EcoHydrology: WATER & ECOSYSTEM ECOLOGY, ESPM 111

Dennis Baldocchi
ESPM
University of California, Berkeley

Topics Covered

• Principles
  – Water Balance
  – Water Potential
• Water in the Soil
• Water in the Air
• Evaporation
• BioPhysical Controls on Evaporation
Hydrological Cycle and Ecosystems

Water and the Environment: Biogeophysical-Ecohydrological View
Chemical Potential of Water

Chemical potential quantifies the driving force for movement of water between two locations.

The chemical potential of water is related to the change in the Gibbs free energy of the system, subjected by pressure, gravity, temperature and minor constituents, e.g., salts.

By convention, Water potential is normalized by $V_w$, the partial molal volume of water ($18.05 \times 10^{-6} \text{ m}^3 \text{ mol}^{-1}$), giving it units of Pressure.

$$\text{kg m}^2 \text{ s}^{-2} / \text{ m}^3 = \text{kg m}^{-1} \text{ s}^{-2} \equiv \text{P} \equiv \text{F/A} = \text{kg m s}^{-2}/\text{m}^2$$

Water Potential

- The total water potential of a system consists of the sum of water potentials forces per unit area associated
  - Pressure (+/-)
  - Osmosis (-)
  - Soil and Plant Matrix (-)
  - Gravitation (+/-)

$$\psi = \psi_p + \psi_\pi + \psi_m + \psi_g$$
• **Turgor (pressure) potential**
  - is related to the hydrostatic pressure, as when someone is blow on or sucking on straw that is inserted in a reservoir of water. Its sign can be positive or negative.

• **osmotic potential**
  - The presence of solutes reduces the activity of water.

• **matric potential**
  - interactions between water and solid surfaces act to reduce the activity of water.

• **gravity Potential**
  - gravitational force is a function of the density of water, the acceleration due to gravity and the height of the water reservoir above or below a reference height:

\[ \psi_g = \rho_w gh \]

---

**Saturated Flow, Pure Water**

\[ \psi = \psi_p + \psi_g \]

\[ 0 = \psi_p + \psi_g ; \]
\[ \psi_p = -\psi_g \]

Takes Negative Pressure (suction) to lift water against gravity

The Gravitational Burden of Water Overhead Imposes a Positive Pressures

Dominated by Pressure and Gravity
Soil Water Retention function for Unsaturated Soils
Water Potential = f(volumetric water content, soil Texture)

Vaira Soil

Water Potential, MPa
-40 -30 -20 -10 0

Volumetric Soil Moisture (cm³ cm⁻³)
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35

Plant-available water:
Difference between field capacity and permanent wilting point

Field Capacity: -0.03 MPa
Permanent Wilting Point: -1.5 MPa
Soil-Plant-Atmosphere-Water Continuum

Water Moves UPWARD because it flows DOWNHILL Energetically

Trees, Drought and Vulnerability to Embolism

Water potential with 50% loss in conductivity

70% of 226 tree species, from 81 sites, operate within 1 MPa of Hydraulic Safety Margin for Injury. Explains Why Drought Decline is Occurring World-Wide

Choat et al 2012 Nature
Atmospheric Humidity

- Relative Humidity,
  - Ratio between ambient, $e_a$, and saturated vapor pressures, $e_s(T)$

$$h_r = \frac{e_a}{e_s(T)}$$

- Absolute Humidity

$$\rho_v = \frac{e_a m_v}{R T_k}$$

- Dew Point Temperature, $T_d$

$$T_d = \frac{24097 \cdot \ln(e_a / 0.611)}{17.502 - \ln(e_a / 0.611)}$$

- Wet Bulb Psychrometry

$$C_w(T_a - T_w) = \frac{\lambda(e_u(T_a) - e_a)}{p}$$

SATURATION VAPOR PRESSURE

$$e_s(T_c) = 0.611 \exp\left(\frac{17.502 \cdot T}{T + 240.97}\right)$$

T (°C) vs. $e_s(T_c)$ (kPa)
Dewpoint Temperature and Vapor Pressure

Dewpoint Scales with Minimum Temperature
Evaporation

• Evaporation is the “physical process by which a liquid or solid is converted to a gaseous state” (Glossary of Meteorology).

• Plant canopies introduce water vapor into the atmosphere via transpiration and the evaporation of water from the soil and free water on the leaves and stems.

