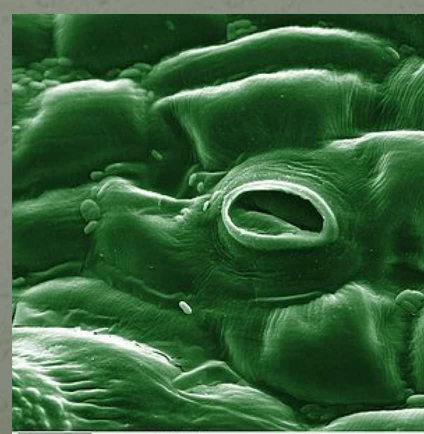
Elements of Physical Hydrology
Catchment Hydrology:
Land-Atmosphere Interactions

Hornberger GM, Raffensperger JP, Wiberg PL , and KN Eshleman. 1998.

Evapotranspiration

- **Evapotranspiration (ET):** process by which liquid water at or near the land surface becomes atmospheric water vapor
    - Evaporation (E): loss of water from wet surfaces
    - Transpiration (T): loss of water from parts of plants
        - **Stomata:** openings on surface of plant leaves that allow for the exchange of gases between the atmosphere and the inside of the leaf.
        - rate of transpiration is regulated by plants and varies across plant species and across time



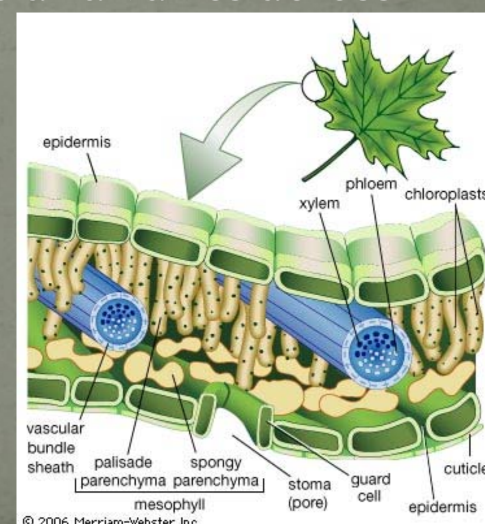
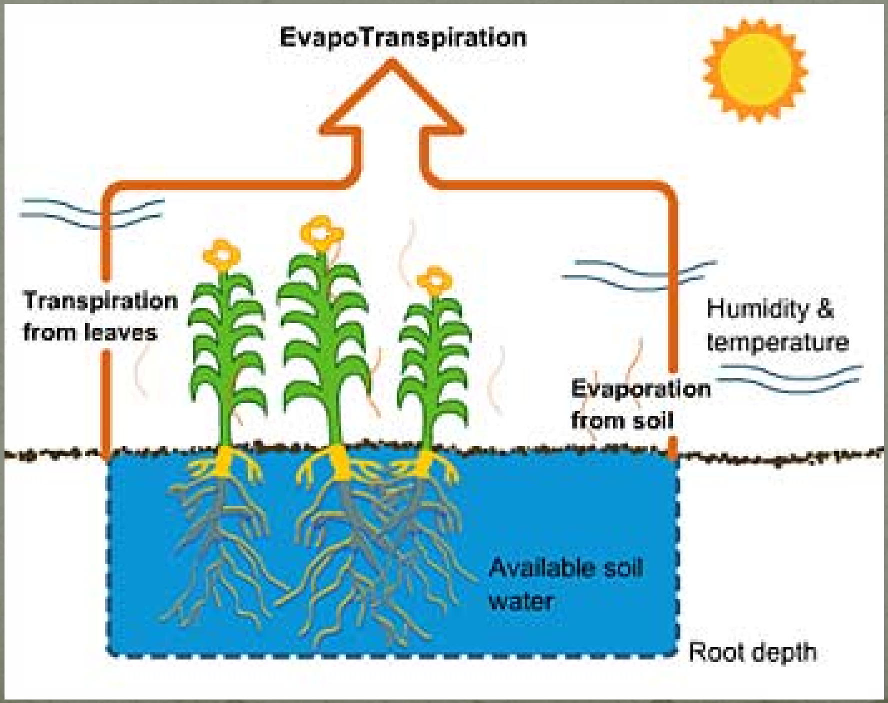


Photo Sources: http://media-2.web.britannica.com/eb-media/89/72189-035-16AD1400.jpg
http://bioweb.uwlax.edu/bio203/s2009/loch_spen/Used%20pics/stoma-wiki.jpg

