Soil moisture

Soil moisture $W_s(t)$ at time t is updated via

$$W_s(t) = W_s(t-1) + [P_t(t) - AET(t) - S(t)] \tag{1}$$

In words, the change in soil moisture is given by the throughfall $P_t(t)$ (rainfall minus what is intercepted by the canopy), minus actual evapotranspiration $AET(t)$, minus the surplus $S(t)$. This is a simple water balance equation.

Throughfall is given by

$$P_t(t) = \begin{cases} P(t) - E_c(t) - (W_i^{max} - W_i(t)), & \text{if } W_i^{max} < P(t) + W_i(t) - E_c(t) \\ 0 & \text{if } W_i^{max} \geq P(t) + W_i(t) - E_c(t) \end{cases} \tag{2}$$

$P(t)$ is precipitation, $W_i(t)$ is the canopy water storage, W_i^{max} is the maximum canopy water storage, and E_c is the canopy water evaporation rate.

If mean daily air temperature is below the snowfall threshold, T_s, all precipitation is treated as snow; otherwise, all precipitation is treated as rain. If mean daily air temperature is above the snowmelt threshold, T_m, a portion of the snowpack is melted:

$$M_s(t) = \begin{cases} 2.63 + 2.55\,T(t) + 0.0912\,T(t) \cdot P(t), & \text{if } T_m < T(t) \\ 0, & \text{if } T_m \geq T(t) \end{cases} \tag{3}$$

Here, $M_s(t)$ denotes snowmelt, which is never allowed to exceed the volume of the snowpack.

Canopy storage is updated via

$$W_i(t) = \begin{cases} W_i(t-1) + [P(t) - P_t(t)] - E_c(t), & \text{if } W_i(t-1) + [P(t) - P_t(t)] - E_c(t) < W_i^{max}(t) \\ W_i^{max}(t), & \text{if } W_i(t-1) + [P(t) - P_t(t)] - E_c(t) \geq W_i^{max}(t) \end{cases} \tag{4}$$

The canopy evaporation is given by

$$E_c(t) = E_{ow} \left(\frac{W_i(t)}{W_i^{max}(t)} \right)^{2/3} \tag{5}$$

where the maximum canopy storage is related to the leaf area index by $W_i^{max}(t) = 0.25\,LAI(t)$. These equations represent water balance applied to the canopy: incoming water via rainfall is first attributed to canopy evaporation, then to fill up canopy storage, and any remaining water becomes throughfall.

Actual evapotranspiration is given by

$$AET(t) = \begin{cases} PET(t), & \text{if } P_t(t) + M_s(t) \geq PET(t) \\ g(W_s(t))\,[PET(t) - P_t(t) - M_s(t)], & \text{if } P_t(t) + M_s(t) < PET(t) \end{cases} \tag{6}$$

In words, actual evapotranspiration will equal potential evapotranspiration PET if there is sufficient moisture via throughfall and snowmelt. Otherwise, the water will be drawn from the soil moisture pool to make up the difference, modified by a drying function given by:

$$g(W_s(t)) = \frac{1 - \exp[-\alpha W_s(t)/W_{cap}]}{1 - \exp[-\alpha]} \tag{7}$$

Here, W_{cap} is the soil storage capacity. For irrigated crops, $g = 1$ at all times.

Potential evapotranspiration is calculated via the Hamon method:

$$PET(t) = 330.2\,\Lambda\,\rho_{sat}(t) \tag{8}$$

Here, Λ is the fractional day length and $\rho_{sat}(t)$ is the saturation vapor density of water. The fractional day length is given by

$$\Lambda = \frac{1}{\pi} \cos^{-1} [-\tan\phi \tan\delta] \tag{9}$$

where ϕ is the latitude and δ is the solar declination, given by

$$\delta = -23.44 \cos \left[\frac{360}{365} (N + 10) \right] \tag{10}$$

where N is the day of the year. The saturation vapor density $\rho_{sat}(t)$ is given by

$$\rho_{sat} = \frac{2.167\ P_{sat}(t)}{T(t) + 273.15} \tag{11}$$

where $P_{sat}(t)$ is the saturation vapor pressure of water, given by the Tetens equation:

$$P_{sat}(t) = \begin{cases} 0.61078\ \exp\left[\frac{17.26939\ T(t)}{T(t)+237.3}\right], & \text{if } T(t) \geq 0 \\ 0.61078\ \exp\left[\frac{21.87456\ T(t)}{T(t)+265.5}\right], & \text{if } T(t) < 0 \end{cases} \tag{12}$$

where $T(t)$ is the daily mean temperature (°C).

If crops are being grown in the grid cell, potential evapotranspiration is modified during the growing season by a crop-specific scalar factor $k_c(t)$. Outside of the growing season it is modified by a generic scalar factor $k_c(t)$:

$$PET_c(t) = \begin{cases} k(t)\ PET(t), & \text{outside growing season} \\ k_c(t)\ PET(t), & \text{during growing season} \end{cases} \tag{13}$$

where $k(t) = k_{min} + (k_{max} - k_{min})(1 - \exp[-0.7\ LAI(t)])$.

Soil moisture surplus S is given by:

$$S(t) = \begin{cases} W_s(t) + P_t(t) + M_s(t) - AET(t) - W_{cap}, & \text{if } W_{cap} < W_s(t) + P_t(t) + M_s(t) - AET(t) \\ 0, & \text{if } W_{cap} \geq W_s(t) + P_t(t) + M_s(t) - AET(t) \end{cases} \tag{14}$$

In words, if there is leftover moisture beyond the soil storage capacity then it is attributed to surplus.

Irrigation

Irrigation is required when soil moisture falls below a crop-specific threshold W_{ct}, measured relative to the soil storage capacity:

$$W_{ct} = s_c W_{cap} \tag{15}$$

The optimal irrigation amount is then the difference between the crop-specific threshold and the soil storage capacity:

$$I_{net}(t) = \begin{cases} W_{cap} - W_s(t) & \text{if } W_s(t) < W_{ct} \\ 0, & \text{if } W_s(t) \geq W_{ct} \end{cases} \tag{16}$$

Inefficiencies in water extraction, conveyence, and application (including farmer decisions) lead to more irrigation water being withdrawn that is required:

$$I_{gross}(t) = \frac{I_{net}(t)}{r_I} \tag{17}$$

The volume $I_{net}(t)$ is applied to the soil moisture and the remainder is partitioned between non-beneficial evaporation $E_{nb}(t)$, surface runoff $R_{ro}(t)$, and percolation $R_{perc}(t)$:

$$E_{nb}(t) = min[(PET_c(t) - AET(t)), (I_{gross}(t) - I_{net}(t))] \tag{18}$$

$$R_{perc}(t) = r_p(I_{gross}(t) - I_{net}(t) - E_{nb}(t)) \tag{19}$$

$$R_{ro}(t) = (1 - r_p)(I_{gross}(t) - I_{net}(t) - E_{nb}(t)) \tag{20}$$

r_p controls the partitioning between runoff and percolation (default value is 0.5).

Groundwater volume

The groundwater volume is updated via:

$$W_G(t) = W_G(t-1) + \gamma_S S(t) - \gamma_G W_G(t-1) - I_{gross}(t) + R_{perc}(t) \tag{21}$$

In words, groundwater volume increases due to infiltration from soil moisture surplus, controlled by γ_S (default 0.5), and percolation. Groundwater volume decreases due to irrigation extractions and a fractional leakage controlled by γ_G (default 0.0167).