Contents

1. Bare-soil evaporation

Evaporation from bare soil is globally significant and vitally important to farmers, especially in the management of irrigation. Following infiltration, evaporation from bare soil follows an *atmosphere controlled stage* where evaporation is largely independent of soil moisture content and evaporation occurs near the free-water rate. Then there is a *soil controlled stage* in which evaporation rate is determined by the rate at which water can be conducted to the surface rather than by atmospheric conditions.

During stage 1, we can estimate the average evaporation rate $\overline{E}_1$ using free-water evaporation (generally Penman is the best). If this stage has a duration t_1, the total stage 1 evaporation is $F_1 = \overline{E_1} t_1$. And the water content in the soil at the end of this stage is θ_1.

After stage 2 is underway, we can calculate the cumulative evaporative loss at time t as

$$F_{soil}(t) = F_1 \left[1 + (8/\pi^{1/2}) ln(t/t_1)\right], t > t_1 \tag{1}$$

where the rate of stage 2 evaporation is:

$$E_2(t) = (8/\pi^{1/2}) \overline{E_1} \frac{t_1}{t} \tag{2}$$

2. Transpiration

Transpiration is the evaporation of water from the vascular system of plants into the atmosphere. Water is absorbed through the plant roots, translocated through the vascular system of the roots, stem and branches and leaves, then to the stomatal cavities. Water moves to the ambient air through the stomata. Stomata is the place where CO_2 is dissolved into the water. The evaporation of water is the unavoidable result. Notably, water moves through the plants through pressure gradients

The main difference between transpiration and open-water evaporation is that plants can exert some physiological control over the size of the stomatal openings, and hence the ease of vapor movement by the action of *guard cells*.

Transpiration is a two-step process in which water moleculaes pass from the stomatal cavity to the leaf surface and from the leaf surface into the atmosphere.

Figure 1: Figure 7-12 from Dingman Book

2a. *Atmospheric Conductance*

Let's re-write the basic equation as:

$$E = K_{at} C_{at} (e_s - e_a) \tag{3}$$

where $K_{at} = \frac{0.622\rho_a}{P\rho_w}$ and $C_{at} = \frac{v_a k^2}{ln((z_m - z_d)/z_0)^2}$. The zero-plane displacement z_d and roughness height z_0 can be approximately related to the height of vegetation

z_{veg} as:

$$z_d = 0.7 z_{veg} \quad (4)$$

$$z_0 = 0.1 z_{veg} \quad (5)$$

2b. *Leaf Conductance*

Determined by the number of stomata per unit area and the size of the stomatal openings. Stomatal densities range from 10,000 to 100,000 stomata per square centimeter. While we can find values for maximum leaf conductance for different land cover types, remember that plants control the size of the openings. The following control this:

1. Light intensity
2. Ambient CO_2 concentration
3. leaf-air vapor-pressure difference
4. leaf temperature
5. leaf water content

$$C_{leaf} = C*_{leaf}\; f_k(K_{in}) f_\rho(\Delta\rho_v) f_T(T_a) f_\theta(\Delta\theta) \quad (6)$$

where $C*_{leaf}$ is the maximum leaf conductance.

Figure 2: Figure 7-13 from Dingman Book

We can think of a vegetated surface as a large number of leaf conductances in parallel. The total conductance of a number of conductances in parallel equals the sum of the individual conductances. We use the "big leaf" concept where the size of the big leaf is reflected in the **leaf-area index** LAI defined as $LAI =$ *total area of leaf surface above ground area A / A*. And canopy conductance is then given by:

$$C_{can} = f_s\, LAI\, C_{leaf} \quad (7)$$

where f_s is a shelter factor due to the fact that some leaves are shaded (0.5-1). LAI varies throughout the year for deciduous forests.

2c. *Penman-Monteith Model*

We can modify the Penman (combination) model for evaporation from a free-water surface to accomodate for transpiration. First we can write it in terms of atmospheric conductance:

$$E = \frac{\Delta(K + L - G) + \rho_a c_a C_{at}(e_a * - e_a)}{\rho_w \lambda_v (\Delta + \gamma)} \tag{8}$$

Monteith (1965) showed that the equation can be modified to represent the evapotranspiration rate ET from a vegetated surface by incorporating canopy conductance:

$$E = \frac{\Delta(K + L - G) + \rho_a c_a C_{at}(e_a * - e_a)}{\rho_w \lambda_v (\Delta + \gamma(1 + C_{at}/C_{can})} \tag{9}$$

This equation is the **Penman-Monteith Equation**. This equation has been successfully tested in many environments and has become the most widely used approach to estimate evapotranspiration from land surfaces.