Evapotranspiration

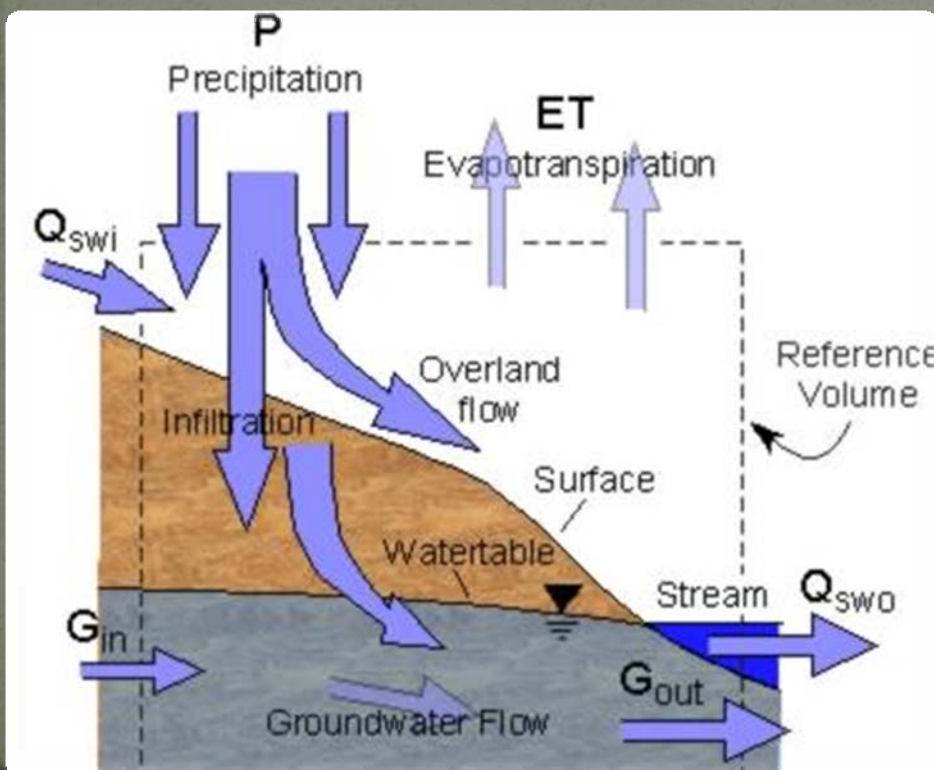
- 2/3 of precipitation that falls on continents is evapotranspired
  - of that: 97% is ET from land surfaces; 3% is open water evaporation
- Two ingredients: water (precipitation) & energy (solar radiation)
- ET is where the surface-water balance & surface-energy balance meet



http://www.westone.wa.gov.au/toolbox6/hort6/html/resources/visitor_centre/fact_sheets/images/et.jpg

Water Balance

- Evapotranspiration(ET) can be estimated through a water balance approach if the change in storage and all inputs and outputs except ET are known



$$\frac{dV}{dt} = p(t) + r_{si}(t) + r_{gi}(t) - r_{so}(t) - r_{go}(t) - et(t)$$

* It is difficult & unrealistic to be able to accurately quantify all the terms in a water balance for a basin to solve for ET.

Energy Balance

- First law of thermodynamics: net energy received at the land surface must be conserved.

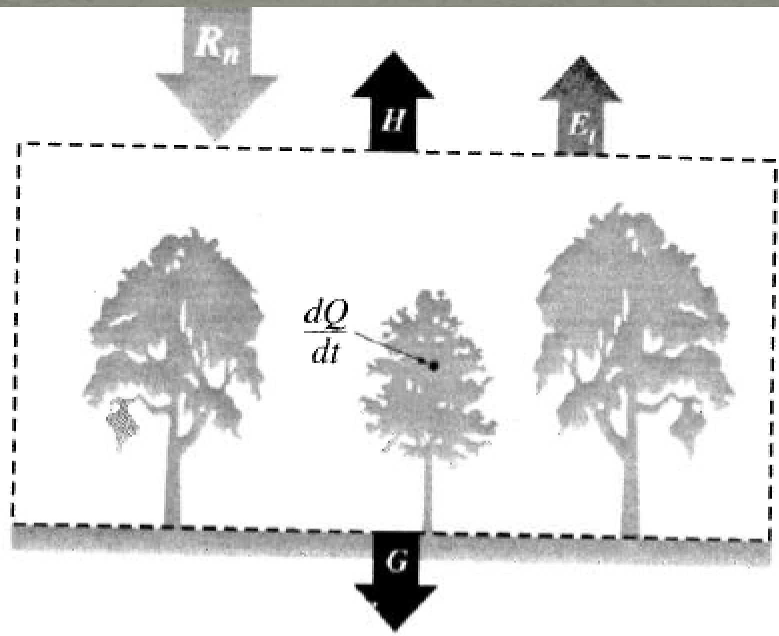


Figure 2.9 A control volume for energy conservation. Solar energy (R_n) entering the control volume must be balanced by fluxes of energy out of the volume and by the time rate of change in energy stored (dQ/dt).

