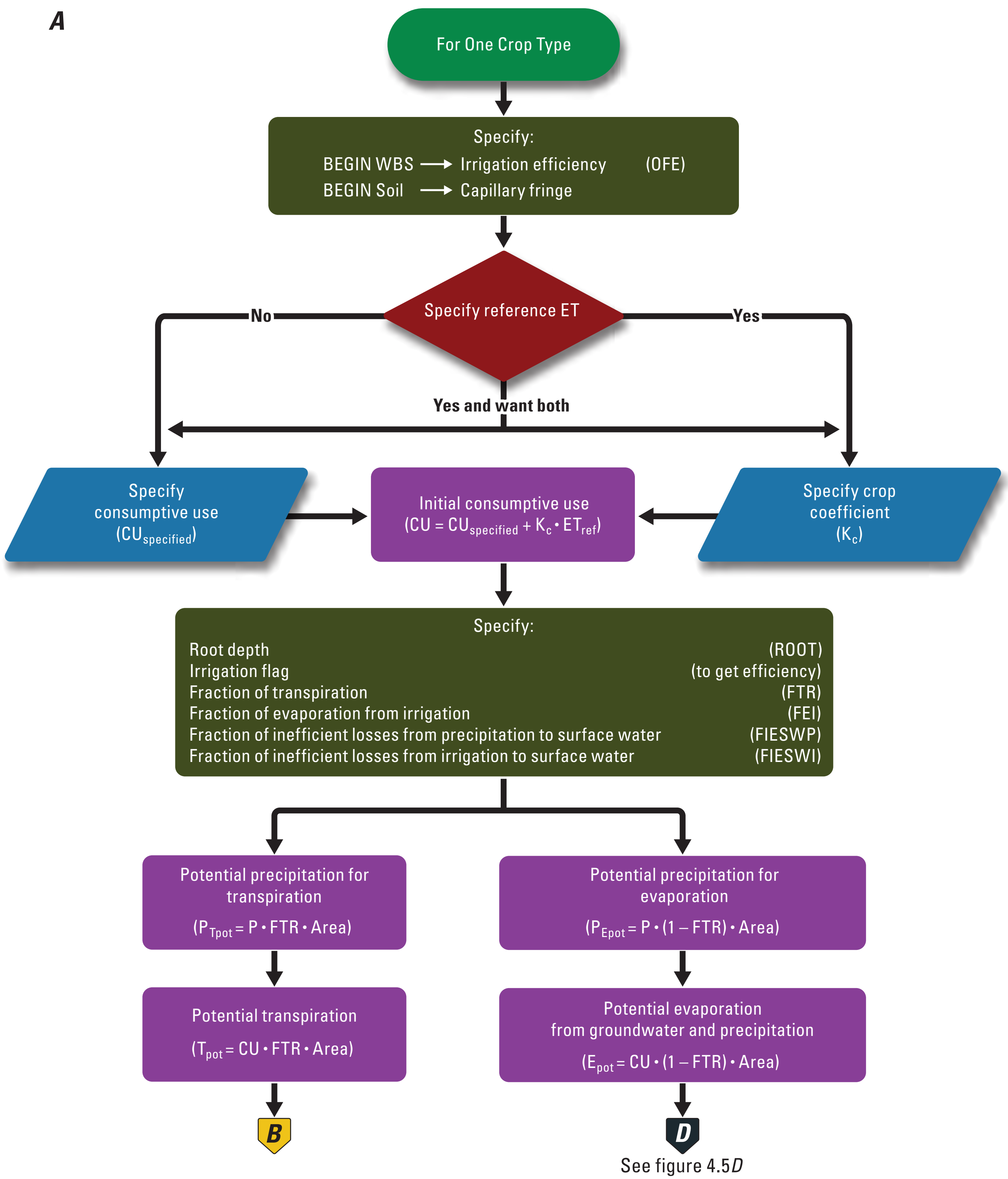

Figure 4.5. The FMP (farm process) evapotranspiration calculation and data requirements.

