Evaporation

- ☞ The evaporation process
  - ☞ Estimation of evaporation from water surface
    - Water balance method
    - Mass transfer method
    - Energy budget method
    - Combined method
  - ☞ Potential evapotranspiration

Evaporation in hydrology

Water supply reservoir

- Loss of resources

Soil moisture condition

- Affect runoff conditions

Continuous watershed simulation models

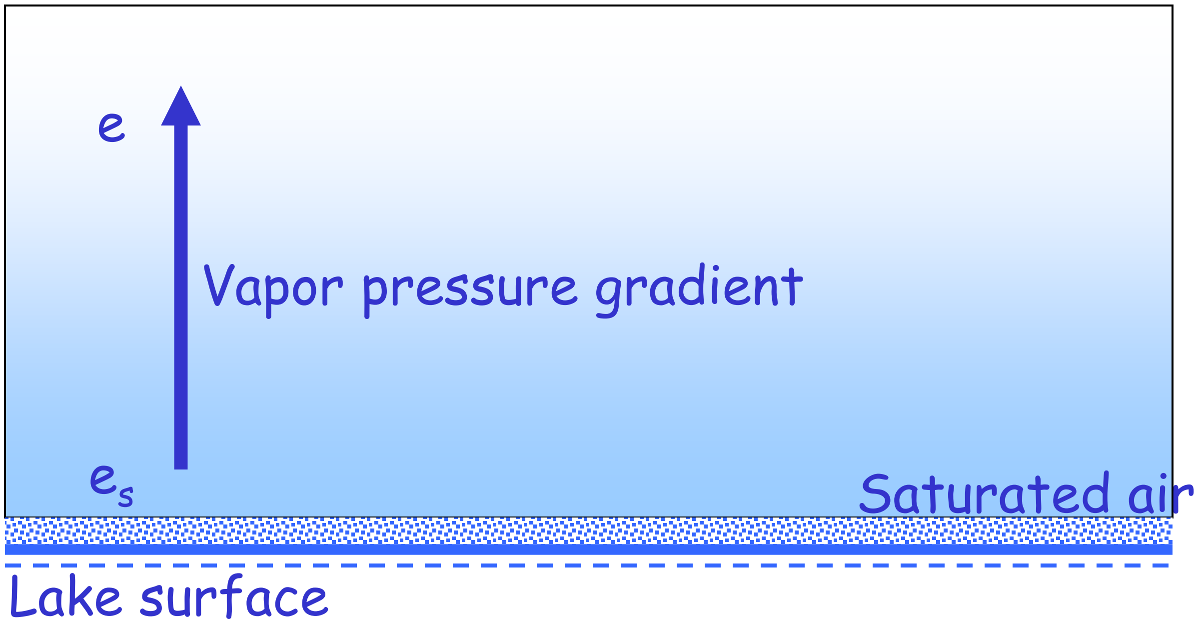
- Overall water balance

Atmospheric science

- generation of precipitation

Agricultural science

- soil moisture available for plants


e
Vapor pressure gradient
e_s
Saturated air
Lake surface

Factors affecting evaporation

1. Availability of energy (latent heat)
   - Q_e: Energy available for evaporation [cal/cm^2-day]
   - E : evaporation [cm/day]
   - L_e : latent heat of evaporation [cal/g]

$$Q_e = ML_e \qquad [M : \text{mass}]$$

$$= E \times (1\ \text{cm}^2)\rho L_e$$

$$E = \frac{Q_e}{\rho L_e} \qquad [\text{cm/day}]$$

2. Saturation deficit, e_s-e
   - Evaporation rate proportional to e_s-e

$$E = C(e_s - e)$$

3. Temperature

- Warm water will evaporate faster (less latent heat required)

$$L_e = 597.3 - 0.57\ T \qquad [cal/g], \quad T \text{ in } ^\circ C$$

- Warm air can hold more vapor

4. Wind

- Removes saturated air and maintains vapor pressure gradient.

Transpiration

- Vegetation

Potential evapotranspiration

Potential evapotranspiration from land surface

≈

Evaporation from open water surface

Actual evapotranspiration depends on the dryness of the soil.

Method 1: Water budget

Applicable to lake evaporation

$$\Delta storage = input - output$$

$$\Delta S = (I + P) - (O + E + GW)$$

Or $E = -\Delta S + I + P - O - GW$

I : inflow [cm]
P : precipitation [cm]
O: outflow [cm]
E : Evaporation [cm]
GW: Groundwater seepage [cm]

Limitations:

- Estimation of seepage (GW)
- Estimation of precipitation

Mass transfer method

Evaporation driven by

- Vapor pressure gradient
- Wind speed

$$E = f(u)(e_s - e_a)$$
$$= (a + b\,u)(e_s - e_a)$$

e_s : saturation vapor pressure at temperature above surface

e_a : vapor pressure at some level above surface

u : wind speed at some level above surface

a,b : empirical constants

Example

Using Meyer's formula

$$E = 0.0269\left(1 + \frac{u_8}{16}\right)(e_s - e_a) \qquad [cm/day]$$

$[u_8 \text{ in km/h}, \; e \text{ in mb}]$

determine lake evaporation for a month in which

- average air temperature = 20°C,
- average water temperature = 15 °C,
- average wind speed at 8 m = 15 km/h
- average relative humidity is 50%