Evaporation:
EcoPhysiological Viewpoint

$E = \frac{\rho m_v (e_s(T) - e_a)}{m_a \sum R}$

Current=potential/resistances $I = \frac{V}{R}$

Evaporation is a function of the ratio between potential difference in humidity, V, and the resistances against that potential, R

$R =$ resistances, stomata & boundary layer =1/G, conductances

$m_v$ and $m_a$ are molecular masses for vapor and dry air
EVAPORATION is Energy Driven: Meteorologist Viewpoint

\[ \lambda E = R_n - H - G - S - P_s \]

- Net Radiation (Rn) is partitioned into
  - Sensible Heat Exchange (H)
  - Latent Heat Exchange (λE)
  - Soil Heat Exchange (G)
  - Heat Storage in the Air and Vegetation (S)
  - Photosynthesis (Ps)
  - Bowen Ratio, β, λE/H

\[ \lambda E = \frac{R_n - G}{1 + \beta} \]

Potential Evaporation

- “the evaporation from an extended surface of a short grass that is supplied with water and the canopy covers the ground completely.”

UC Davis Lysimeter

ESPM 111 Ecosystem Ecology
Potential vs Actual Evaporation

Monteith, 1981 QJRMS

Conflicting Controls on Evaporation, Supply of Water vs Demand by Available Energy

\[ \lambda E = \rho \lambda \frac{q_s(T_a) - q_e}{R_w} \]

\[ \lambda E = R_t - G - \rho c_p \frac{T_s - T_a}{R_w} \]
Penman Monteith Eq

- $\lambda E$ is a balance between the supply and demand for moisture
- Reconciles the Meteorological and Physiological Viewpoints

$$\lambda E = \frac{s(R_n - S) + \rho \cdot C_v \cdot G_{H} \cdot D}{s + \gamma + \gamma \frac{G_{H}}{G_s}}$$

s: slope of $e_s(T)$ and $T$ curve
$\gamma$: pychrometric constant
$G_s$ & $G_H$: surface and aerodynamic conductances

Big-Leaf Surface Conductance, $G_s$

$$f(LAI, \text{soil moisture, photosynthetic capacity}(N))$$
Effects of Functional Types and Surface Resistance

Landscape Differences on Evaporation Rates, normalized by Available Energy
On Short Time Scales, Grass ET > Forest ET

Baldocchi and Xu, 2008 Adv Water Res

Ryu, Baldocchi, Ma and Hehn, JGR-Atmos, 2009
Stomatal Conductance Scales with N, via Photosynthesis

Wilson et al. 2001, Tree Physiology
Schulze et al 1994, Annual Rev Ecology

Does Biodiversity affect Evaporation?

ESPM 111 Ecosystem Ecology
Stand Age also affects differences between ET of forest vs grassland

Marc and Robinson, 2007 HESS

EcoHydrology, Evaporation & Soil Moisture

ESPM 111 Ecosystem Ecology
Evaporation and Drought

Grassland D70-300, 2001

Oak Savanna, 2002 D105-270

Grass Uses Water Quick as Possible, Then Die
Baldocchi et al. 2004

Oaks meter out Water Conservatively

Budyko Evaporation-Precipitation Relationship

From Farquhar and Roderick, 2007

ESP M 111 Ecosystem Ecology
Annual Evaporation of Forests is, on average, about one-half Precipitation

Baldocchi and Ryu, 2010, book chapter

Why is the Arctic so Wet, if it can be Classified as a Desert by its Meager Rainfall ( < 300 mm/y)?

Equilibrium Evaporation

\[ E_{eq} = \frac{1}{\lambda} \frac{s}{s + \gamma} R_n \]

\[ \frac{s}{s + \gamma} \approx 0.432 + T_a \cdot 0.0116 \]

\[ E_{eq} = \frac{1}{2.41MJ/kg} \cdot 0.39 \cdot 1000MJm^{-2}y^{-1} = 161mm \]

ppt >> \( E_{eq} \)

ESPM 111 Ecosystem Ecology
<ET> = 500 mm/y == 63,000 km³/y


MODIS-Driven Product Using Biophysics via Cloud Computing

Down-Scale to Regions for Policy and Management Decisions


Points to Ponder

- How does land use (conifer/deciduous forests vs grasslands) affect energy and water balances?
- How does biodiversity affect evaporation and water yield?
- What will happen to Evaporation with Global Warming and Higher CO2 concentrations?
Role of Land Use on ET:
On Annual Time Scale, Forest ET > Grass ET

Ryu, Baldocchi et al, JGR-Atmos, 2010
Summary

LONG-TERM CONTROLS

STATE FACTORS

BIOTA

TIME

PARENT MATERIAL

CLIMATE

Interactive controls

Indirect controls

Direct controls

Plant functional types

Soil resources

Surface roughness

Photosynthetic capacity

Stomatal conductance

Water availability

Precipitation

Boundary-layer conductance

Water holding capacity

Net radiation / VPD

CHAPIN ET AL. 2010 JGR Atmos

ESPM 111 Ecosystem Ecology