Appendix 5. Landscape and Root-Zone Processes and Water Demand and Supply

This appendix provides a conceptual overview of consumptive use and how it is calculated. The concepts are presented first, with few equations. Then, the description of the mathematics used in the farm process (FMP) and how each of its components is calculated are presented. For the readers who are interested in the mathematics of the concepts, the equation numbers have been provided in the concept sections.

Concepts of Landscape and Root-Zone Processes

The landscape and root-zone processes in the farm process (FMP) package consider two types of water budgeting for the control volume, which is defined by the horizontally delineated land-surface areas and the vadose zone that extends to the water table (fig. 5.1). Initially, in the MF-FMP, these areas were called Farms (Schmid and others, 2006a; Schmid and Hanson, 2009a, 2009b), but subsequent applications of the farm process have advanced this definition to Water-Balance Subregions (WBS) that include regions other than agricultural farms (Hanson and others, 2014a). These WBS can include irrigated and non-irrigated farms, natural vegetation, and urban areas. In some subregions, consumptive use can be zero or non-vegetative. Examples of non-vegetative use include percolation requirements for managed aquifer recharge (MAR) systems or urban demand. Three types of budgeting are associated with these WBS:

- Mass balance between physical inflow and outflow components to and from the control volume (FMP output block keyword FARM_BUDGET to produce FB_DETAILS.out).
- Operational balance between the irrigation water demand and the water supply from different surface or groundwater components to meet this demand (FMP output block keyword FARM_DEMAND_SUPPLY_SUMMARY to produce FDS.out).
- Detailed information on land-use water supply, demand, consumption, runoff, and deep percolation (FMP crop block keyword PRINT BYFARM_BYCROP).

In the real world, the physical water balance is always achieved (that is, mass is not created or lost), but the “economic balance” between supply and demand may not be maintained. For instance, farmers may apply more water than the true crop irrigation requirements, an unforeseen drought may limit irrigation, or non-irrigated lands that depend solely on precipitation may not get enough water in drought seasons and get too much water in wet seasons.

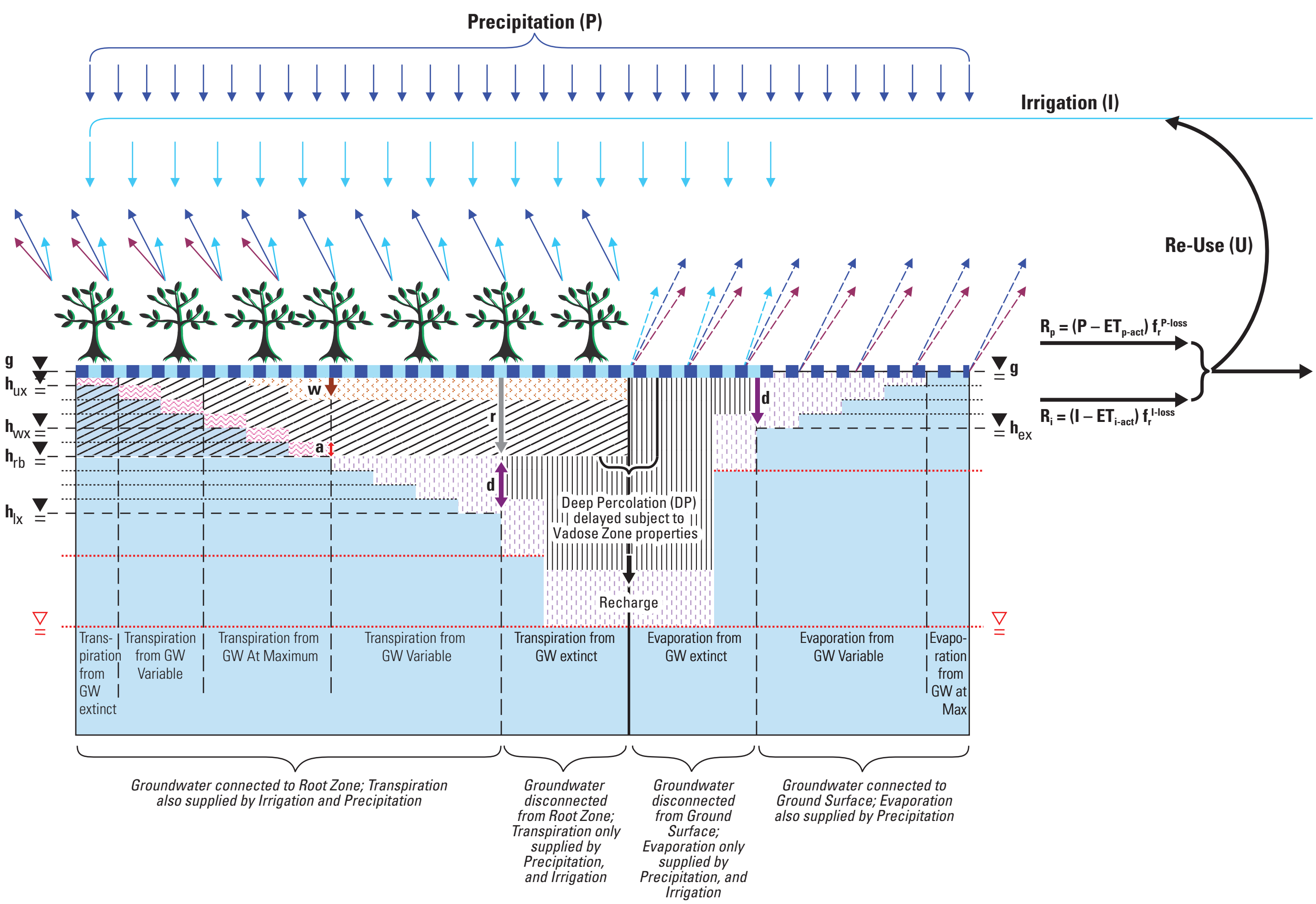
A simplified conceptual schematic of the root zone and landscape processes simulated in FMP is shown in figure 5.1. The general mass-balance equation for the root zone with changes in soil water from time step to time step is given in equation 5.1:

$$P^{t+1} + I^{t+1} - ET_{gw-act}^{t+1} - ET_{c-act}^{t+1} - R^{t+1} - DP^{t+1} = \frac{\theta^{t+1} - \theta^{t}}{\Delta t} \quad (5.1)$$

$$\text{where } R^{t+1} = R_p^{t+1} + R_i^{t+1}$$

where

P	is precipitation $[LT^{-1}]$,
I	is irrigation water $[LT^{-1}]$,
$ET_{gw\text{-}act}$	is groundwater uptake by roots $[LT^{-1}]$,
$ET_{c\text{-}act}$	is the total actual crop evapotranspiration $[LT^{-1}]$,
R	is the runoff from precipitation and irrigation $[LT^{-1}]$,
R_p	is the surface runoff from precipitation $[LT^{-1}]$,
R_i	is the surface return flow of irrigation water $[LT^{-1}]$,
DP	is the deep percolation that leaves the root zone as the moisture moves downward $[LT^{-1}]$,
θ^{t+1}	is the soil moisture at the end of a time step $[L^3/L^2]$,
θ^{t}	is the soil moisture at the beginning of a time step $[L^3/L^2]$,
Δt	is the time-step length [T], and
t	is the time-step index (-).



EXPLANATION

P	Precipitation
I	Irrigation
U	Re-use of irrigation water
DP	Deep percolation
R_p	Returnflow related to precipitation
R_i	Returnflow related to irrigation
$f_r^{P\text{-loss}}$	Fraction of inefficient losses to surface-water runoff related to precipitation
$f_r^{I\text{-loss}}$	Fraction of inefficient losses to surface-water runoff related to irrigation
$T_{gw\text{-act}}$	Portion of actual transpiration fed by groundwater*
$T_{p\text{-act}}$	Portion of actual transpiration fed by precipitation*
$T_{i\text{-act}}$	Portion of actual transpiration fed by irrigation*
$E_{gw\text{-act}}$	Portion of actual evaporation fed by groundwater*
$E_{p\text{-act}}$	Portion of actual evaporation fed by precipitation*
$E_{i\text{-act}}$	Portion of actual evaporation fed by irrigation*
$ET_{p\text{-act}}$	Portion of actual evapotranspiration fed by precipitation*
$ET_{i\text{-act}}$	Portion of actual evapotranspiration fed by irrigation*
g	Ground-surface elevation (L)
h	Groundwater head elevation (L)
h_{rb}	Head elevation at which head is at the bottom of the root zone (L)
h_{ux}	Head elevation at which top of anoxia fringe reaches ground-surface elevation with rising head (elevation of upper transpiration extinction) (L)
h_{wx}	Head elevation at which bottom of the wilting zone reaches ground-surface elevation with rising head (elevation of wilting zone extinction) (L)
h_{lx}	Head elevation at which top of capillary fringe is at bottom of root zone, hrb (elevation of lower transpiration extinction) (L)

a — Depth of anoxia zone (L)

w — Depth of wilting zone (L)

r — Depth of root zone (L)

d — Depth of capillary fringe (L)

Vadose Zone

Groundwater

Canopy receiving irrigation and precipitation

Exposed and wetted by irrigation and precipitation

Exposed and wetted only by precipitation

Head elevations used in equations 8, 9, 10, and 14

Groundwater head disconnected from Root Zone or Ground Surface

(* assuming no changes in soil-water storage for the length of the time-steps)

Figure 5.1. Schematic representation of root zone and land-use processes simulated by FMP (modified from Dogrul and others, 2011).

The mass-balance equation used for the root zone within a time step in the FMP assumes steady-state soil water and includes iteratively changing flow terms dependent on the groundwater head (h) of the previous iteration:

$$P^{t+1} + I^{k+1}\left(h^k\right) + ET_{gw-act}^{k+1}\left(h^k\right) - ET_{c-act}^{k+1}\left(h^k\right) - R^{k+1}\left(h^k\right) - DP^{k+1}\left(h^k\right) = 0 \quad (5.2)$$

The current version of the FMP does not consider changes in soil-water storage in the root zone (that is, right hand side of equation 5.2 = 0). The FMP does simulate changes in storage in the deeper vadose zone below the root zone through the optional linkage to the unsaturated-zone flow package (UZF; Niswonger and others, 2006) by treating deep percolation out of the root zone as quasi-infiltration to the deeper vadose zone.

In the FMP, equation 1 is solved for each cell at each iteration (eq. 5.2). Because many of the terms depend directly or indirectly on h, $ET_{gw\text{-}act}$ and $ET_{c\text{-}act}$ vary with groundwater head where the water table is shallow enough for evaporation or transpiration to cause losses of groundwater.

The sections that follow describe how the ET terms in equation 5.2 are computed. Many of these terms depend on the groundwater head and other previously calculated ET flow terms. Therefore, the sequence of the description of these terms is aligned with the order of terms in equation 5.1 and is arranged accordingly in the sequence of calculation. The equations are summarized in a the “Mathematical Representation of Consumptive-Use Components” section. For simplicity, indices for time step (t) and iteration (k) are omitted in the expressions that follow. Variable names relative to those in previous user guides (Schmid and others, 2006a; Schmid and Hanson, 2009b) have been simplified for use in this document.

Applied irrigation (I) and return flows from excess irrigation (R, runoff, and DP, deep percolation) in equations 5.1 and 5.2 depend on partly head-dependent ET flow terms as part of the irrigation requirement calculation (see the “Irrigation Water,” “Runoff,” and “Deep Percolation” sections). The irrigation demand (total farm delivery requirement, TFDR) depends on the head-dependent component of the crop-irrigation requirement (CIR). If the water supply is sufficient, the surface- or groundwater supply is driven by the irrigation demand. Therefore, the irrigation water supplied by surface water or by groundwater pumping depends indirectly on the head-dependent CIR. This head and flow dependency of the FMP is characteristic of dynamic head-, flow-, and deformation-dependent linkages in MF-OWHM2 (Hanson and others, 2014a; Schmid and others, 2014).