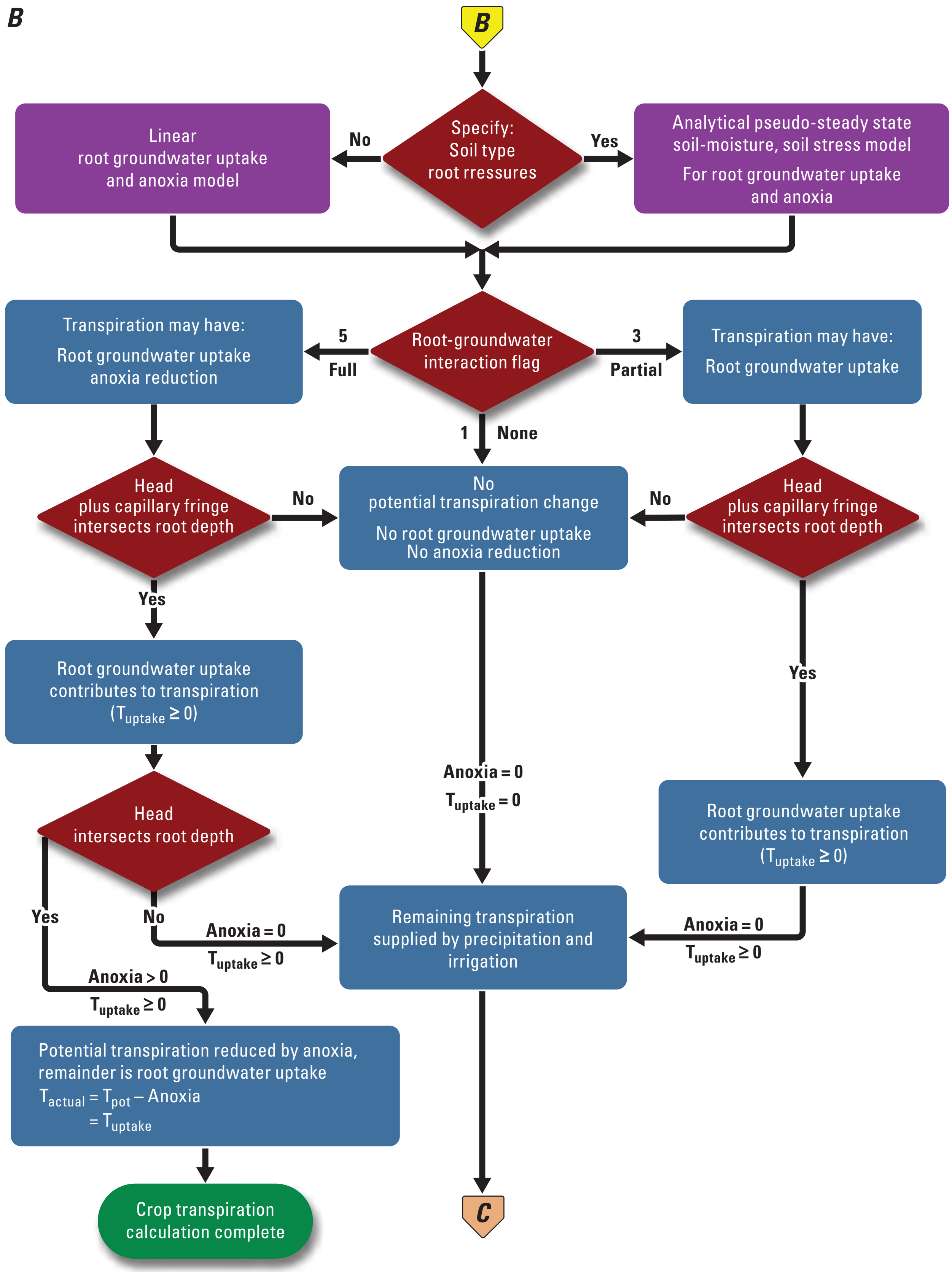

Figure 4.5. —Continued

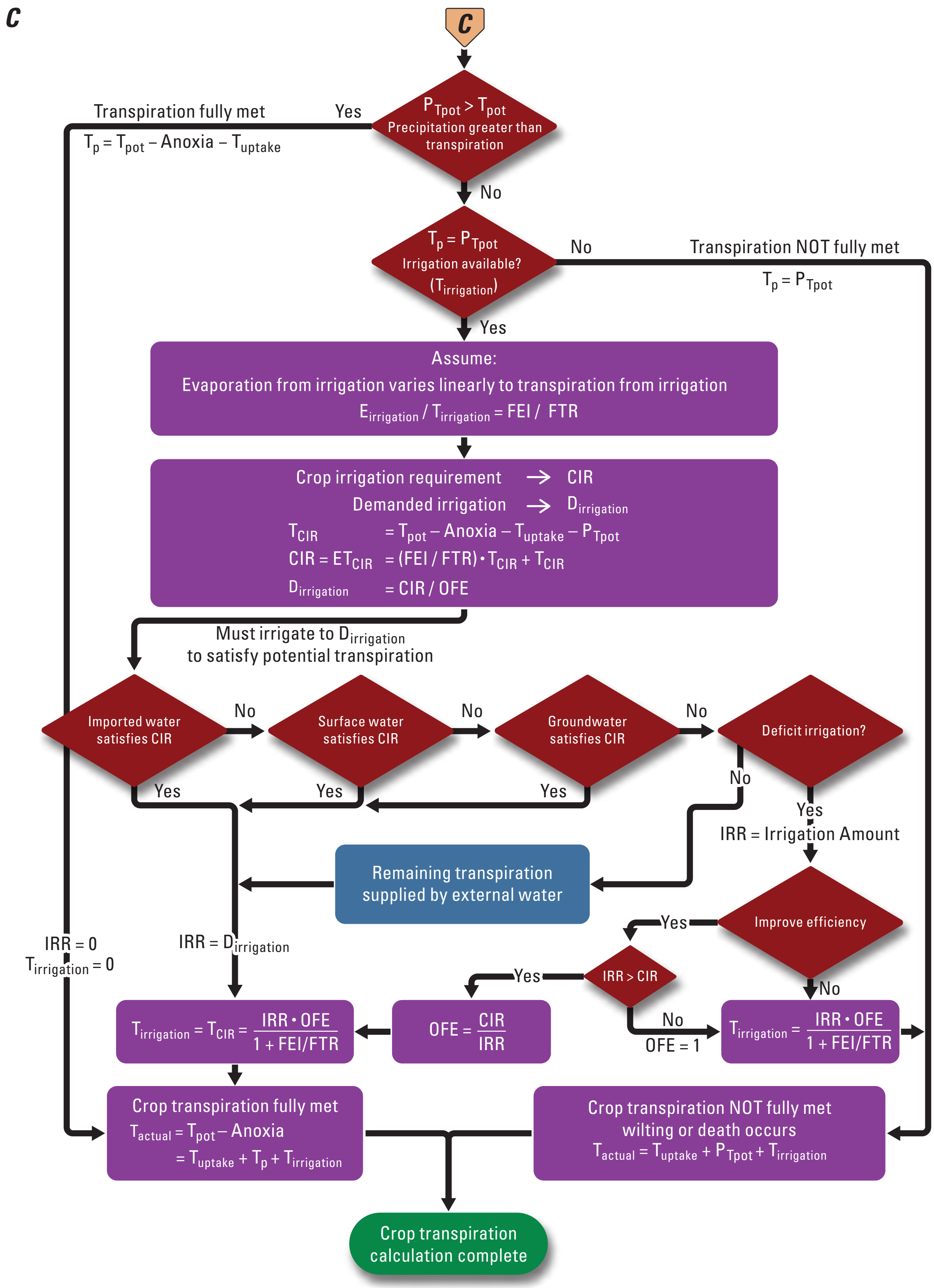