Solution

Saturated vapor pressure above water surface

Air temperature above surface ≈ water temperature = 15 °C

$$e_s = 2.7489 \times 10^8 \exp\left(-\frac{4278.6}{(T = 25) + 242.79}\right)$$

$$= 17.0 \text{ mb}$$

Vapor pressure at height of 8 m

$e_s(20\ °C) = 23.3$ mb

$e = RH\ e_s = 0.5 \times 23.3 = 11.7$ mb

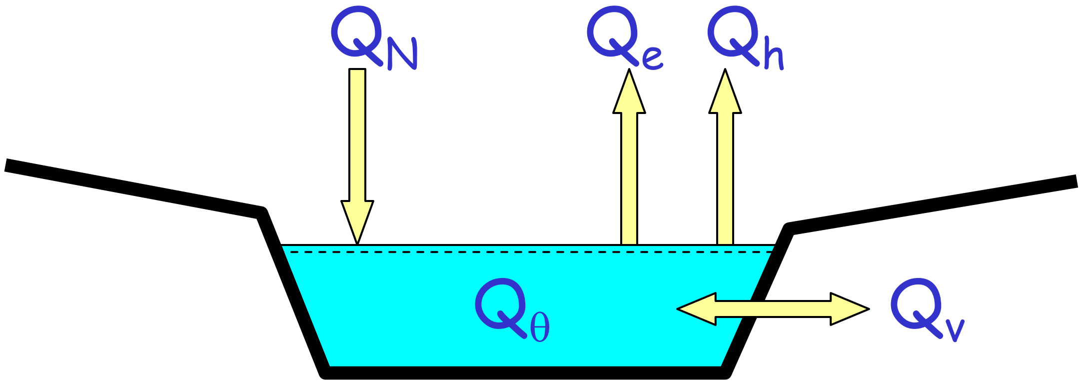
$$E = 0.0269\left(1 + \frac{u_8}{16}\right)(e_s - e_a)$$

$$= 0.0269\left(1 + \frac{25}{16}\right)(17.0 - 11.7)$$

$$= 0.37 \text{ cm/day}$$

$$= 11.1 \text{ cm/month}$$

Energy budget method



Q_N : net radiation [cal/cm^2-day]

(solar radiation – reflection – radiation from lake)

Q_e : evaporation energy

Q_h : sensible heat transfer (water heats the air)

Q_v : advected energy

Q_θ : change in stored energy

$$Q_N = Q_e + Q_h - Q_v + Q_\theta$$

Energy budget method

Sensible heat transfer difficult to measure

$$Q_h \approx R \times Q_e$$

where

$$R = \gamma \frac{T_s - T_a}{e_s - e_a} \qquad \text{[Eq. 1.16]}$$

T_a : air temperature [°C]
T_s : water surface temperature [°C]
e_a : vapor pressure of the air [mb]
e_s : saturation vapor pressure at water surface temp. [mb]
γ : psychrometric constant = 0.66 (P/1000), P in mb

Energy budget method

Daily evaporation depth: $E = \frac{Q_e}{\rho L_e}$ [cm/day]

Energy balance

$$Q_N = Q_e(1+R) - Q_v + Q_\theta$$
$$= E\rho L_e(1+R) - Q_v + Q_\theta$$

or $$E = \frac{Q_N + Q_v - Q_\theta}{\rho L_e(1+R)} \quad [cm/day]$$

with Q in [cal/cm^2-day]

L_e in [cal/g]

ρ in [g/cm^3]

Combined method (Penman)

Combined 'mass transfer' and 'energy budget':

$$E\rho L_e = \frac{\Delta}{\Delta+\gamma} Q_N + \frac{\gamma}{\Delta+\gamma} E_a$$

[units as before – Eq. 1.17]

Δ : slope of e_s vs t curve (at air temperature - equation 1.18)

$E_a = \rho L_e (a + bu)(e_{sa} - e_a) \quad [cal / cm^2 - day]$

where a,b : empirical constants

e_{sa} : saturation vapor pressure at air temp.

e_a : actual vapor pressure

Example (textbook Ex. 1.5B)

Assume Meyer's formula applies to a lake:

$$E = 0.0269\,(1+0.1\,u)(e_s-e_a)$$ [cm/day]

u in mi/h, e in mb

Given:

$T_a = 32.2°C$

$u = 32$ km/h = 20 mi/h

RH = 30%

$Q_N = 400$ cal/cm^2-day

estimate daily evaporation using Penman's formula.

Solution

$$\Delta = \frac{2.7489 \times 10^8 \times 4278.6}{(T + 242.79)^2} \exp\left(- \frac{4278.6}{T + 242.79} \right) \qquad [eq. 1.18]$$

with $T = 32.2°C, \ \Delta = 2.72 \text{ mb}/°C$

Actual and saturation vapor pressure:

$$e_{sa}(T = 32.2°C) = 48.1 \text{ mb} \qquad [eq. 1.6]$$

$$e_a = RH \times e_{sa} = 0.3 \times 48.1 = 14.4 \text{ mb}$$

Latent heat of evaporation at air temperature:

$$L_e = 597.3 - 0.57 \times 32.2 = 579 \text{ cal}/g \qquad [eq. 1.7]$$

$$E_a = \rho L_e 0.0269(1+0.1\,u)(e_{sa} - e_a)$$
$$= 1 \times 579 \times 0.0269(1 - 0.1 \times 20)(48.1 - 14.4)$$
$$= 1590 \text{ cal/cm}^2\text{–day}$$

Penman's equation:

$$E\rho L_e = \frac{\Delta}{\Delta + \gamma} Q_N + \frac{\gamma}{\Delta + \gamma} E_a$$
$$= \frac{2.72}{2.72 + 0.66} 400 + \frac{0.66}{2.72 + 0.66} 1590$$
$$= 632 \text{ cal/cm}^2 - \text{day}$$

Or:

$$E = \frac{632}{1 \times 579} = 1.1 \text{ cm/day}$$