2d. *Interception*

Interception is the process by which precipitation falls on vegetative surfaces where it is subject to evaporation. It can be a significant fraction of total evapotranspiration. You can have canopy interception and Litter interception. Quite difficult to model - usually use regression analysis to model.

3. Potential Evapotranspiration

Potential evapotranspiration (PET) is the rate at which evapotranspiration would occur from a large area completely and uniformly covered with growing vegetation which has access to an unlimited supply of water and without advection or hat storage effects. It is important to note, however, that that:

- Transpiration, even at the potential rate, involves stomatal impedance to the diffusion of water vapor so it is better to use the term potential evaporation.

- Wet or moist surface is not the same as one that has an adequate moisture supply for the roots of an actively growing vegetation.
- PET is often measured by meteorological data observed under nonpotential conditions, which would not be the same as air under potential conditions. So sometimes we call this the apparent E_p or E_{pa}.

NOTE: over short non-wet vegetation with adequate moisture, the evapotranspiration is often similar to the evaporation from open water under the same conditions, this is likely due to the fact that stomatal impedance is compensated by the larger roughness values resulting in larger transfer coefficients.

3a. *Temperature-Based Method (Thornthwaite)*

Based on an empirical formula by Thornthwaite (1948). This method calculates PET as a function of temperature and day length.

$$PET_H = 29.8D\frac{e*_a}{T_a + 273.2} \tag{10}$$

where PET_H is in mm/day, D is day length in hr and $e*_a$ is the saturation vapor pressure (kPa) at the mean daily temperature T_a in $^\circ C$.

3b. *Combination Method*

Use the Penman-Monteith equation, calculating C_{leaf} with $f_\theta(\Delta\theta) = 1$. The reference crop defined by Shuttleworth (1194) is a grass of 120mm. $C_{can} = 14.5mm/s$

3c. *Radiation-Based Method (Priestly Taylor)*

If the air above a surface is completely saturated, the second term in the Penman equation drops. And the evaporation can be expressed as:

$$E = \frac{\Delta(K + L - G)}{\rho_w \lambda_v (\Delta + \gamma)} \tag{11}$$

Investigations have shown, however, that these conditions are rarely encountered, if ever. However, based on this idea Priestly and Taylor (1972) used this relationship to find an empirical relation for evaporation over wet surfaces in conditions of minimal advection.

$$E = \frac{\alpha_{PT}}{\rho_w \lambda_v} \frac{\Delta}{(\Delta + \gamma)} (K + L - G) \tag{12}$$

Where α_{PT} is a constant that ranges from about 1.2-1.3 over advection-free water surfaces and moist land surfaces with short vegetation. This relationship has been found to work remarkably well, and furthermore has been modified to include different vegetation stresses to use with remote sensing (Fisher et al. 2008).

3d. *Pan-Based method*

The potential evapotranspiration for short vegetation is very similar to free-water evaporation. Lower canopy conductance of vegetation fortuitously compensates for the lower atmospheric conductance over a pan.

4. Actual Evapotranspiration

In hot arid regions, potential evapotranspiration greatly exceeds precipitation so that average actual evapotranspiration is water-limited and essentially equal to average precipitation. In regions with abundant rainfall in all seasons, evapotranspiration is limited by the available energy so that average evapotranspiration is essentially equal to average potential evapotranspiration.

4a. *Soil-Moisture Functions*

Based on computing the potential evapotranspiration using the above methods, and then computes the actual evapotranspiation as:

$$ET = F(\theta_{rel}) PET \tag{13}$$

where θ_{rel} is the **relative water content**

$$\theta_{rel} = \frac{\theta - \theta_{pwp}}{\theta_{fc} - \theta_{pwp}} \tag{14}$$

where θ is the current water content, θ_{fc} is the field-capacity, and θ_{pwp} is the permanent wilting point of the root-zone.

Another way of doing this is by using the Penman-Monteith equation and modifying the canopy conductance.

Figure 3: Figure 7-24 from Dingman Book

$$\frac{ET}{PET} = \frac{\Delta + \gamma\left(1 + \frac{C_{at}}{C_{can}[f_\theta(\Delta\theta)=1]}\right)}{\Delta + \gamma\left(1 + \frac{C_{at}}{C_{can}[f_\theta(\Delta\theta)]}\right)} \quad (15)$$

5. Measurement

Water Balance involves measuring water inputs and outputs and changes in storage and solving the water-balance equation. Limited by precision of measurements.

Lysimeter artificially enclosed volume of soil for which inflows and outflows of water can be measured. Range from 1 to 150 m^3. Usually considered to give excellent measurements.

Eddy Correlation Often cosidered to be the true evaporation rate.

Priestly Taylor Recently used with satellite data. Seems to give reasonable results.