Consumptive Use and Evapotranspiration

Consumptive use is commonly defined as actual evapotranspiration (ET), which includes both plant transpiration and evaporation in an agricultural area (Colorado’s Decision Support Systems, 1995; Gelt and others, 1999; European Environment Agency, 2004). The primary objective of estimating the consumptive use in the FMP is to estimate evapotranspiration and its separate transpiration and evaporation components (fig. 5.1), that is, crop water use and bare-soil evaporation of water. At a steady state of soil moisture, ET is composed of six components from three sources: groundwater, precipitation, and irrigation ($T_{gw\text{-}act}$, $E_{gw\text{-}act}$, T_p, E_p, T_i, E_i,). By calculating the natural components of groundwater uptake and precipitation first, the FMP can back out the crop-irrigation requirement, CIR, composed of the sum of the irrigation requirement necessary to fulfil the crop water demand for transpiration and the related evaporation losses from irrigation. Because the CIR varies with changing groundwater levels in each model cell, it has been formulated to be head dependent. For calculating the irrigation water demand, the FMP uses the computed actual evapotranspiration, $ET_{c\text{-}act}$, as the target crop consumptive use to be met. For this computation, the FMP offers options reflecting different concepts where stresses to water uptake, such as wilting and anoxic conditions in the unsaturated root zone, are either specified through the input data or explicitly simulated by the FMP.

The transpiration and evaporation components are derived from the crop consumptive use or potential crop ET and the transpiration and evaporative crop coefficients. Potential crop ET, $ET_{c\text{-}pot}$, can be specified for each crop or calculated internally as the product of specified reference ET, ET_r, and crop coefficients, K_c. Using a specified fraction of transpiration, K_t, $ET_{c\text{-}pot}$ is separated into potential crop transpiration, $T_{c\text{-}pot} = K_t\,ET_{c\text{-}pot}$, and potential crop evaporation, $E_{c\text{-}pot} = (1-K_t)\,ET_{c\text{-}pot}$. Separating E and T losses in data input is in line with multi-component ET models (Shuttleworth and Wallace, 1985; Kustas and Norman, 1997; Guan and Wilson, 2009), some variably saturated flow models (for example, HYDRUS, Simunek and others, 1999; or SWAP, Kroes and van Dam, 2003), or with the use of transpiration (K_{cb}) and evaporation (K_e) crop coefficients (Allen and others, 1998). The FMP differs from the last one by not computing K_c with separate K_{cb} and K_e coefficients, but by making use of literature data on K_c and K_{cb} to preprocess fractions of transpiration as ratios of K_c and K_{cb}. Preprocessing or estimating K_t fractions, however, is required from the user in advance rather than being calculated by the FMP.

Change in Evapotranspiration with Varying Water Levels

The primary objective of the FMP's evapotranspiration and root zone concepts is to evaluate crop-irrigation requirements for time steps as they exist in most groundwater models as opposed to irrigation scheduling software. For typical conditions of groundwater flow, suitable time steps are on the order of weeks or months, rather than days. For such time intervals, in the FMP, a convergence between inflows into and outflows out of the root zone is assumed. In the absence of precipitation and irrigation, this means that the flux from groundwater across the bottom of the root zone equals the transpiration flux into the atmosphere across the ground surface (fig. 5.2). In the presence of precipitation and irrigation, the transpiration flux equals the sum of its component fluxes from groundwater, precipitation, and irrigation (fig. 5.3). These simple mass balances of the root-zone control volume are only possible in the absence of any change in soil-water storage in the root zone. Contrary to irrigation scheduling, which requires a consideration of daily changes in soil-water storage, in the FMP it is assumed that changes in soil-water storage can be neglected for time steps commonly used in groundwater modeling (steady-state soil-moisture assumption). The FMP is not designed to simulate any situation where changes in soil-water storage have to be considered, such as short time steps or root-zone processes in deep root zones (on the order of several meters) that have high soil-water storage potential. Typically, for most agricultural settings under irrigation, soil moisture is well managed. Conversely, natural vegetation or dry-land farming may have more variable soil moisture in some settings and soil types.

The steady-state soil-moisture assumption in the FMP was evaluated using HYDRUS2D soil-column models (fig. 5.2 and 5.3). As figure 5.3 shows, however, the uptake from all three sources (groundwater, precipitation, and irrigation) does not reach the potential transpiration as specified in HYDRUS2D. The HYDRUS2D simulations demonstrated how the resulting fluxes of the actual transpiration from groundwater as the only source merge with fluxes across the water table when approaching a pseudo steady state (fig. 5.4). In addition, the variation of maximum possible actual transpiration from groundwater and irrigation concomitant with changing depths to water was determined (fig. 5.4) along with its linear approximation (figs. 5.5 and 5.6). Each diagram is split into two parts: transpiration on the left and evaporation on the right. The source of water for transpiration and evaporation can vary depending on the head. The source of water for transpiration can be precipitation (T_p), irrigation (T_i), or groundwater (T_{GW}). Transpiration from groundwater can be further subdivided into transpiration from the saturated zone ($T_{gw\text{-}sat}$) and transpiration from the unsaturated zone ($T_{gw\text{-}unsat}$). Similarly, the source of water for evaporation can be precipitation (E_p), irrigation (E_i), or groundwater (E_{GW}). It is assumed that irrigation is applied at a rate just sufficient to keep transpiration at its maximum rate.

The section that follows describes two different FMP concepts about how consumptive-use components (split into separate evaporation and transpiration flux components from precipitation, irrigation, and groundwater uptake) and crop irrigation requirement vary concomitant with changing water levels (fig. 5.6). Both concepts are piecewise linear approximations of these six flux terms and assume soil water to be at steady state. The two concepts only differ by changes in transpiration for water levels ranging between ground surface and the bottom of the root zone, but not by changes in transpiration for water levels below the root zone or for changes in evaporation concomitant with varying water levels.

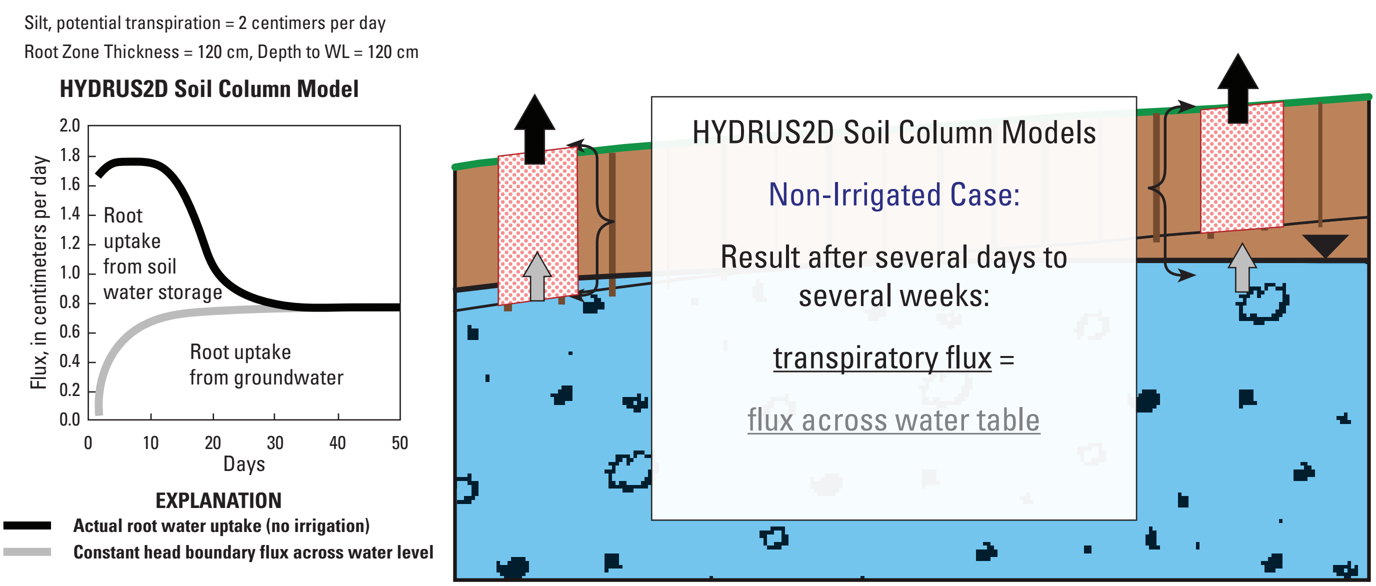


Figure 5.2. Benchmarking of steady-state assumption between transpiration from groundwater and flux across the water table for a non-irrigated case (modified from Schmid and others, 2006b).

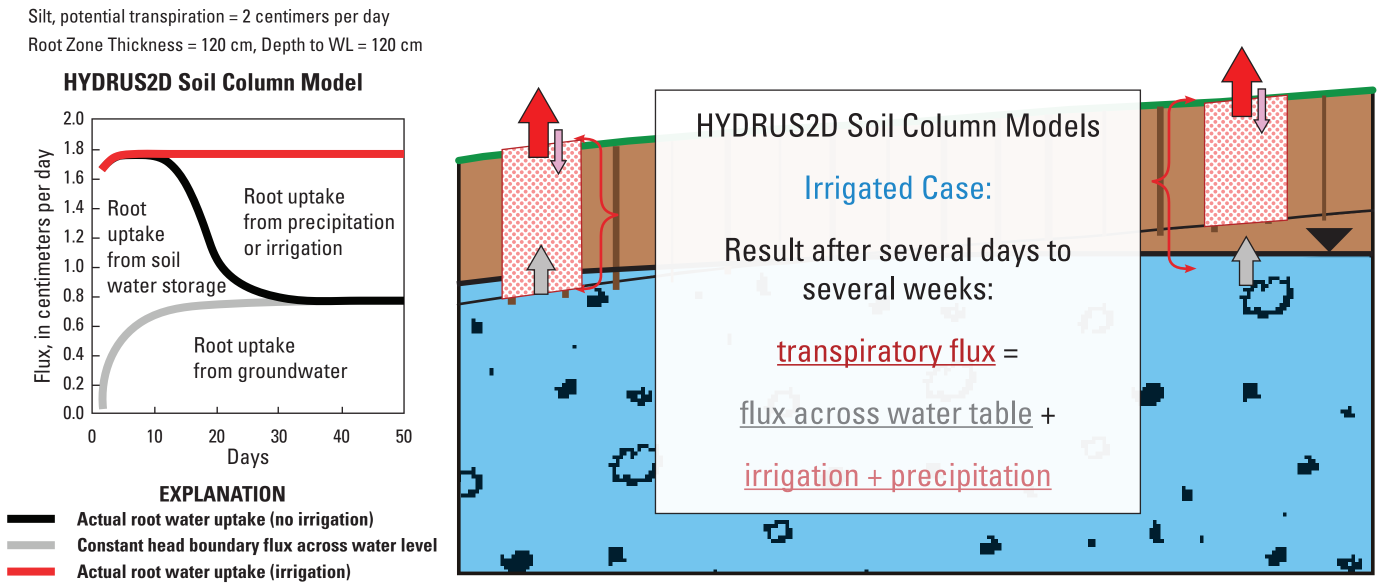


Figure 5.3. Benchmarking of steady-state assumption between transpiration from groundwater and irrigation and flux across the water table for an irrigated case (modified from Schmid and others, 2006b).