Figure 4.5. —Continued

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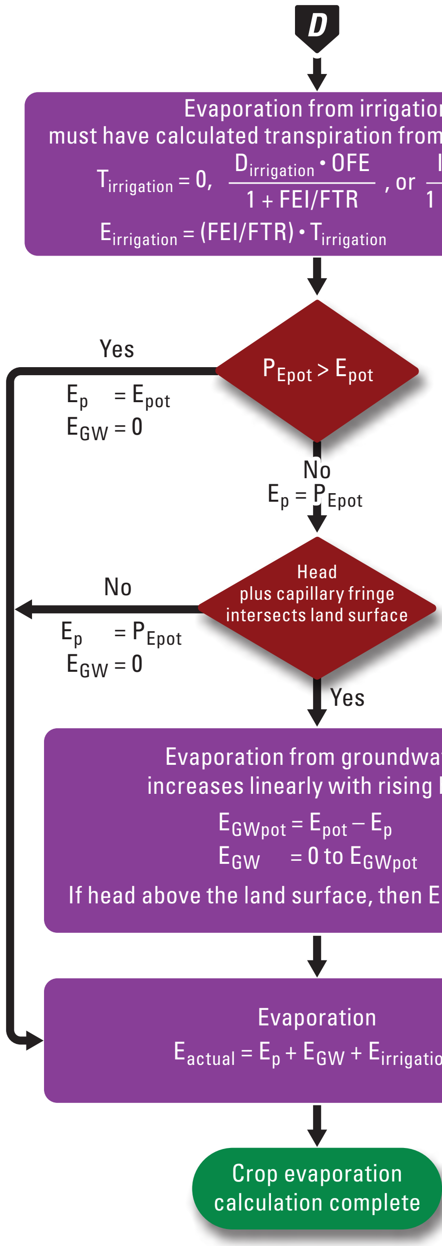

