EVAPORATION

CH-3

Definition

- Evaporation is the process by which the precipitation reaching the earth's surface is retuned to the atmosphere as water Vapour.

Very important variable of, water balance (Hydrological cycle)
• as worldwide about 75% of continental precipitation evaporates
• Most difficult variable to estimate for a whole catchment including its **space-time variability**
• Sensitive to global changes

Evaporation

- E_0: open water evaporation (often the reference E)
- E_s: evaporation from soil
- E_I: interception evaporation

Transpiration

- E_T: transpiration of living plants (and animals/humans)

Evapotranspiration := sum of all E-fluxes

- E_{pot}: potential evapotranspiration (no moisture shortage)
- E_{act}: actual evapotranspiration (can be lower than Epot depending on moisture availability)

FACTORS AFFECTING THE RATE OF EVAPORATION

- **Vapor Pressure:** Evaporation is proportional to the difference between the saturation vapor pressure at water temperature (ew) and air temperature (ea) $E_L = C\,(e_w - e_a)$
- **Temperature:** The rate of evaporation increases with an increase in water temperature

– the relation evaporation rate with air temperature is not significance but it has a general trend of increasing of Evaporation with increases of air Temperature

- **Atmospheric Pressure:** A decrease in barometric pressure/increase of altitudes/ increase the Evaporation
- **Wind:** Wind aids in removing the evaporated water vapour from the zone and creates space for evaporation
  - But, if the wind velocity is large enough to remove the evaporated water vapor, any increase of wind speed doesn’t affect the evaporation rate
  - Thus the rate of Evaporation increases with the increase of wind speed up to a critical speed
  - This critical wind speed value is a function of the size of water surface

- **Soluble Salts:** When the solute is dissolved in water, the vapour pressure of the solution is less than that of pure water, hence the rate of evaporation deceases.
- **Heat storage in water Bodies:**Deep water bodies have more heat storage than shallows.

– A deep lake may store radiation energy in summer and releases it in winter causing less evaporation in summer and more evaporation in winter