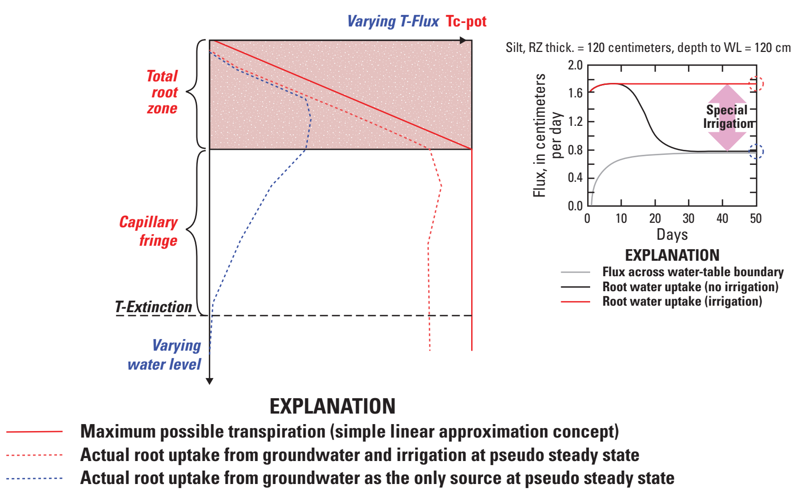


Figure 5.4. Maximum possible actual transpiration based on the assumptions of full uptake under unsaturated conditions and no uptake under saturated conditions pseudo steady-state results from HYDRUS2D for maximum possible transpiration and transpiration from groundwater only (modified from Schmid and others, 2006a, and Schmid and Hanson, 2009c). [RZ, root zone; T, transpiration; $T_{c\text{-}pot}$, maximum potential transpiration; WL, water level]

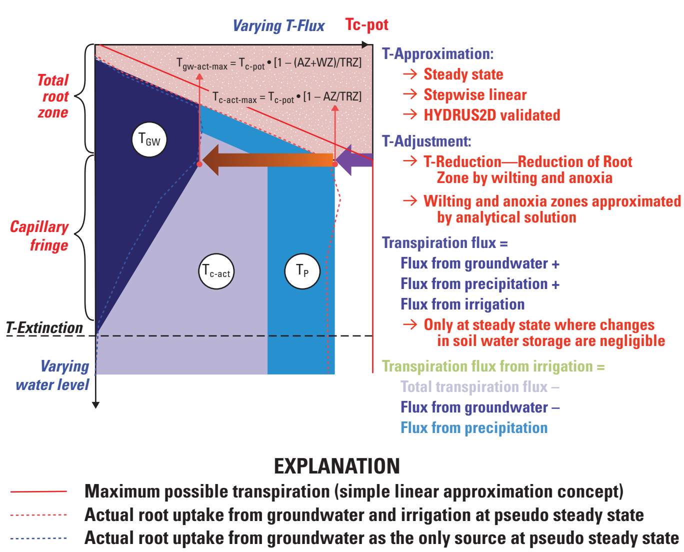


Figure 5.5. Linear approximation of pseudo steady-state groundwater uptake by roots; results from HYDRUS2D (modified from Schmid and Hanson, 2009c). [AZ, anoxia zone; WZ, wilting zone; and TRZ, transpiration root zone]

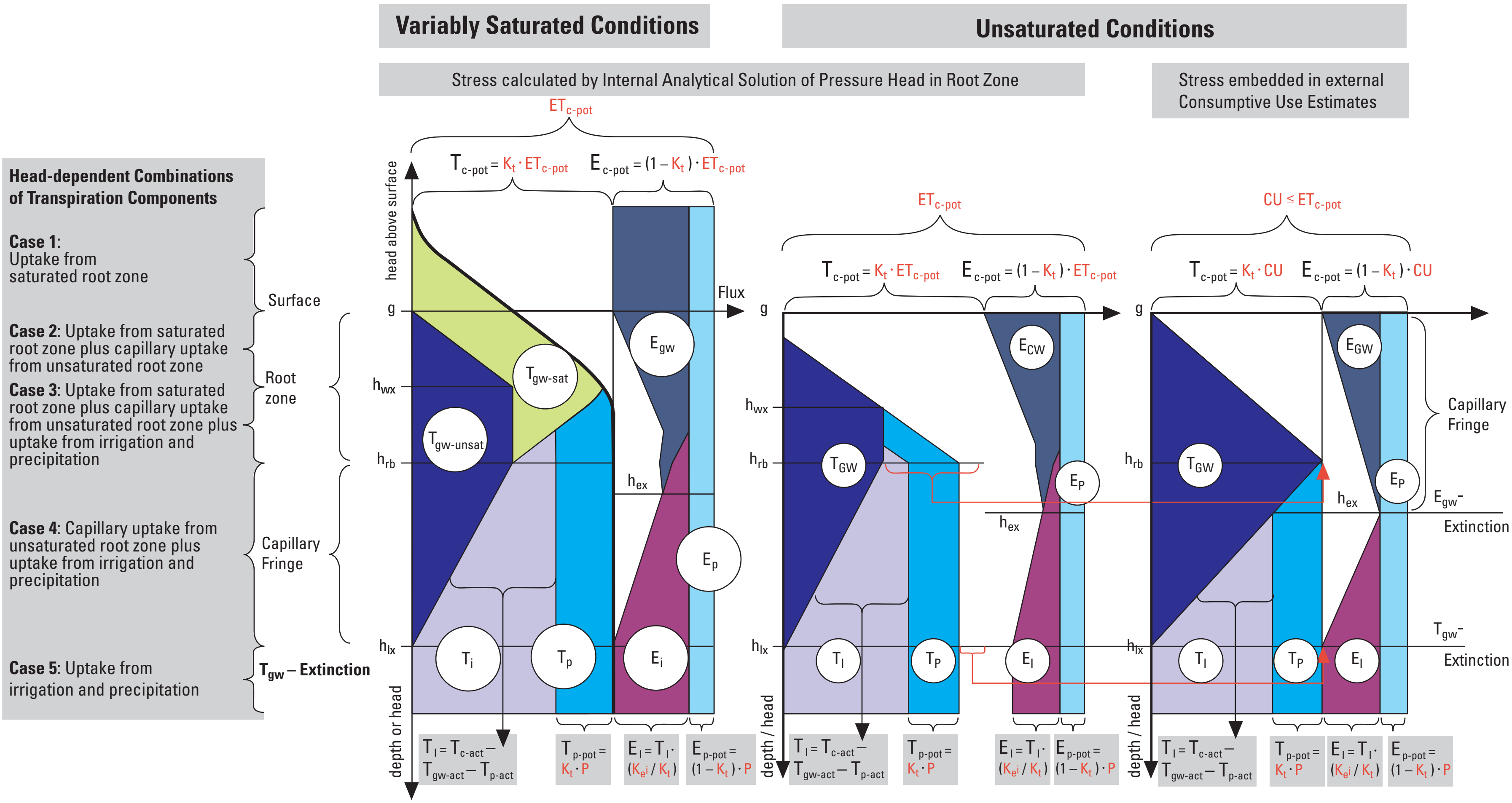


Figure 5.6. Conceptual approximations to change of crop consumptive-use components with varying head: left, reduced consumptive-use concept under variably saturated conditions; middle, reduced consumptive-use concept under unsaturated conditions; right, non-reduced consumptive-use concept under unsaturated conditions (modified from Schmid and others, 2006a; Schmid and Hanson, 2009a). The fraction of the potential evaporation or transpiration from each source as a function of head is shown by the colored regions in each diagram.

Transpiration for Water Levels Above the Base of Root Zone

Groundwater-Root Zone Interaction with Implicit Stress Assumption (Non-reduced Consumptive Use)

Assumptions for the non-reduced consumptive-use conceptual model are as follows:

- The “non-reduced consumptive-use” concept represents a piecewise linear approximation of transpiration when groundwater levels are between the bottom of the root zone and the ground surface without further reduction of maximum possible uptake (which is assumed to equal a specified consumptive use).
- When groundwater levels are between the bottom of the root zone and the ground surface, there is a linear decrease in transpiration as the groundwater level rises (red solid line in fig. 5.4). The active root zone is reduced proportionally to the depth of groundwater in the root zone and is inactive for anoxic conditions caused by saturation with groundwater. For example, if the water level rises to half the depth of the root zone, the potential transpiration would also be reduced by half. Wilting conditions are ignored and not assumed to reduce the active root zone.
- When water levels are at or below the bottom of the root zone, the entire root zone is available for uptake, and the actual transpiration can, at maximum, be equal to the potential transpiration.
- The potential transpiration is distributed equally over the root zone.

The appropriate use of the “implicit stress assumptions” are described as follows. If consumptive-use data already account for some in situ factors and stresses that constrain the actual ET, that is, if $ET_{c\text{-}pot}$ is derived from field measurements with “non-ideal” partially stressed conditions or from Moderate Resolution Imaging Spectroradiometer (MODIS) data, which may reflect a priori stressed ET. In such cases, the user would not want to further reduce the estimated transpiration to a smaller fraction of maximum uptake, unless the root zone became fully saturated. In other words, water-stress response is at optimum for an entirely unsaturated root zone and zero for saturated conditions. Lacking any better data needed to use the “reduced consumptive-use” conceptual model, such as a crop-specific water stress response function, however, the user may also default to the “non-reduced consumptive-use” concept knowing that it overestimates the transpiration from groundwater and, hence, underestimates the crop-irrigation requirement.

Groundwater and Root-Zone Interaction with Explicit Stress-Response Calculation (Reduced Consumptive Use)

Assumptions for the “reduced consumptive use” conceptual model are the following:

- The “reduced consumptive use” concept represents a step-wise linear approximation of transpiration when groundwater levels are between the bottom of the root zone and the ground surface, where maximum uptake is reduced by conditions of wilting and anaerobiosis.
- The potential crop transpiration is reduced to the actual crop transpiration in proportion to the reduction of the total root zone volume to an active root zone by wilting or anoxia (figs. 5.4 and 5.5) for negative ranges of pressure heads (unsaturated conditions) or by hydrostatic pressure for positive ranges of pressure heads (saturated conditions).
- The response of crops to stresses of wilting or anoxia is specified as crop-specific pressure heads at which uptake is either zero, indicating wilting or anaerobiosis points (Feddes and others, 1976), or at maximum (Prasad, 1988; Mathur and Rao, 1999; Simunek and others, 1999).

The appropriate use of the “explicit stress assumptions” or “reduced consumptive use” follows the assumption of a potential transpiration under unstressed conditions, as used in the HYDRUS2D soil column models, as an atmospheric boundary condition. Commonly, $ET_{c\text{-}pot}$ input data or related crop coefficients ($ET_{ref}/ET_{c\text{-}pot}$) are derived under “unstressed conditions” as, for instance, described by Allen and others (1998) for ET_c. Under stress, even at conditions of maximum uptake (such as when the water level is at the bottom of the root zone), the potential transpiration cannot be reached. Stresses that impair uptake are conditions of wilting and anoxia. This concept uses an analytical solution of the HYDRUS2D results from the vertical pressure head distribution for varying potential transpiration, soil types, root-zone depths, and crop-specific stress responses to mimic these stresses. Matching crop-specific critical pressure heads, between which uptake is possible, with an analytical solution of vertical pressure-head distribution allows the approximation of an active root zone reduced by zones of anoxia and wilting. This allows the FMP to decrease transpiration proportionately to the reduction in the active root zone volume. Using $ET_{c\text{-}act}$ as input data for this option would erroneously double-account for simulated stresses already inherent in the measurement.

The “reduced consumptive-use” concept was initially developed to allow root uptake of groundwater only for crops from unsaturated root zones, that is, for stress-response functions at critical negative pressure heads (Schmid and others, 2006a).

