Evapotranspiration

Alan Mair
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Hawaiian Water Cycle
Definitions

• Evaporation:
  – Flux of water vapor from open water surface, wet vegetation, or wet soil

• Transpiration:
  – Water vapor transfer to the atmosphere occurring primarily through the stomata of living plants

• Evapotranspiration:
  – Total flux of water vapor from the surface to the atmosphere

Water Balance

\[ P = RO + ET + RCHG + \Delta S \]

- \( P \) = precipitation
- \( RO \) = surface runoff
- \( ET \) = evapotranspiration
- \( RCHG \) = groundwater recharge
- \( \Delta S \) = change in storage
Energy Balance

\[ R_{net} = G + H + LE \]

- \( R_{net} \) = net radiation
- \( G \) = soil heat flux
- \( H \) = sensible heat flux
- \( LE \) = latent heat flux

Conceptual Models

[Diagram showing conceptual models of energy and water balance in a forest ecosystem, including processes like canopy interception, stemflow, throughfall, and various water and energy pathways.]
Potential ET

• “the amount of water transpired in a given time by a short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile”

Penman, 1948

Reference ET

• "the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m (4.72 in), a fixed surface resistance of 70 sec m⁻¹ (70 sec 3.2ft⁻¹) and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground”

Allen et al., 1998
Estimating Potential Evapotranspiration (PE)

- Penman (1948)
- Thornthwaite and Mather (1955)
- Hamon (1961)
- Monteith (1965)
- Priestley and Taylor (1972)

Penman Equation

\[
ET_o = \frac{(\Delta R_{net} - G)}{\Delta + \gamma} + \frac{\gamma (E_a)}{\Delta + \gamma} / \lambda
\]

- \(ET_o\) = Reference ET [mm/hr]
- \(\Delta\) = Slope of saturation vapor curve [kPa/°C]
- \(\gamma\) = Psychometric constant [kPa/°C]
- \(R_{net}\) = Net radiation [MJ/m²*d]
- \(G\) = Soil heat flux [MJ/m²*d]
- \(E_a\) = \(K_w(a_w + b_w u_2)(e_s - e_a)\) [MJ/m²*d]
- \(K_w\) = units constant
- \(a_w, b_w\) = empirical wind coefficients
- \(u_2\) = wind speed at 2 m [m/s]
- \(e_s - e_a\) = saturation vapor pressure deficit [kPa]
- \(\lambda\) = Latent heat of vaporization (MJ/kg)
Estimating $R_{\text{net}}$

$$R_{\text{net}} = R_{\text{ns}} + R_{\text{nl}}$$

$$R_{\text{ns}} = (1 - \alpha)R_s$$

$$R_{\text{nl}} = -Fe \varepsilon \sigma T^4$$

- $R_{\text{ns}}$ = Net short-wave radiation
- $R_{\text{nl}}$ = Net long-wave radiation
- $R_s$ = Solar radiation
- $\alpha$ = Albedo
- $f$ = Cloudiness function
- $\varepsilon$ = Apparent net clear sky emissivity
- $\sigma$ = Steffan-Boltzman constant
- $T$ = Temperature

Crop Evapotranspiration

$$ET_c = K_c \times ET_o$$

- $ET_c$ = Crop evapotranspiration under no stress
- $K_c$ = Crop coefficient
- $ET_o$ = Reference ET
Authoritative Source of Information


http://www.fao.org/docrep/X0490E/x0490e00.htm#Contents

Estimating Actual ET

Actual ET = f(φ) × ETc

f(φ) = soil moisture function
ETc = crop evapotranspiration under no stress
Key Boundary Parameters for Soil Moisture Function

- **Permanent wilting point (PWP)** or **wilting point (WP)** is defined as the minimal point of soil moisture the plant requires not to wilt.
- **Field capacity** refers to the maximum amount of water that a given soil can retain against the force of gravity.