– The Effect of Heat storage affect the seasonal evaporation than the annual

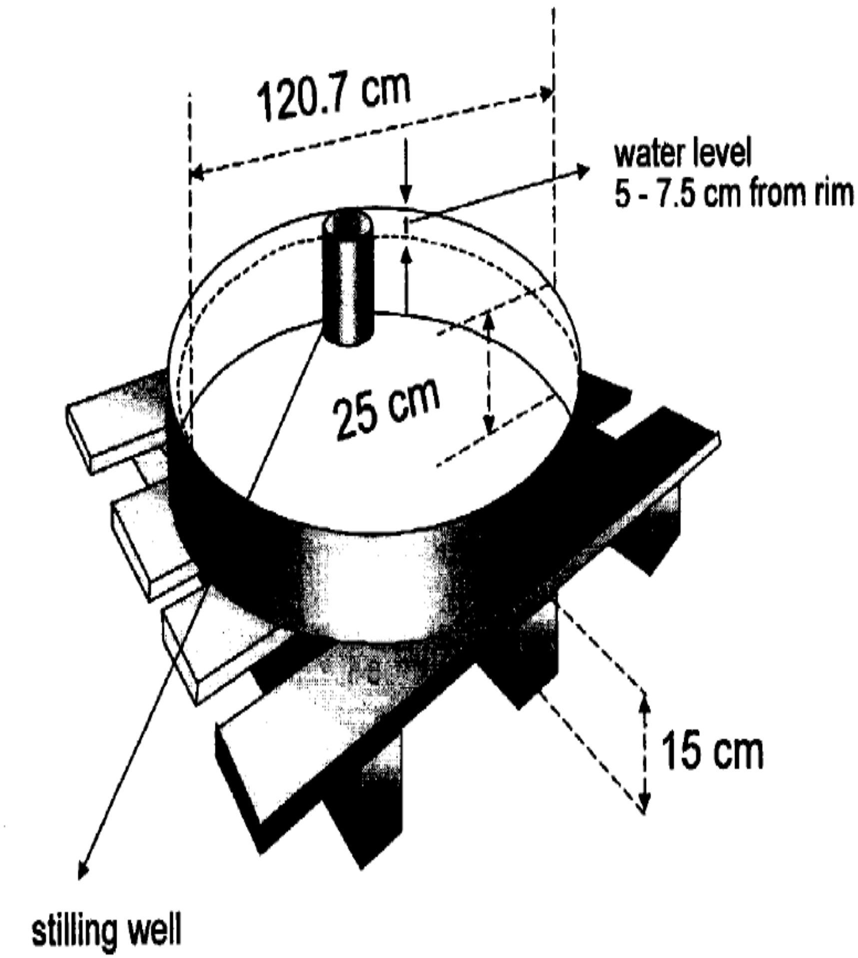
Importance e.g

- **Estimation of Evaporation is importance in many hydrologic problems**
  - Associated with planning and operation reservoirs and irrigation systems
  - To conserve the scares water in the arid zone

MEASUREMENT OF EVAPORATION

- **The amount of water Evaporated from a water surface is estimated by**
  - Using Evaporimeter **(Class A Evaporation Pan)**
  - Empirical and Analytical Method

EVAPORATION FROM A PAN

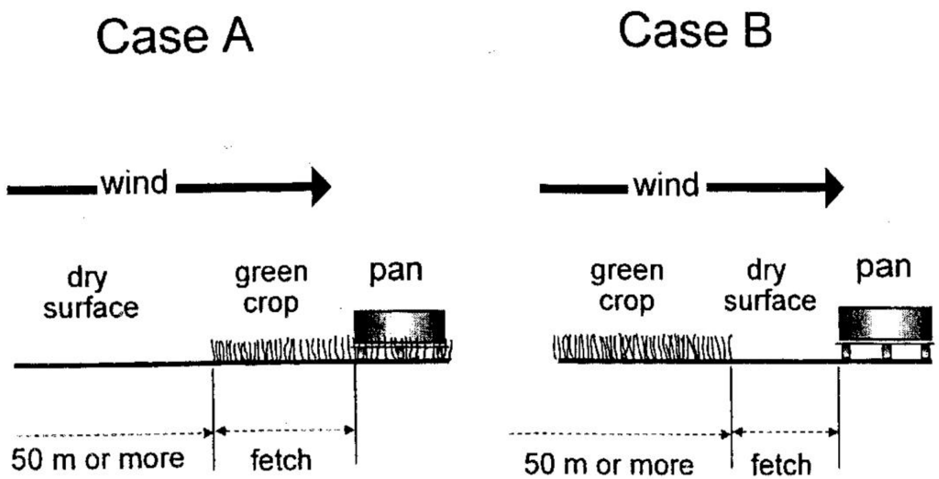


- 1210 mm diameter, 255mm depth, made from unpainted galvanized iron
- the pan placed on the wooden platform of 15cm height from the ground for free air circulation
- Evaporation measurement are made by measuring the depth of water with a hook gauge in a stilling well.

Formula

$$E_a = K_{pan} E_{pan}$$

Ea = actual Evaporation
Kpan = pan coefficient,



$K_{pan} = 0.75$ $K_{pan} = 0.60$

Example

- In a floating class A plan the water height at day one was at 6 AM is 210 mm, and at the next morning (also at 6 AM) the water level was estimated to a depth of 220 mm.During that day a precipitation event of 15 mm occurred. What was the evaporation?

Empirical and Analytical Methods

- Water-Budget Method: It involves writing of the water balance equation of the lake and determining the evaporation from the knowledge of other variables.