Certain applications, however, such as riparian evapotranspiration (for example, willow trees) and certain rice irrigation procedures, required an expansion of the concept to allow for possible uptake from saturated portions of the root zone (phreatic zones), where there are positive ranges of pressure heads (Schmid and Hanson, 2009b). Moreover, the concept accounts for the eventual reduction of uptake as positive pressure heads increase in the saturated root zone or, for ponding conditions, up to a user-specified limit of water level above the ground-surface elevation. This concept allows the simulation of water uptake and irrigation requirements for natural vegetation or crops rooting in soils that are fully or partially saturated. Full or partial saturation is achieved by the groundwater level rising into the root zone or even above the ground surface (for example, in alluvial valleys). Under such conditions, irrigation is required only for vegetation specified as irrigated crops where uptake from groundwater does not fully satisfy the potential transpiration.

Stress-Response Functions

Varying hydraulic pressure heads in a root zone imposes different levels of stress on a crop, resulting in water uptake ranging between a maximum and zero. The relationship between dimensionless water uptake, α ($0 \leq \alpha \leq 1$), and pressure head, ψ, is called a 'stress response function' (fig. 5.7). Such a crop-specific stress response function can be defined by four critical pressure heads at which water uptake is at its maximum (ψ_2, ψ_3) or at which water uptake ceases either as a result of anoxia or of wilting (ψ_1, ψ_4). Note that if all four pressures are set to zero, then the stress-response function is not used.

Among several sources in the literature, Taylor and Ashcroft (1972) and Wesseling (1991) provide the most detailed databases for stress-response pressure heads for numerous crops. If data are lacking for aerobic crops, $\psi 1$ (anoxia) may be approximated as the air entry pressure head, ψ_a, in the water-retention function, where the water content, θ, approaches the porosity, n. Common bounds for the field capacity, if known, may provide an approximation of the value for ψ_2 (normally between –0.06 and –0.3 bar or –60 and –300 centimeter pressure head). A maximum allowable depletion (in percent) describes the reduction of the water content at field capacity. The minimum allowable water content, below which transpiration is reduced, can be related to a pressure head to approximate the value of ψ_3. The permanent wilting point for most crops, ψ_w, is at about −15 bar or −15,000-centimeter pressure head and can be used as an indication of the ψ_4 value. The approximation of ψ_1 though ψ_4 from the air-entry pressure head, a range of field-capacity pressure heads, the maximum allowable depletion, and the permanent wilting point can be difficult for some crop types, however. Although the air-entry pressure head and the field capacity vary by soil type, the maximum allowable depletion and the permanent wilting point vary by crop type. Because the FMP requires stress-response pressure heads to be crop-type specific attributes, the user is encouraged to search the literature for databases of strictly crop-type related stress-response pressure heads.

The FMP simplifies the stress-response function to a step function, where water uptake is considered at maximum between the averages of ψ_1 and ψ_2 and of ψ_3 and ψ_4 (fig. 5.7). Zones in the root zone where conditions of wilting or anoxia eliminate water uptake (in the FMP, wilting or anoxia zones) are found by matching these averages of crop-specific anoxia- or wilting-related pressure heads to a vertical steady-state pressure-head distribution.

Analytical Solution of Vertical Pressure-Head Distribution

Pressure-head distributions across the depth of a root zone can be approximated by various models of the vertical pressure-head configuration across the root zone (fig. 5.7). One approach is to solve for vertical transient pressure-head distributions using Richard's equation-based variable-saturation flow models. These require soil-water constitutive input parameters and may be computationally expensive when linked to regional groundwater models, however. Instead, the FMP uses analytical solutions of vertical steady-state pressure-head distributions derived from transient, Richard's equation-based variably saturated soil-column models upon convergence of actual root uptake and upward fluxes across the water table after time intervals of several days to weeks (fig. 5.4). These soil-column models were developed using HYDRUS2D (Simunek and others, 1999) for various soil-specific soil-water constitutive parameters, crop-specific stress-response functions, root-zone depths, depths to groundwater, and rates of potential transpiration where groundwater is the only source of water for root uptake (Schmid, 2004). For groundwater rising above the root-zone base, a wilting zone in the upper part of the root zone decreased linearly, and an anoxic fringe above the water table remained constant until its top reached ground surface. For other HYDRUS2D simulations, infiltration (for example, from precipitation or irrigation) was added as an additional source of water for root uptake. The actual transpiration, $T_{c\text{-}act,}$ did not reach $T_{c\text{-}pot,}$ however, because infiltration wetting-fronts also can have pressure heads at which the crop's response to anoxia reduces transpiration (Drew, 1997). Hence, even for root zones not influenced by groundwater, $T_{c\text{-}act}$ cannot exceed an anoxia-constrained maximum possible $T_{c\text{-}act\text{-}max}$. Adding infiltration in excess of $T_{c\text{-}act\text{-}max}$ resulted in transpiration-inefficient losses. $T_{c\text{-}act\text{-}max}$ may be diminished further if pressure heads of a wetting front are higher than those of an anoxia fringe above a water table or if drainage in lower parts of the root zone causes wilting.

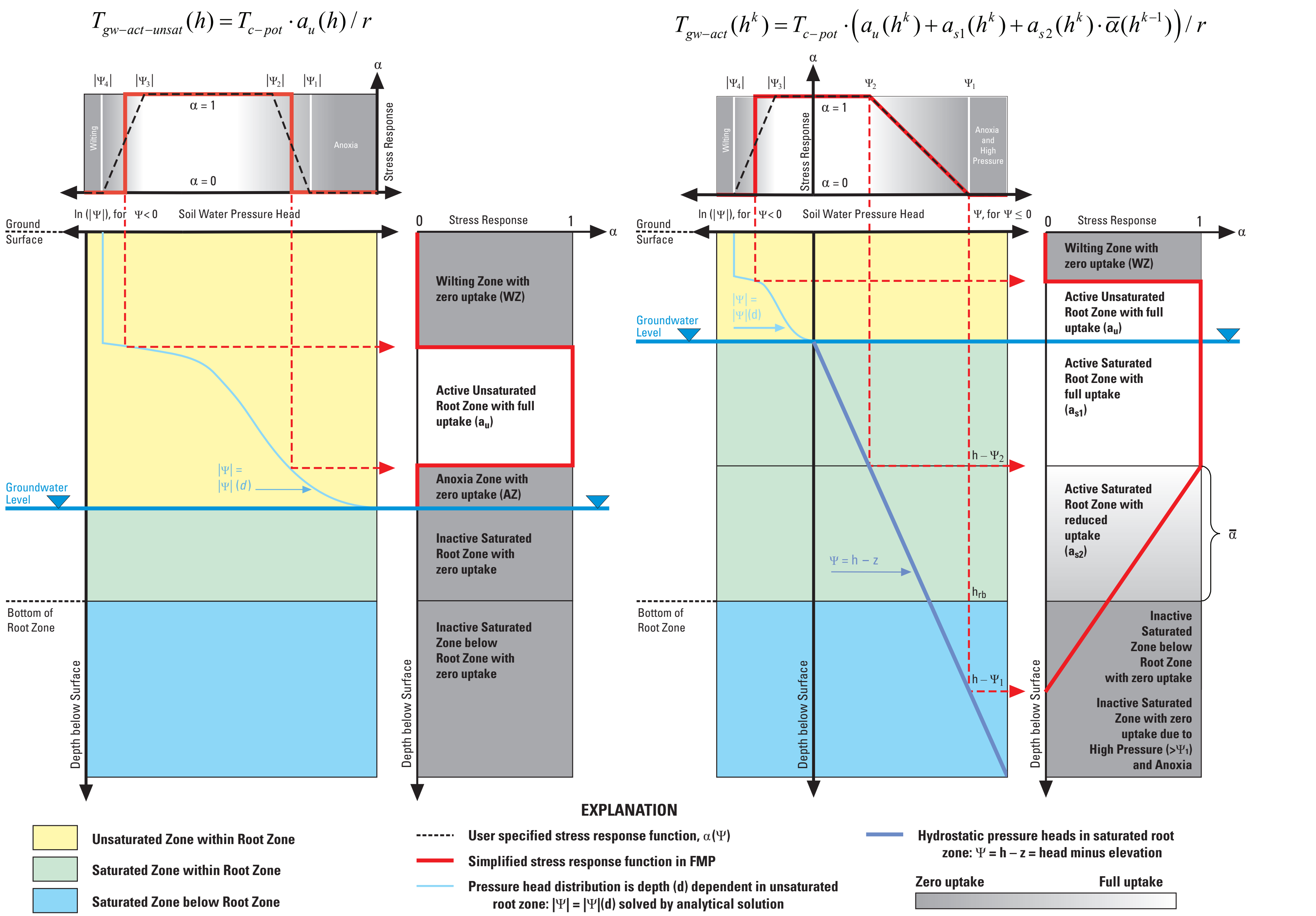


Figure 5.7. Root-zone pressure head relative to groundwater level for unsaturated conditions (left) and variably saturated conditions (right), where the top shows a crop-specific stress-response function and the bottom shows analytical function fitting the vertical pressure-head distribution by depth (modified from Schmid and Hanson, 2009a).

Matching Crop Stress Response to the Root-Zone Pressure Head

Root Uptake Under Unsaturated Conditions

Regions of the root zone with pressure heads less than the average of ψ_4 and ψ_3 or greater than the average of ψ_2 and ψ_1 are considered inactive wilting and anoxia zones, respectively (WZ, AZ). For a water level at the base of the root zone (h_{rb}), the residual active unsaturated root zone (a_u) is equal to the total root zone minus WZ and AZ (eq. 5.5 for $h_{wx} \geq h > h_{rb}$). As the groundwater level rises, the vertical pressure-head distribution is shifted upward. The active root zone and the AZ remain constant, but the WZ at the top end of the pressure-head distribution is gradually eliminated until the water level reaches a point where the depth of the WZ is zero (water level at that point = h_{wx}). For water levels rising beyond this point, the active unsaturated root zone is reduced linearly (eq. 5.5) for $h_{ux} > h > h_{wx}$ until the top of the anoxia fringe above the water level reaches the ground-surface elevation (fig. 5.5). At this position of the water level, transpiration reaches extinction (water level at that point = h_{ux}). The vertical range over which pressure heads are less than the wilting-point pressure head is found by assuming groundwater to be the only source for transpiration.

Root Uptake Under Variably Saturated Conditions

For deep root zones and for groundwater levels in the root zone, roots can take up water under unsaturated as well as saturated conditions. Above the groundwater level, uptake can be zero or full under unsaturated conditions in the WZ and the active unsaturated root zone (AURZ), respectively. For crops characterized by positive critical pressure heads ψ_1 and ψ_2, the active unsaturated root zone (a_u) is not restricted by anoxia (AZ = 0; fig. 5.7). Below the groundwater level, uptake can be full or reduced in the active saturated root zone (fig. 5.7):

- Uptake is full under saturated conditions for a region of positive pressure heads in the root zone that range from zero at the groundwater level to the user-specified pressure head ψ_2. This region of the root zone is defined as the active saturated root zone 1 (a_{s1}). In this zone, the stress response to water uptake, α, is equal to one, indicating that full uptake is possible. For water levels rising above the ground-surface elevation (GSE), the a_{s1} extends from the GSE to where the critical pressure head ψ_2 is found.

- Uptake is reduced under saturated conditions for a region of positive pressure heads that range from ψ_2 (full uptake) to ψ_1 (zero uptake) or the pressure head at the base of the root zone, whichever is least. We define this region of the root zone as active saturated root zone 2 (a_{s2}). In this zone, the stress response to water uptake, α, is taken to be equal to the average of stress responses, $\bar{\alpha}$, owing to pressure heads that are found in the root zone between ψ_2 and ψ_1 or the pressure head at the base of the root zone. Where ψ_1 is found below the base of the root zone (fig. 7), a_{s2} is not bound by ψ_1, but by a nonzero pressure head at the base of the root zone.