Figure 4.5. —Continued

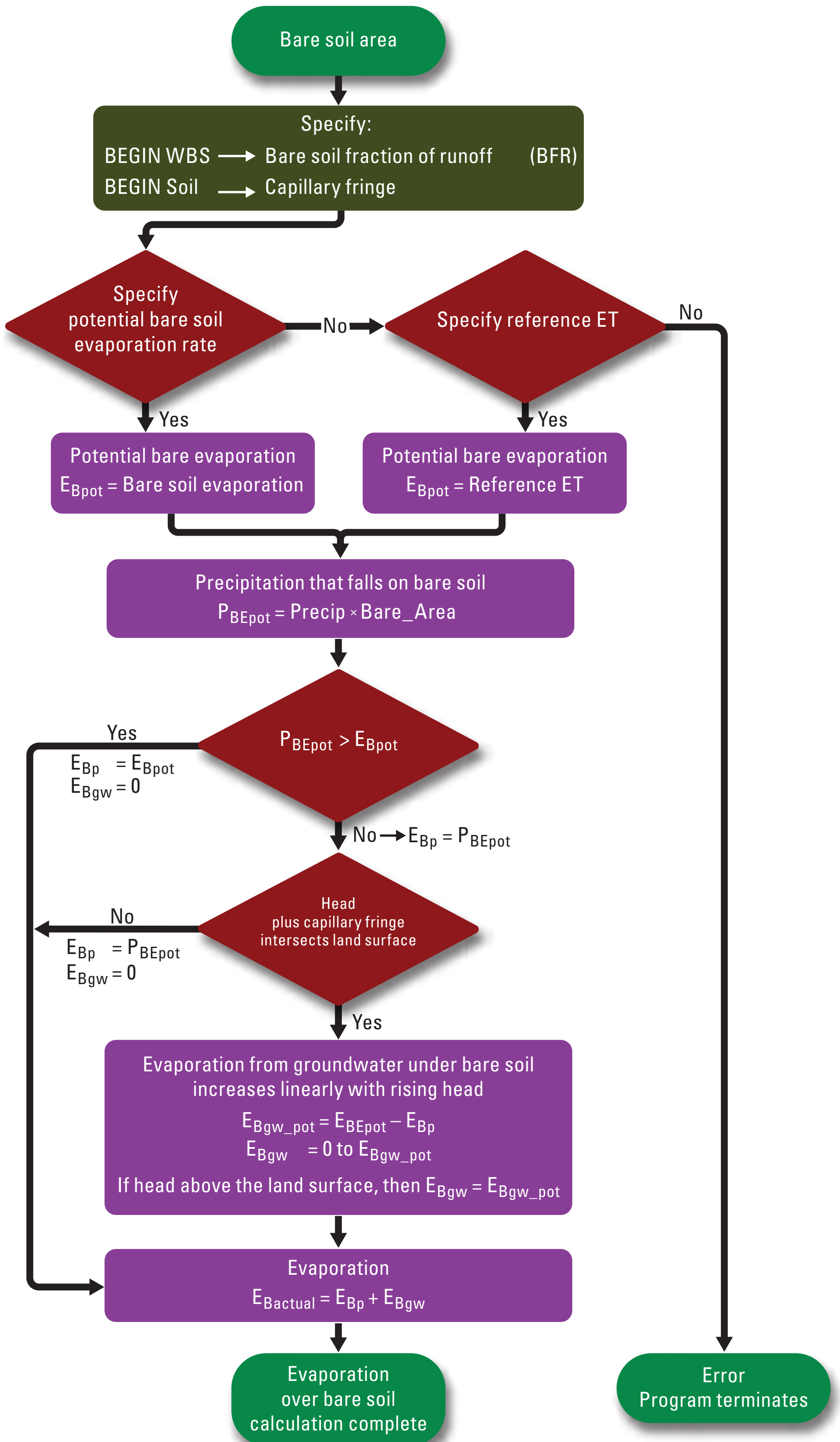

Figure 4.6. Overview of bare-soil evaporation component calculation for consumptive use. [Bare Soil represents any area that is not defined by an FMP land use (Crop).]

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