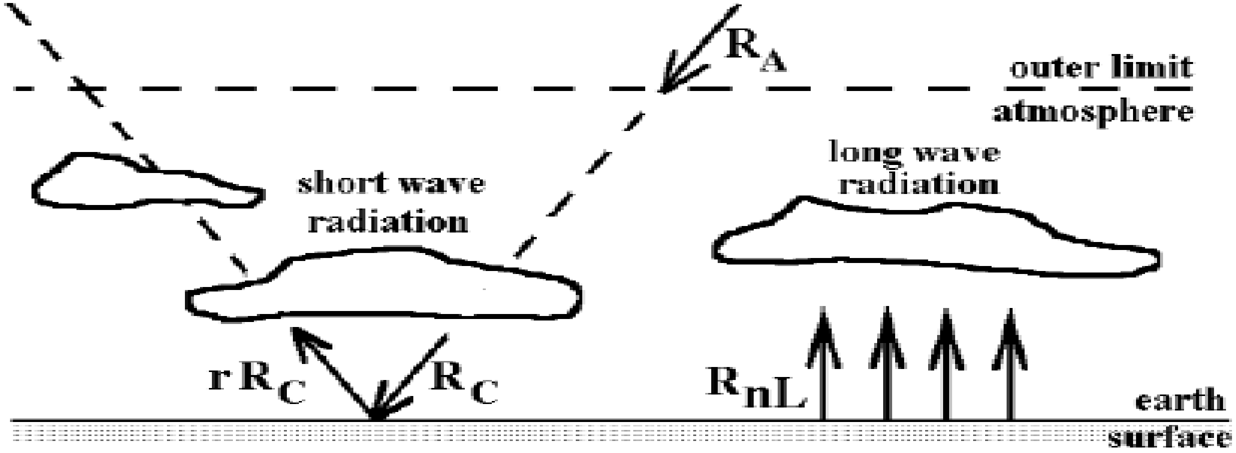
Example

- A reservoir had an average surface area of 20km2 during June 1982. In that month the mean rate of inflow =15m3/s, outflow =10m3/s, monthly rainfall = 10cm and a change in storage =10million m3. Take the seepage losses to be 1.8cm and Estimate the Evaporation in that month.

Energy- Budget Method

- This method is an application of the law of conservation of energy

– The energy available for evaporation is determined by considering the incoming, outgoing, and stored energy in the water body over time.



$$H_n = H_a + H_e + H_g + H_s + H_i$$

Where H_n = net heat energy received by the water surface

$H_n = H_c\,(1\text{-}r)\text{-}H_b$

In which $H_c(1\text{-}r)$ = incoming solar radiation into a surface of reflection coefficient (albedo) r

H_b = back radiation (long wave) from water body

H_a = sensible heat transfer from the water surface to air

H_e = heat energy used up in evaporation

$He = \rho L E_L$ ρ = density of water,

L =latent heat of evaporation ,

E_L = evaporation in mm

H_g = heat flux into the ground

H_s = heat stored in water body

H_i = net heat conducted out of the system by water flow (advected)

- All the energy terms are in calories per day and they are measured or evaluated indirectly except Ha, which also estimated using ***Bowen's ratio***

$$\beta = \frac{H_a}{\rho L E_L} = 6.1 \times 10^{-4} \times p_a \frac{T_w - T_a}{e_w - e_a}$$

Where P_a = atmospheric pressure in mm of mercury,

e_w = saturated vapour pressure in mm of mercury

e_a = actual vapour pressure in air in mm of mercury

T_w= water surface temperature in ^oc

T_a = air temperature in ^oc

- for short time period the terms Hs and Hi are very small and they are negligible in the equation

$$E_L = \frac{H_n - H_g - H_s - H_i}{\rho L (1 + \beta)}$$

Example

Calculate the evaporation rate from an open water source, if the net radiation is 300W/m^2 and air temperature is 30^{o}c . Assume value of zero for sensible heat, ground heat flux, heat stored in water body and advected energy. The density of water at 30^{o}c =996kg/m^3.