For water levels at and above the base of the root zone, the uptake under saturated conditions over distance r from the surface to the groundwater elevation (r) is formulated in eqs. 5.3 and 5.6. Noticeably, a_{s1}, a_{s2}, and $\bar{\alpha}$ depend on the vertical location of the hydrostatic pressure heads ψ_1 and ψ_2 (head elevations $h-\psi_1$ and $h-\psi_2$) because ψ_1 and ψ_2 move vertically up or down as the water level rises or falls. The terms a_{s1}, a_{s2}, and α depend on the simulated groundwater level and, therefore, are head-dependent terms. To avoid the term $a_{s2} \cdot \bar{\alpha}$ becoming nonlinear in head, we evaluate $\bar{\alpha}$ on the basis of the head of the previous iteration (k–1), whereas a_{s2} is related to the head of the current iteration (k) in equation 5.3, which calculates actual transpiration from groundwater under variably saturated conditions:

$$T_{gw-act}\left(h^k\right) = T_{c-pot}\left(h^k\right)\left(\frac{a_u\left(h^k\right) + a_{s1}\left(h^k\right) + a_{s2}\left(h^k\right)\bar{\alpha}\left(h^{k-1}\right)}{r}\right) \tag{5.3}$$

Although figure 5.7 demonstrates a situation for a specific water-level elevation, figure 5.6 illustrates the conceptual approximation to the change of all transpiration and evaporation components concomitant with varying groundwater level. Depending on where the water level is positioned (above, in, or below the root zone), five different cases of combinations of up to four transpiration components are possible. These components are fed by capillary rise from groundwater (unsaturated root zone), by direct uptake from groundwater (saturated root zone), by irrigation, or by precipitation. For instance, for case 3 (fig. 5.6), the water level rises only slightly above the base of the root zone and wilting still might occur in the drying top soil. Transpiration is fed by groundwater uptake from the unsaturated and saturated part of the root zone. The deficit between the transpiration from groundwater and the maximum possible transpiration may be supplemented by precipitation or irrigation.

If the water level continues to rise (case 2, fig. 5.6), however, all possible transpiration is from groundwater uptake from the unsaturated and saturated root zone. Finally, when the water level rises above the ground surface and ponds, uptake is only from the saturated root zone (case 1, fig. 5.6).

Examples 1, 2, and 3 (fig. 5.8) show how the total transpiration uptake from the saturated root zone (light-green curve) is composed of the uptake from the fully active and partially active parts of the saturated root zone. The uptake from the fully active root zone (light-blue curve) is a piecewise linear approximation (eq. 5.6 in the “Mathematical Representation of Consumptive-Use Components” section). The uptake from the partially active root zone (purple curve) depends on the product of two head-dependent terms: the depth of this zone and the average stress response, $\bar{\alpha}$, in this zone. Therefore, as shown in figure 5.8, this part of the uptake is nonlinear as head changes (eq. 5.6). For select positive ψ_1 and ψ_2 values, the range of positive pressure heads with reduced uptake ($\psi_1 - \psi_2$) can be less than the thickness of the total root zone. In this case, the “partial uptake zone,” a_{s2}, and the average stress response, $\bar{\alpha}$, in that zone can remain constant as water level changes if the elevation where ψ_2 is found (head – ψ_2) is less than the ground-surface elevation, and the elevation where ψ_1 is found (head – ψ_2) is greater than the base of the root zone.

Transpiration for Water Levels between the Root Zone and the Extinction Depth

Transpiration is simulated for groundwater levels between the base of the root zone and the extinction depth in the same way for the crop consumptive-use concepts (fig. 5.6) and is assumed to decrease linearly with depth. As the groundwater level drops below the root zone, the actual transpiration from groundwater $T_{gw\text{-}act}$ is assumed to decrease linearly from the respective maximum actual transpiration from groundwater, $T_{gw\text{-}act\text{-}max}$, at the base of the root zone to zero at a transpiration-extinction depth (defined to be equal to the height of the capillary fringe) below the root zone (eqs. 5.5 and 5.6 for $h_{rb} \geq h > h_{lx}$ in the “Mathematical Representation of Consumptive-Use Components” section). For a groundwater level above the base of the root zone, the total actual transpiration $T_{c\text{-}act}$ is assumed to remain constant at the maximum actual transpiration $T_{c\text{-}act\text{-}max}$ (fig. 5.6 and eq. 5.4 for $h \geq h_{rb}$ in the “Mathematical Representation of Consumptive-Use Components” section).

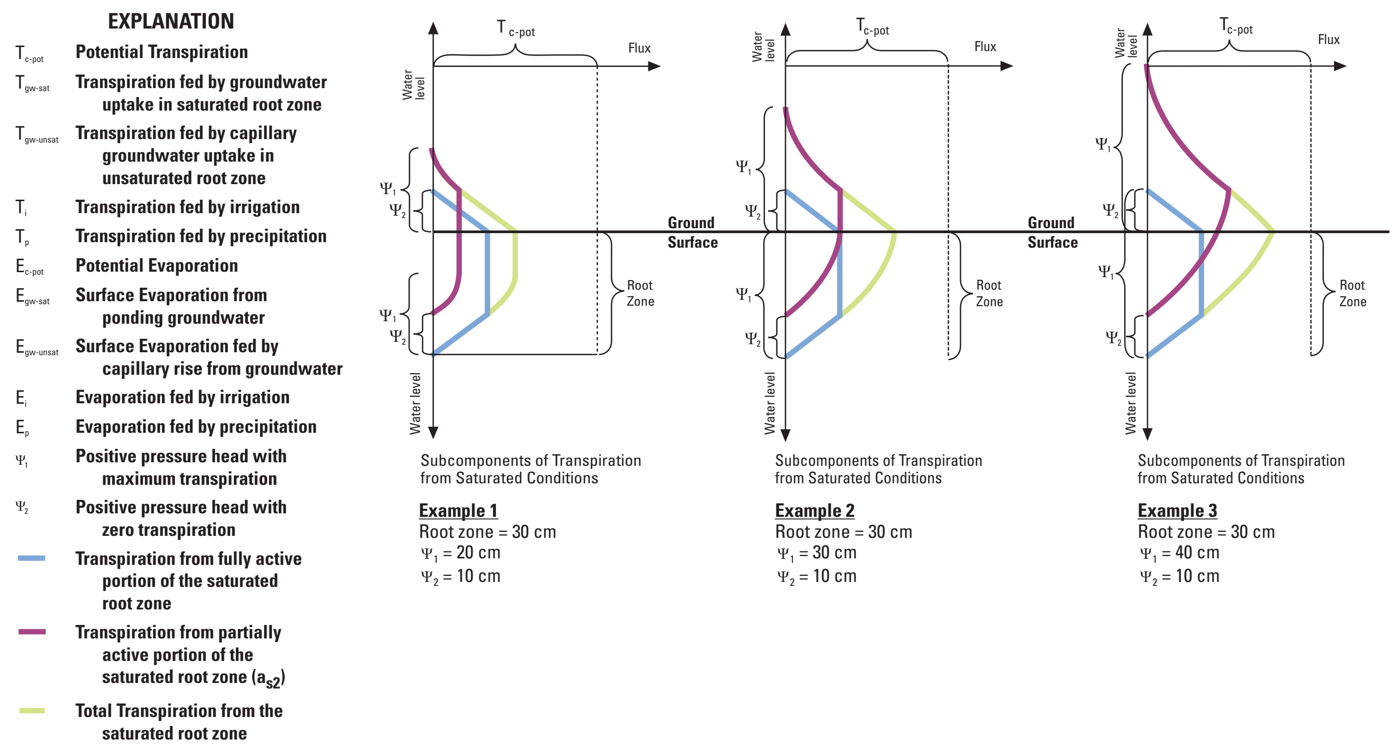


Figure 5.8. Change in water uptake for transpiration from fully and partially active parts of the saturated root zone as water levels vary (three examples with different ψ_1 values; modified from Schmid and Hanson, 2009a). [cm, centimeter]

Transpiration from Precipitation

As transpiration from groundwater increases with rising groundwater level, the amount of actual transpiration provided by precipitation, $T_{p\text{-}act}$, decreases as long as it is less than the available potential transpiration from precipitation that is needed. Hence, in this range of water levels, $T_{p\text{-}act}$ is head-dependent (fig. 5.6 and eq. 5.7 for $T_{p\text{-}pot} > T_{c\text{-}act} - T_{gw\text{-}act}$ in the "Mathematical Representation of Consumptive-Use Components" section).

Crop-Irrigation Requirement

The irrigation requirement for transpiration in each model cell (T_i; fig. 5.6) is simulated by subtracting the actual transpiration from groundwater $T_{gw\text{-}act}$ and the actual transpiration from precipitation $T_{p\text{-}act}$ from the total potential transpiration. After adding the irrigation needs for evaporation (E_i; eq. 5.9 in the "Mathematical Representation of Consumptive-Use Components" section) to compensate surface-evaporation losses from irrigation, this yields the estimate of the crop-irrigation requirement, CIR (eq. 5.8 in the "Mathematical Representation of Consumptive-Use Components" section). Because CIR depends on head-dependent terms, it is also head-dependent.

Evaporation for Water Levels Between Ground Surface and the Extinction Depth

Evaporation from groundwater is simulated for groundwater levels between the ground surface and the evaporation extinction depth, h_{lx} (fig. 5.6). The maximum actual evaporation from groundwater, $E_{gw\text{-}act\text{-}max}$, is assumed to equal the proportion of the saturation water-vapor pressure deficit over exposed no-crop areas (potential evaporation $E_{c\text{-}pot}$) that is not compensated by evaporation of precipitation (E_p), where $E_{gw\text{-}act\text{-}max} = E_{c\text{-}pot} - E_p$. For the crop consumptive-use concepts, the extinction of evaporation from groundwater is likely when the highest point of the capillary fringe is below the ground surface (Robinson, 1958). Thus, evaporation from groundwater, $E_{gw\text{-}act}$, is assumed to decrease linearly with the groundwater level from the maximum actual evaporation from groundwater, $E_{gw\text{-}act\text{-}max}$, at the ground surface to no evaporation at the evaporation extinction depth (defined to be equal to the height of the capillary fringe) below ground surface (eq. 5.10 in the "Mathematical Representation of Consumptive-Use Components" section).

Mathematical Representation of Consumptive-Use Components

The FMP calculates a maximum actual transpiration ($T_{c\text{-}act}$, eq. 5.4) and proportions of transpiration fed by uptake from groundwater ($T_{gw\text{-}act}$, eq. 5.5 for unsaturated and eq. 5.6 for variably saturated conditions), precipitation ($T_{p\text{-}act}$, eq. 5.7), and supplemental irrigation ($T_{i\text{-}act}$, eq. 5.8), assuming no changes in soil-water storage between time steps and equal spatial distribution of roots and potential transpiration ($T_{c\text{-}pot}$) in the root zone. In summary, the estimate of actual from potential transpiration in the FMP is formulated as three components distinguished by water source: groundwater, precipitation, and irrigation.