- The energy may change among its possible forms (kinetic, thermal, radiant, potential) but it must be conserved.

Energy Balance

- All matter has **internal energy (**E_u) due to kinetic & potential energy associated with individual molecules
  - There are several types of internal energy
    - **Sensible Heat**: portion of internal energy that is proportional to temperature. It is the heat you would "sense" by contact or touch
      - Specific heat capacity (c_p): provides a measure of how a substance's internal energy changes with temperature

$$c_p = \frac{dE_u / m}{dT}$$

      - Specific heat capacity is the amount of heat required to raise the temperature of a unit of mass by 1°C

Energy Balance

- There are several types of internal energy
  - **Sensible Heat**
  - **Latent Heat:** portion of internal energy that *cannot* be sensed or felt. It is the amount of internal energy that is released or absorbed during a phase change , *at a constant temperature*
    - **Latent heat of vaporization:** the required energy that is needed to convert liquid to a vapor

$$\lambda_v = 2.45 \times 10^6 \text{ J kg}^{-1} \quad (\text{at } 20°\text{C})$$

    - which means we need to add ~2.5million joules of energy to evaporate 1 kilogram of water

Energy Balance

- Energy balance approach to evaporation is based on the fact that evaporation involves an energy flux (of latent heat energy to the atmosphere)
  - Therefore the rate of evaporation can be described in context of an energy balance equation

$$\frac{dQ}{dt} = R_n - G - H - E_l$$

- R_n = net solar radiation input
- G = energy output through conduction to the ground
- H= net ouput of sensible heat to the atmosphere
- E_l =output of latent heat to the atmosphere (latent heat flux)
- Q =amount of heat energy stored in

  the control volume per unit area of surface

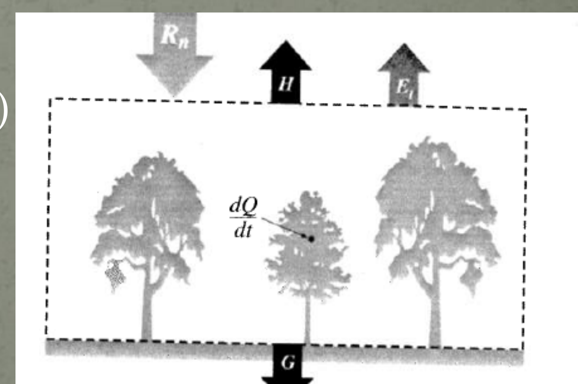


Figure 2.9 A control volume for energy conservation. Solar energy (R_n) entering the control volume must be balanced by fluxes of energy out of the volume and by the time rate of change in energy stored (dQ/dt).

- Energy balance equation

$$\frac{dQ}{dt} = R_n - G - H - E_l$$

- Solve for E_l latent heat flux

$$E_l = R_n - G - H - \frac{dQ}{dt}$$

- Latent heat flux is related to the rate of ET through the latent heat of vaporization (*et* = evapotranspiration rate)

$$et = \frac{E_l}{\rho_w \lambda_v}$$

- Substitute and rearrange to solve for *et*

$$et = \frac{R_n - G - H - dQ/dt}{\rho_w \lambda_v}$$

- For wet surface conditions, *et* is governed by the supply of radiant energy, the relative dryness of the air, and the efficiency of the wind in removing the water.
  - example: water quickly evaporates from wet clothes on a dry day compared to a humid day
  - Field experiment to explore that relationship:

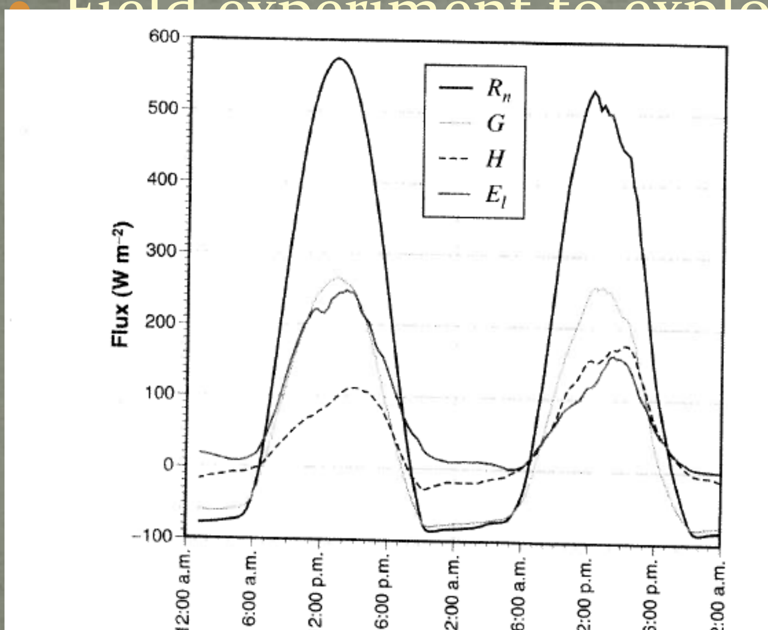


Figure 2.10 Measured energy fluxes from an experimental field in California. As the surface dries during the experiment, the latent heat flux (E_l) is reduced and the sensible heat flux (H) increased. Data courtesy of John D. Albertson.