Actual ET as Function of Soil Moisture
Simple Weather Station

- Temperature
- Wind speed
- Humidity
- Solar radiation
  - Short wave radiation only

Advanced Weather Station

- Temperature
- Wind speed
- Humidity
- Soil heat flux
- Net radiation
  - Short & long-wave radiation
Spatial & Temporal Variability

Long-term Trends

ET Rate = 57%
1971-97

ET Rate = 63%
1998-2009
Climate Simulations

**Reference ET**

**Present**

**Future**

**Precipitation**
Throughfall

- Designed by T. Giambelluca & A. Ziegler
- Pendant loggers, Onset Computer Corp.
- Installed at 3 sites dominated by non-native tree species

Stemflow
Double Mass Curve Analysis

- Commonly used data analysis approach for checking consistency of a hydrological or meteorological record and is considered to be an essential tool before taking it for analysis purpose.
Rain gage vs. Rain gage

21% reduction in rainfall catch from Sep 2006 to Sep 2008

Stream gage vs. Rain gage
Stream gage vs. Stream gage

West Oahu Gage Network
Missing Data Estimation

Rainfall Interpolation Methods

Traditional
• Station average
• Thiessen polygon
• Inverse distance weighted
• Isohyetal methods

Geostatistical
• Univariate kriging
  – Ordinary, Simple, Universal
• Multivariate kriging
  – Co-kriging
  – Secondary data
  • Elevation
  • Radar
  • Distance from maximum
Example of Comparison

Performance Comparison
Hawaii Rainfall Atlas of 2012

• http://rainfall.geography.hawaii.edu/

Streamflow
Surface Runoff Generation

Types of Surface Runoff

Infiltration excess overland flow

Saturation excess overland flow

Dry soil

Saturated soil

Note: Enlarged soil particles are not drawn to scale.

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Gaining vs. Losing Stream

Gaining

Losing

Losing

Upper Valley

Mid Valley

Mid & Lower Valley

Reference: Oki et al. 2006
Stream Gage

Stream Flow Measurement
Stream Flow Calculations

\[ A_s = \left( \frac{d_1 + d_2}{2} \right) w_1 + \ldots + \left( \frac{d_{n-1} + d_n}{2} \right) w_n \]

\[ wp_{yl} = \text{wetted perimeter} = 2d_{\text{max}} + \sum \frac{w}{m} \]

Measure velocity in the center of each compartment at 0.4d cm from the bed.

Rating Curve

![Graph showing discharge vs. stage relationship](image-url)
Flow Duration Curve

Rainfall-Runoff Relationship
Realtime Streamflow Data


Recharge
Soil Water Balance

\[ P = RO + ET + RCHG + \Delta S \]

- \( P \) = precipitation
- \( RO \) = surface runoff
- \( ET \) = actual evapotranspiration
- \( RCHG \) = groundwater recharge
- \( \Delta S \) = change in soil moisture storage

Deep Percolation ≡ Recharge

\[ RCHG = P - RO - ET - \Delta S \]
Recharge Estimation Methods

- **Surface Water Techniques**
  - Channel water budget
  - Stream hydrograph separation
  - Seepage meters
  - Isotopic & heat tracers
  - Watershed models

- **Unsaturated Zone Techniques**
  - Lysimeters
  - Zero-flux plane
  - Darcy’s law
  - Tracers
    - Chemical/isotopic
    - Nuclear testing
    - Chloride
  - Numerical modeling

- **Saturated Zone Techniques**
  - Water table fluctuation method
  - Darcy’s law
  - Groundwater dating
    - Tritium
    - Chlorofluorocarbons (CFCs)
    - Tritium/helium-3
  - Chloride mass balance
  - Numerical modeling
Jeju Island, South Korea

Comparison of Recharge Estimates

• Water table fluctuation (WTF)
• Chloride mass balance (CMB)
• CFC-12 dating
• Tritium renewal
• Soil water balance (SWB)
Soil Water Balance Estimate

Mean Island Recharge = 883 mm/yr