Actual crop transpiration is estimated as follows:

$$T_{c-act} = \left\{ \begin{array}{l} 0 \\ T_{c-pot} \dfrac{h_{ux} - h}{r} \\ T_{c-pot} \left(1 - \dfrac{a}{r} \right) = T_{gw-act-\max} \end{array} \right\} \quad h_{ux} = g - a \quad \begin{array}{c} h \geq h_{ux} \\ h_{ux} > h > h_{rb} \\ h \leq h_{rb} \end{array} \tag{5.4}$$

Actual transpiration from groundwater under unsaturated conditions is shown here:

$$T_{gw-act} = \begin{Bmatrix} 0 \\ T_{c-pot}\left(\dfrac{a_u}{r}\right) = T_{gw-act-\max} \\ T_{gw-act-\max}\left(1-\dfrac{h_{rb}-h}{d}\right) \end{Bmatrix} \quad \begin{Bmatrix} a_u = g-a-h \\ a_u = r-a-w \end{Bmatrix} \quad \begin{matrix} h \ge h_{ux} \\ \begin{Bmatrix} h_{ux} > h > h_{wx} \\ h_{wx} \ge h > h_{rb} \end{Bmatrix} \\ h_{rb} \ge h > h_{lx} \\ h \le h_{lx} \end{matrix} \tag{5.5}$$

Actual transpiration from groundwater under variably saturated conditions is estimated as follows:

$$\begin{array}{l} T_{gw-act} \\ = \begin{Bmatrix} 0 \\ T_{c-pot}\left(a_u + a_{s1} + a_{s2}\,\bar{\alpha}\right) \\ T_{gw-act-\max}\left(1-\dfrac{h_{rb}-h}{d}\right) \\ 0 \end{Bmatrix} \begin{array}{l} h \ge g+\varphi_1 \\ \begin{Bmatrix} a_u = 0 & & & & & \\ a_u = g-h & h > g & \vee & & & a=0 \\ a_u = r-w & g > h > h_{wx} & & h > h_{rb} & & a=0 \\ a_{s1} = 0 & h_{wx} \ge h > h_{rb} & & & & \\ a_{s1} = r & h < h_{rb} & \vee & & & a_u = 0 \\ a_{s1} = g-\left(h-\varphi_2\right) & h > g & \wedge & h-\varphi_2 > g & & a_u = 0 \\ a_{s1} = \varphi_2 & h > g & \wedge & h-\varphi_2 < h_{rb} & & a=0 \\ a_{s1} = h-h_{rb} & h < g & \wedge & h-\varphi_2 < h_{rb} & & a=0 \\ a_{s2} = 0 & h < g & \wedge & h-\varphi_2 > h_{rb} & \bar{\alpha} = \left(a_g + a_{rb}\right)/2 & \\ a_{s2} = r & h-\varphi_2 < h_{rb} & \vee & h-\varphi_1 > g & & a_u, a_{s1} = 0 \\ a_{s2} = \left(g-\left(h-\varphi_2\right)\right)a & h-\varphi_2 > g & \wedge & h-\varphi_1 < h_{rb} & \bar{\alpha} = a_g/2 & a_u, a_{s1} = 0 \\ a_{s2} = \left(\varphi_1-\varphi_2\right)a & h-\varphi_2 > g & \wedge & h-\varphi_1 > h_{rb} & \bar{\alpha} = 1/2 & a=0 \\ a_{s2} = \left(h-\varphi_2-h_{rb}\right)a & h-\varphi_2 < g & \wedge & h-\varphi_1 > h_{rb} & & a=0 \\ & h-\varphi_2 < g & \wedge & h-\varphi_1 < h_{rb} & \bar{\alpha} = \left(1+a_{rb}\right)/2 & \end{Bmatrix} \\ h_{rb} \ge h > h_{lx} \\ h \le h_{lx} \end{array} \end{array} \tag{5.6}$$

Actual transpiration from precipitation is estimated in this way:

$$T_{p-act} = \begin{Bmatrix} 0 \\ T_{c-act} - T_{gw-act} \\ T_{p-pot} \end{Bmatrix} \quad \begin{matrix} h \ge h_{wx} & with & h_{wx} = g-r+w \\ h < h_{wx} & \wedge & T_{p-pot} > T_{c-act} - T_{gw-act} \\ h < h_{wx} & \wedge & T_{p-pot} \le T_{c-act} - T_{gw-act} \end{matrix} \tag{5.7}$$

Actual transpiration from irrigation is estimated as follows:

$$T_{i-act} = T_{c-act} - T_{gw-act} - T_{p-act} \tag{5.8}$$

Actual evaporation from irrigation is estimated as follows:

$$E_{i-act} = T_{i-act}\left(\frac{K_e^i}{K_t}\right) \tag{5.9}$$

Actual evaporation from groundwater is estimated in this way:

$$E_{gw-act} = \begin{Bmatrix} E_{c-pot} - E_{p-act} \\ \left(T_{c-act} - T_{gw-act}\right)\left(1 - \dfrac{g+h}{d}\right) \\ 0 \end{Bmatrix} \quad \begin{matrix} h \geq g \\ g < h < h_{ex} \\ h \leq h_{ex} \end{matrix} \quad \text{with} \quad h_{ex} = g - d \tag{5.10}$$

where

- a is the depth of the anoxia fringe [L];
- w is the depth of wilting zone [L];
- r is the total depth of root zone [L];
- d is the depth of capillary fringe [L];
- g is the ground-surface elevation [L];
- h is the groundwater-head elevation [L];
- a_u is the active unsaturated root zone;
- a_{s1} is the active saturated root zone at maximum uptake;
- a_{s2} is the active saturated root zone at reduced uptake;
- $\bar{\alpha}$ is the average of stress responses found in a_{s2};
- φ_1 is the positive pressure head at which water uptake ceases as a result hydrostatic pressure;
- φ_2 is the pressure head at which water uptake is at maximum;
- h_{rb} is the groundwater-head elevation at the base of the root zone [L];
- h_{ux} is the head elevation at which the top of anoxia fringe (*a*) above the water level reaches ground-surface elevation (*g*) with rising head, which is called the elevation of upper transpiration extinction [L];
- h_{wx} is the head elevation at which the bottom of the wilting zone, w, reaches ground-surface elevation (*g*) with rising head, which is called the elevation of wilting zone extinction [L];
- h_{lx} is the head elevation at which the top of capillary fringe (*d*) is at base of root zone (h_{rb}) which is the elevation of lower transpiration extinction [L];
- h_{ex} is the head elevation at which top of capillary fringe (*d*) reaches ground-surface elevation (*g*) which is the elevation of evaporation extinction [L];
- K_t is the transpiration fraction of $ET_{c\text{-}pot}$; and
- K_e^i is the evaporation fraction of $ET_{c\text{-}pot}$ related to irrigation.

In the "reduced consumptive-use" concept in the unsaturated root zone, $T_{c\text{-}act}$ varies linearly in equation 5.4 between the elevation of upper transpiration extinction, h_{ux}, and the elevation of the root-zone base, h_{rb}. For heads below the root-zone base, $T_{c\text{-}act}$ is constant and reduced by the ratio between the thicknesses of the anoxia fringe, a, and the total root zone, r. In equation 5.5, $T_{gw\text{-}act}$ varies linearly between the elevation of upper transpiration extinction, h_{ux}, and the elevation of wilting zone extinction, h_{wx}. For heads between h_{wx} and root-zone base, $T_{gw\text{-}act}$ is constant and reduced from $T_{c\text{-}pot}$ to a maximum actual transpiration from groundwater, $T_{gw\text{-}act\text{-}max}$, by the ratio of the sum of thicknesses of the anoxia and wilting zones, a + w, to the total root zone, r. $T_{gw\text{-}act}$ also varies linearly between the head elevations of the root-zone base and the lower transpiration extinction, h_{lx}.

For crops able to take up water from a variably saturated root zone, $T_{gw\text{-}act}$ is supplied from the active unsaturated root zone, a_u, the active saturated root zone with maximum uptake, a_{s1}, and the active saturated root zone with reduced uptake, a_{s2} (eq. 5.6).

The calculation of a_u is as explained previously, and the only difference is that the anoxic zone, a, is absent. The uptake from the fully active root zone, $T_{gw\text{-}act\text{-}as1}$, is a piecewise linear approximation that varies linearly between the elevations of ponding water level above the ground surface and the elevation in the saturated root zone at which the positive hydrostatic pressure head equals ψ_2, if it is above the base of the root zone (head – ψ_2). If the water level is below the surface and ψ_2 is still above the base of the root zone, $T_{gw\text{-}act\text{-}as1}$ is constant and reaches ψ_2. If the water drops below the surface and ψ_2 is below the base of the root zone, then $T_{gw\text{-}act\text{-}as1}$ is reduced linearly to zero as the water level reaches the base of the root zone. The uptake from the partially active root zone depends on the product of two head-dependent terms: the depth of this zone and the average stress response, $\bar{\alpha}$, in this zone. Therefore, this part of the uptake varies nonlinearly with changing head. For select positive ψ_1 and ψ_2 values, the range of positive pressure heads at which uptake is reduced ($\psi_1 - \psi_2$) may be less than the thickness of the total root zone. In this case, the "partial uptake zone," a_{s2}, and the average stress response, $\bar{\alpha}$, in that zone can remain constant with a moving water level, as long as the elevation of ψ_2 (head – ψ_2) is less than the ground-surface elevation and as long as the elevation of ψ_1 (head – ψ_1) is greater than the base of the root zone. In equation 5.7, $T_{p\text{-}act}$ is equal to $T_{p\text{-}pot}$, except when limited to the remainder of $T_{c\text{-}act}$ that is not yet satisfied by transpiration from $T_{gw\text{-}act}$.

For the non-reduced consumptive use concept, wilting and anoxia above the water level are not simulated (a = 0, w = 0 in eq. 5.4 and 5.5), but $T_{c\text{-}pot}$ is still linearly reduced to $T_{c\text{-}act}$ (eq. 5.4) or $T_{gw\text{-}act}$ (eq. 5.5) as the active root zone is reduced by a rising water level. $T_{c\text{-}act}$ equals $T_{c\text{-}pot}$ for water levels below the root-zone base, and $T_{gw\text{-}act}$ reaches $T_{c\text{-}pot}$ for water levels at the root-zone base.

The actual evaporation from precipitation, $E_{p\text{-}act}$, is equal to the potential evaporation from precipitation, $E_{p\text{-}pot}$, if precipitation in open areas exceeds $E_{p\text{-}pot}$ and is equal to precipitation in open areas if $E_{p\text{-}pot}$ exceeds the precipitation. The potential evaporation from irrigation, $E_{i\text{-}pot}$, can be reduced in open and exposed areas if not fully wetted. Evaporation fractions of $ET_{c\text{-}pot}$ related to irrigation, $K_e^{\,i}$, therefore, can be smaller than ($1–K_t$). If ET input data reflect local wetting patterns of irrigation methods and a reduction in evaporation is implicitly accounted for, then the user should keep $K_e^{\,i} = (1–K_t)$. In equation 5.9, the actual evaporation from irrigation, $E_{i\text{-}act}$, accounts for losses of irrigation to evaporation and varies proportionally to the irrigation requirement for transpiration by a ratio of $K_e^{\,i}$ and K_t.

The remaining saturation water-vapor pressure deficit for the exposed areas that is not yet satisfied by $E_{p\text{-}act}$ or $E_{i\text{-}act}$ is assumed to be met by evaporation of capillary groundwater as long as the groundwater level in a cell keeps the capillary fringe partially above the extinction depth. The evaporation from groundwater, $E_{gw\text{-}act}$, varies linearly concomitant with the groundwater level (eq. 5.10) between zero for groundwater heads below the elevation of evaporation extinction, h_{ex} (which equals surface elevation, g, minus capillary fringe, c), and a maximum for heads rising to or above ground surface, g.

Irrigation Water

Irrigation water, *I* (in root-zone mass-balance eqs. 5.1 and 5.2), is equal either to irrigation demand or to irrigation supply. Irrigation water is equal to demand-driven-by-agricultural, urban, or natural vegetation consumptive use (that is, demand not met by precipitation or uptake from groundwater) if it can be met by irrigation supply components. Irrigation water is equal to supply if supply is restricted by any shortage or constrained by controls on stream diversions, pumping, and imported water. In short, the FMP follows a demand-driven, but supply-constrained system. This section discusses the computation of unmet water demand, which in cases of supply sufficiency equals the quantity of irrigation water, *I*. Situations where *I* is different from the unmet water demand are discussed in the "Balance Between Water Supply and Demand" section.