•Surface was wet on Day 1, partially dry on Day 2

•Latent heat flux is nearly twice as much as the heating of the air on the wet day

•On the drier day, those 2 terms are nearly equal

- **<u>Potential Evapotranspiration (PET):</u>** rate of *et* under prevailing solar input and atmospheric properties if the surface is fully wet.
  - when the surface is wet the ratio of et to PET will be unity
  - when surface is completely dry, the ratio will go to zero

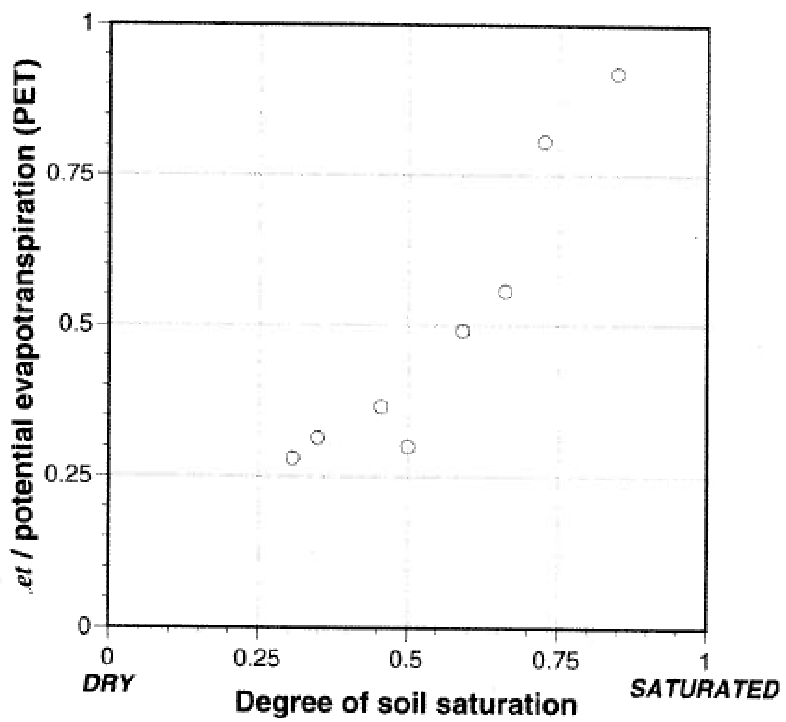


Figure 2.11 The ratio of actual *et* to PET decreases as the available soil moisture decreases. Data courtesy of John D. Albertson.

Actual et was determined through measurements of velocity and vapor pressure in the atmosphere.

PET was measured by time domain reflectometry (TDR)

Bowen Ratio

- replaces the sensible heat flux term with an expression of the ratio of sensible to latent heat flux is the Bowen Ratio *($B = H/E_l$)*
- Removes *H* from the energy balance equation:

$$E_l + H = E_l(1 + B) = R_n - G - \frac{dQ}{dt}$$

- Allows for calculation of *et*:

$$et = \frac{R_n - G - dQ/dt}{\rho_w \lambda_v (1 + B)}$$

- Bowen ratio is a function of the gradients of temperature and water vapor pressure in the air above the surface:

$$B \propto \frac{T_s - T_a}{e_s - e_a}$$

- As the surface becomes warm (T_s increases) and dry (e_s decreases), the Bowen ratio tends to increase. Consequently the sensible heat flux increases relative to the latent heat flux

Key Points from the Chapter

- ET from a basin includes a variety of different vaporization processes, including evaporation from open water, soils & vegetation surfaces & from transpiration from plants
- ET can be estimated using the mass balance approach, with the appropriate assumptions and appropriate field data
- Energy balance approach is based on the principle of conservation of energy in which the radiant received energy (R_n) is partitioned between the latent heat flux (E_l) to the atmosphere, the sensible heat flux (*H*) to the atmosphere, the heat flux to the ground (*G*), and the change in energy stored in the control volume (dQ/dt)
- Overland surface water may be limited in availability (dry soils) and rates of ET are then reduced compared to those over a fully wet surface.
- Bowen ratio uses an estimate of the ratio of sensible heat flux (*H*) to latent heat flux (E_l), $B=H/E_l$ such that *et* may be estimated from the energy balance.