In the FMP, the crop-irrigation requirement, CIR, is equal to the sum of actual transpiration from irrigation and evaporation from irrigation, $ET_{i\text{-}act}$ (eqs. 5.8, 5.9, and 5.11). It is computed for each model cell at each transient time step. It assumes a pseudo-steady state between all flows into and out of the root zone at the end of time intervals, typical for MODFLOW. The FMP calculates an irrigation-delivery requirement for a specific time step iteratively on the basis of a dynamically updated groundwater head-dependent evaporative crop-irrigation requirement, CIR = $ET_{i\text{-}act}$, and CIR yields *I* if increased by inefficient losses at that time step (eq. 5.12). The CIR is computed only for cells that have land use defined as either an irrigated urban landscape or an irrigated agricultural crop. It is zero for cells with non-irrigated land use. The total irrigation water demand for each WBS (TFDR) is computed as cell delivery requirements for all cells in the unit (eq. 5.13).

Crop irrigation requirement equals the actual evapotranspiration from irrigation at each cell as follows:

$$CIR^{t,k}\left(h^{t,k-1}\right)=ET_{i-act}^{t,k}\left(h^{t,k-1}\right)=T_{i-act}^{t,k}\left(h^{t,k-1}\right)+E_{i-act}^{t,k}\left(h^{t,k-1}\right) \tag{5.11}$$

where

CIR is the crop irrigation requirement for each cell [LT^{-1}];
$T_{i\text{-}act}$ is the proportion of the actual transpiration supplied by irrigation [LT^{-1}];
$E_{i\text{-}act}$ is the actual evaporation loss from irrigation [LT^{-1}] proportional to $T_{i\text{-}act}$; and
$h_{t,k-1}$ is the head at the previous iteration, k–1, for a particular time step, t.

Irrigation delivery requirement at each cell, c, is adjusted as follows:

$$I^{t,k}\left(h^{t,k-1}\right)=\frac{ET_{i-act}^{t,k}\left(h^{t,k-1}\right)}{e^{t}} \tag{5.12}$$

where

I is the irrigation delivery requirement [LT^{-1}], and
e_t is the on-farm efficiency of the delivery system (dimensionless).

Total delivery requirement at each farm, f, or WBS is the summation over nc cells as follows:

$$TFDR_f^{t,k}\left(h^{t,k-1}\right)=\sum_{c=1}^{nc} I_c^{t,k}\left(h_c^{t,k-1}\right) \tag{5.13}$$

where

$TFDR$ is the total farm delivery requirement for a specific farm [LT^{-1}].

The on-farm efficiency is defined as the fraction of the total irrigation water that is used beneficially on the farm.

Runoff

In general, overland runoff can be composed of several flow components, such as (1) direct runoff, (2) interflow from excess precipitation and irrigation, (3) runoff generated by infiltration in excess of the saturated hydraulic conductivity of the unsaturated zone beneath the root zone, and (4) runoff from groundwater discharge and from rejected infiltration in areas of high groundwater levels. The FMP captures many, but not all these components. The FMP was initially developed to assess flood and basin-level irrigation along the Rio Grande of New Mexico (Schmid and others, 2009) or the Sacramento and San Joaquin Valleys of California (Schmid and Hanson, 2009a), where slopes are gradual and direct runoff is negligible, but interflow runoff can matter in different intensities for irrigation and precipitation. Hence, FMP simulates the second runoff component (fig. 5.9). The last two runoff components are available in the FMP by a linkage to the UZF (unsaturated-zone flow) package (Schmid and Hanson, 2009b) for vadose zones that extend below the root zone (fig. 5.9).

The FMP computes runoff, R (in root-zone mass-balance eqs. 5.1 and 5.2), as the proportion of crop-inefficient losses from precipitation or irrigation that contributes to runoff. Runoff related to precipitation, R_p, is calculated as follows:

$$R_p=\left(P-ET_{p-act}\right)f_r^{P-loss} \tag{5.14}$$

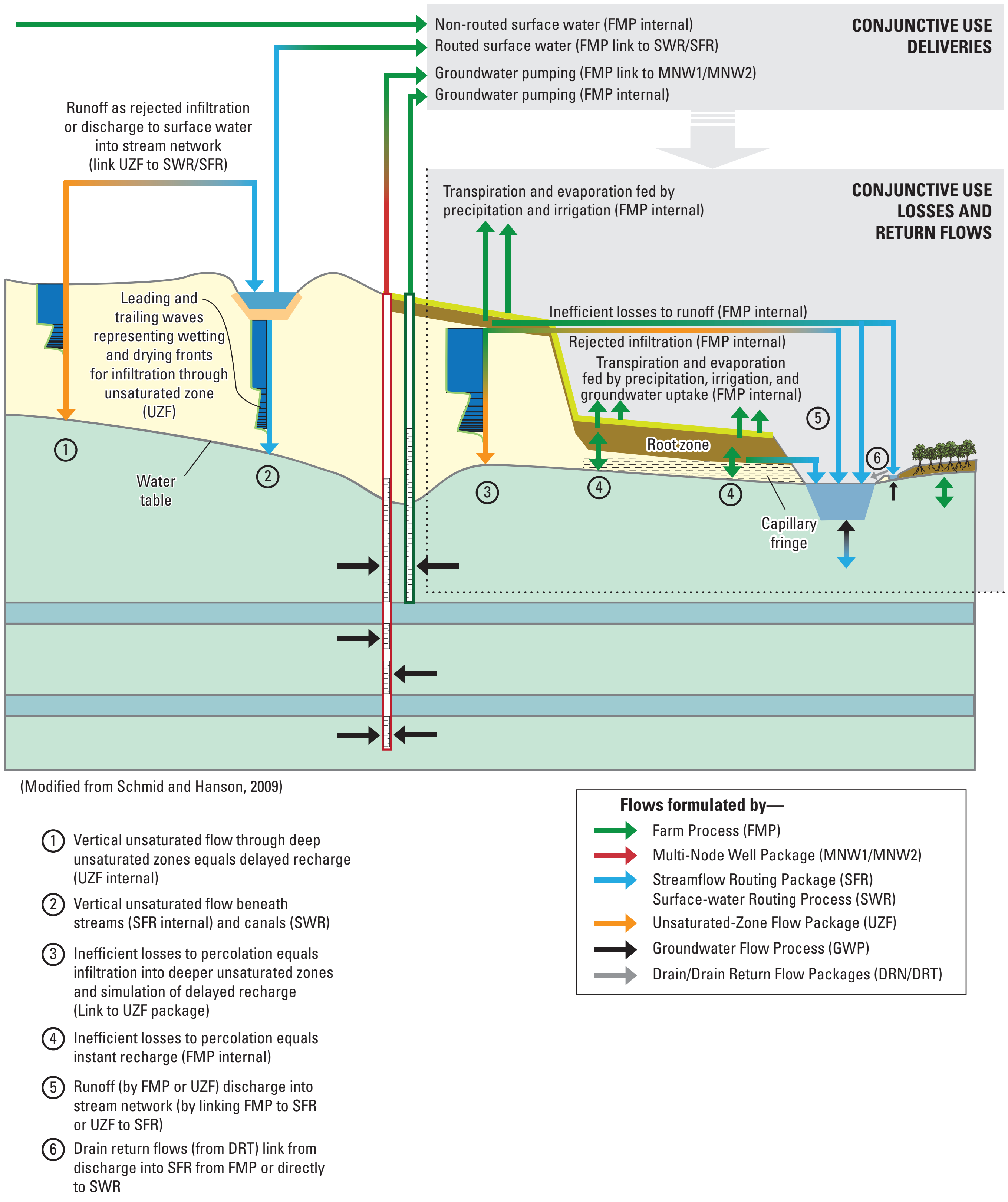


Figure 5.9. Interdependencies of flows in a hydrologic system simulated by the MF-OWHM (modified from Schmid and Hanson, 2009b).

Runoff related to irrigation, R_i, is calculated as follows:

$$R_i = \left(I - ET_{i-act}\right) f_r^{I-loss} \tag{5.15}$$

where

ET_{p-act} and ET_{i-act} are the parts of actual ET, ET_{c-act}, supplied by precipitation or irrigation [LT^{-1}], respectively, and

f_r^{P-loss} and f_r^{I-loss} are fractions of the respective crop's inefficient losses from precipitation or irrigation that go to runoff, given as time-series data.

Losses from precipitation or irrigation that do not contribute to runoff are assumed to become deep percolation.

The FMP assumes that all precipitation or irrigation is initially available for crop evapotranspiration before runoff in the form of crop inefficient losses. That is, runoff is generated as part of these inefficient losses only after ET_{c-act} is calculated. Fractions of the inefficient losses to surface-water runoff are specified for each virtual crop type for each stress period. Surface-water runoff is assumed to depend on irrigation method, which, in turn, may depend, in part, on the crop type. Because rainfall intensity and irrigation application methods further influence runoff, the FMP requires input of two separate fractions for inefficient losses to surface-water runoff: one related to precipitation, f_r^{P-loss}, and another one related to irrigation, f_r^{I-loss}, which may be omitted or set to placeholder zero values for non-irrigated crop types, such as natural vegetation. Instead of specifying f_r^{P-loss} and f_r^{I-loss} manually, the FMP also provides an alternative option to calculate these fractions on the basis of local (cell-by-cell) slope of the surface.

In the FMP, irrigation return flow is routed to any user-specified stream reach (called semi-routed return flow) or, alternatively, the FMP can search for a stream reach nearest to lowest elevation of the farm, where return flow is assumed to gather (called fully routed return flow). The stream network is simulated by a linkage between the FMP and the SFR (streamflow routing package of MODFLOW). Re-use of irrigation return flow is not explicitly modeled in the FMP. The user has the option to return the entire runoff from precipitation and irrigation losses to points of diversion either to the farm, from which the runoff originates, or to a downstream farm. In this way, runoff becomes available for diversions and can be re-used.

Deep Percolation

The FMP computes deep percolation, DP (eqs. 5.1 and 5.2), as the sum of deep percolation of precipitation and irrigation to below the root zone. It is the user-specified proportion of losses of precipitation and irrigation that are not consumptively used by plants and not lost to surface-water runoff (as explained in the "Runoff" section). Deep percolation is calculated as follows:

$$DP = \left(P - ET_{p-act}\right)\left(1 - f_r^{P-loss}\right) + \left(I - ET_{i-act}\right)\left(1 - f_r^{I-loss}\right) \tag{5.16}$$

This approach assumes no delay between percolation past the base of the root zone and recharge to the uppermost active aquifer (fig. 5.9, item 4).

For deep vadose zones that extend far below the root zone, the FMP also offers the calculation of a delay of DP by using a linkage between the FMP and the unsaturated-zone flow (UZF) package (Niswonger and others, 2006), passing the FMP-generated DP below the root zone to the UZF package as quasi-"applied infiltration" to the vadose zone below the root zone (fig. 5.9, item 3). This linkage allows the coupling of some farms between the FMP and UZF, but still retains the option of "stand-alone" UZF infiltration areas. The FMP-calculated percolation is passed on and partitioned by the linked UZF package to different components, including various runoff components, actual infiltration into the deeper vadose zone under farms, unsaturated-zone storage under farms, and recharge. In the UZF package, vertically downward flow through the unsaturated zone is simulated by a kinematic wave approximation to Richards' equation, which, in turn, is solved by the method of characteristics (Smith, 1993; fig. 5.9, items 1, 2, and 3). The approach assumes that unsaturated flow responds to gravity potential gradients only and ignores negative potential gradients; the approach further assumes uniform hydraulic properties in the unsaturated zone for each vertical column of model cells. The Brooks-Corey function is used to define the relation between unsaturated hydraulic conductivity and water content (Brooks and Corey, 1966).

Water Demand and Supply

The FMP calculates the irrigation water demand and attempts to match it with available supply components, which may be constrained by natural, legal or policy, or structural constraints (fig. 5.10). This is the core of the FMP's demand-driven and supply-constrained system. Computed or estimated water demand and available water supplies do not always balance, however. In dry years, actual deliveries or water rights allocations may not match water demands. Conversely, in wet years, actual deliveries may exceed what is needed for irrigation to protect surface-water rights, sustain flushing of saline soils, or to increase deep percolation and associated groundwater storage. Non-irrigated areas with natural vegetation rely solely on precipitation, which can be more or less than the actual plant evapotranspiration requirement. The FMP is designed to address (1) most of the issues regarding the computation of water demand, (2) the configuration of different sources of water supply to meet this demand, and (3) the computation of the hydrologic effects of unbalanced demand and supply. The next section discusses features representing total water demand, water-supply components, and the balance between supply-and-demand components.

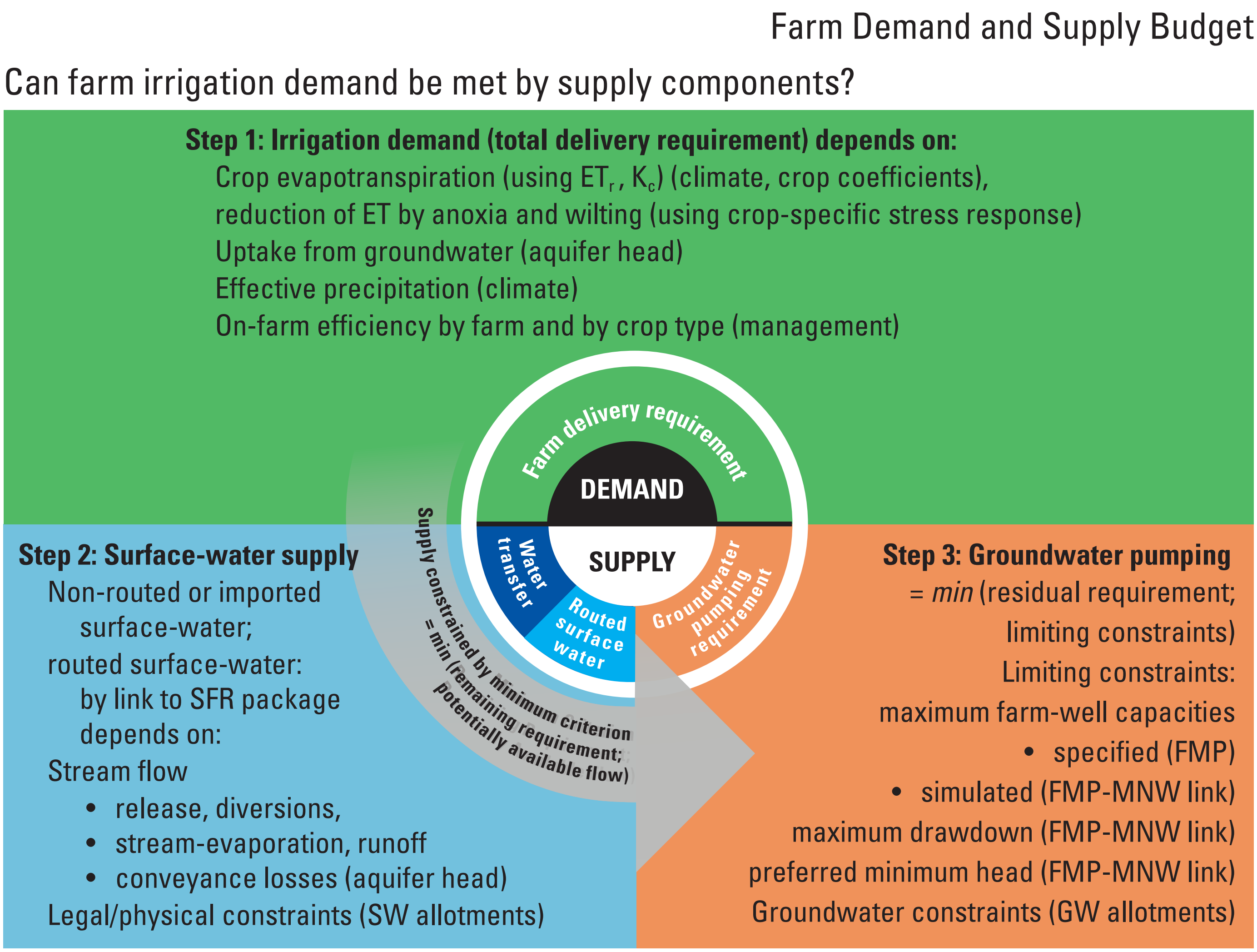


Figure 5.10. Demand-driven and supply-constrained system of the FMP (farm process) water demand and supply components (modified from Schmid and others, 2006b). [min, minimize; NRD, non-routed deliveries; SFR, streamflow routing package; SRD, semi-routed deliveries; RD, fully routed deliveries; GW, groundwater]

Total Water Demand

In addition to irrigation water demand, as discussed in the “Irrigation Water” section, the FMP also allows non-irrigation demand, such as urban, municipal, and industrial, to contribute to the total requested demand to be met with surface-water and groundwater supply components. In the FMP, other non-crop urban demand can be factored into the data input for non-routed deliveries. Inputs to the FMP for non-routed deliveries are computed by subtracting municipal and industrial demand needs from non-routed external water transfers (assuming that they are known). These demands may exceed the water transfers available, resulting in a negative non-routed delivery. This indicates a shortage that must be satisfied, along with water demand for urban irrigated landscapes, by routed surface water and pumped groundwater.

Another non-irrigation demand can target percolation rates for ponds or well injection rates for managed aquifer recharge (MAR) and Aquifer Storage and Recovery (ASR). This demand can be simulated as a “design” irrigation demand of a “virtual zero-transpiration crop” that is based on the known maximum infiltration rate of the ASR pond or injection wells (Hanson and others, 2008, 2014b, and 2015). These and other non-routed deliveries are accounted for separately for each farm.

Water-Supply Components

In the FMP, the initial sources of water to meet the total water demand come from precipitation and root uptake of groundwater. Because of the steady-state assumption, supply does not come from changes in soil moisture stored in the root zone. Any unmet demand is satisfied, in sequence of priority, by imported water, stream diversions, and groundwater pumping (fig. 5.10). Imported water from outside the model domain is simulated as non-routed deliveries (NRD). Multiple types of the NRDs can be specified (for example, for interstate water transfers, water from wastewater-treatment plants, or well fields delivering stored groundwater through ASR operations), which are linked to the water-balance subregions they serve. The NRDs must include information about maximum volumes, sequence of ranking in which each type is used to meet irrigation demand, and whether to route potential excess from the NRDs to the stream network or to injection wells.

Any demand not met by the NRDs is served by deliveries that originate from stream diversions in the model domain. These are simulated as semi- or fully-routed deliveries (SRD or RD; fig. 5.10). Locations in the stream network where the SRDs are withdrawn are specified by the user along modeled stream reaches. The RDs are automatically diverted to a farm from the uppermost stream reach, either from segments that are used for diversion only or from any type of river segment that is in the domain of the respective farm. Natural, legal, or structural constraints can pose limitations on surface water. The SRDs or RDs are limited by the available stream flow or by legal constraints such as equal or prior appropriation allotments (fig. 5.10). Specification of diversion rates for a streamflow diversion from a main-stem river to a diversion segment are possible through data input to the SFR package. These “river-to-canal” diversions can be specified along a segment near or farther upstream from the segment that contains the SRDs or RDs as “canal-to-farm” diversions. Subject to any canal water losses or gains between the “river-to-canal” and “canal-to-farm” diversion points, this mechanism can be used to construct a demand-driven and supply-constrained surface-water delivery system that is implicitly linked to the potential amount of water simulated to be conveyed in the stream to the point of diversion and delivery.

Any residual delivery requirement not met by NRDs, SRDs, nor RDs is supplied by the fourth source of water, groundwater pumping from farm wells at user-specified cells. Wells are associated with the WBS they serve through a unit-identification code; therefore, each well can be either inside or outside each WBS. The groundwater pumping in each WBS equals the sum of either the residual delivery requirement or the cumulative maximum pumping capacity, whichever is less (fig. 5.10). For single-aquifer wells (fig. 5.9), the maximum pumping capacity is specified, but for the FMP multi-aquifer wells linked to the MNW (multi-node well) package (fig. 9, Halford and Hanson, 2002; Konikow and others, 2009), a maximum capacity is simulated. Multi-node wells can represent non-uniform wellbore inflow from vertical, fully or partially penetrating, multi-aquifer wells.

The inflow is both head- and transmissivity-dependent. This allows for additional wellbore flow between model layers or aquifers, typical of large irrigation-supply wells. The wellbore flow can occur during both periods of pumping and no pumping. The MNW2 improvements from MNW1 include partial penetration, multiple MNW wells in one model cell, and better identification of FMP-MNW linked wells (Hanson and others, 2014a). The FMP-MNW linkage also allows for additional constraints on farm-well pumpage using the head and drawdown features of the MNW package (fig. 5.10), which simulate the loss in pressure as water flows through the aquifer toward the well. Pumpage rates will depend on the radius of each multi-node farm well, the aquifer properties. and the hydrologic head. Therefore, they may be less than the user specified flow rates.

The WELLFIELD option in the FMP allows for a redistribution of stored groundwater from recovery wells or well fields used for MAR and ASR to receiving farms; the redistribution amounts are related to the cumulative demand of these farms. This pumpage is, in the case of the recovery wells of an ASR, recovered and reused water that originally was diverted from the stream network and percolated to groundwater by the ASR pond. The pumpage of any well field is distributed as simulated NRDs to receiving farms and given priority over local farm-well pumpage. Farms can receive simulated NRDs from any number of well fields, with fields sequentially supplying demand according to a user-specified priority designated in the input data (Schmid and Hanson, 2009b). Whenever one well field’s pumpage is limited by rate, head, or drawdown constraints, the well field next in priority then contributes to the simulated demand of the NRDs. These ASR and multi-aquifer farm-well features are unique to the FMP and provide more potential linkages to the use and reuse of water resources in the framework of a supply-constrained and demand-driven water balance (Hanson and others, 2008).

Balance between Water Supply and Demand

The FMP does not simulate changes in soil-moisture storage; therefore, no depletion in soil moisture can contribute to satisfying the crop water demand. It is assumed that for most modeling applications and typical managed irrigation practices, this distinction has minor consequences because most irrigation is provided on a regular basis during the growing season. Hence, an imbalance between irrigation demand and irrigation supply components is not buffered by a soil-water reservoir. This becomes apparent at the first iteration of an FMP time step. In case of supply deficit, the FMP requires that at each time step, a solution to a deficit problem must be found according to the user’s choice. The user has the choice to assume that (1) the necessary water supply must be guaranteed and that the deficiency is made up by alternative sources external to the model domain; (2) the available supply is used, but that after improving the efficiency and minimizing inefficient losses, the actual evapotranspiration is reduced, indicating that crop yields are negatively affected by the deficit irrigation; or (3) profitability of a particular cropping pattern on a farm must be guaranteed by optimizing the profit, subject to crop market benefits and water costs associated with a particular water source. The latter option may lead to a reduction of each cell’s cropped area. Once the FMP detects a deficiency at the first iteration of a time step, the user-selected response to the deficit problem is dynamically applied in the succeeding iterations of the same time step. These features of the FMP provide a broad context for responding to deficits, considering all supply and demand components and spanning all the farms in a watershed or groundwater basin.

In the FMP, the total water supply is made available to meet crop-irrigation requirements and to account for inefficient losses. Water supply in excess of the crop water demand is converted to irrigation return flow and deep percolation using equations 5.15 and 5.16, respectively. Water supply can only exceed the total demand for excess imported water (NRDs) by user specification to either discharge the excess back to the conveyance network or to injection wells.

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