Mass-Transfer Method

It is based on the theories of turbulent mass transfer in the boundary layer to calculate the mass water vapour transfer from the surface to the surrounding atmosphere

Empirical Evaporation Equation

– Meyer's Formula

$$E_L = K_m (e_w - e_a)\left(1 + \frac{u_9}{16}\right)$$

Where U_9 = mean wind velocity (km/hr) taken at 9m height

$U_h = Ch^{1/7}$ C = constant

K_m = coefficient accounting the other factors

= 0.36 for deep

= 0.5 for sallow

Terms

- ***Water vapor***: the amount of water vapor in the atmosphere is directly related to the temperature.

The water vapor content or humidity of air is usually measured as a *vapor pressure*, and the units used is millibar (mb).

- ***Vapor pressure(ea)(e)***: Dalton's law of partial pressures states that the pressure exerted by a gas (its vapor pressure) is independent of the pressure of other gases; the vapor pressure *e* of the water vapor is given by the ideal gas law as

$$e = \rho_v R_v T$$

R_v =*gas constant for water*

T =the absolute temperature

Terms….

- **Actual vapour pressure(ea)-** the actual vapour pressure in the air. Evaporation continues till es=ea

$$e_a = e^\circ (T_{wet}) - g_{psy} (T_{dry} - T_{wet})$$

e_a = Actual vapour pressure [kPa],

$e^\circ(T_{wet})$ = Saturation vapor pressure at wet bulb temperature [kPa],

γ = Psychrometric constant [kPa °C^{-1}],

T_{dry}-T_{wet} = Wet bulb depression, with T_{dry} the dry bulb and T_{wet} the wet bulb temperature [°C].

- *g psy is a coefficient depending on the type of ventilation of the wet bulb*

Terms….

- ***Saturation vapor pressure es*** : For a given air temperature, there is a maximum moisture content the air can hold and the corresponding vapor pressure is called *saturation vapor pressure es* . At this vapor pressure, the rates of evaporation and condensation are equal.

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2}$$

The saturated vapor pressure at T = 20 ^{0}C is given by

$$e_s = 611 \exp(17.27 \frac{T}{237.3 + T})$$

Terms….

- **The relative humidity *Rh*:** It is ratio of actual vapor pressure to its saturation value at a given air temperature T and is given by

$$R_h = \frac{e}{e_s}$$

Terms….

- ***Dew-point temperature Td*** : is the temperature at which space becomes saturated when air is cooled under constant pressure and with constant water-vapor content.
- It is the temperature having a saturation vapor pressure *es* equals to the existing vapor pressure *ea*. Wet bulb thermometer measures the dew point temperature.

Useful tables...

TABLE 3.3 SATURATION VAPOUR PRESSURE OF WATER

Temperature (°C)	Saturation vapour pressure e_w (mm of Hg)	A (mm/°C)
0	4.58	0.30
5.0	6.54	0.45
7.5	7.78	0.54
10.0	9.21	0.60
12.5	10.87	0.71

(contin

Useful tables…

TABLE 3.3 (Continued)

Temperature (°C)	Saturation vapour pressure e_w (mm of Hg)	A (mm/°C)
15.0	12.79	0.80
17.5	15.00	0.95
20.0	17.54	1.05
22.5	20.44	1.24
25.0	23.76	1.40
27.5	27.54	1.61
30.0	31.82	1.85
32.5	36.68	2.07
35.0	42.81	2.35
37.5	48.36	2.62
40.0	55.32	2.95
45.0	71.20	3.66

$e_w = 4.584 \exp\left(\frac{17.27\,t}{237.3 + t}\right)$ mm of Hg, where t = temperature in °C

Example

- A reservoir with a surface area of 250 hectares had the following average values of parameters during a week water temperature =20^{o}C Relative humidity = 40% Wind speed = at 1.0m above the ground = 16km/h. Estimate the average daily evaporation from the lake and the volume of evaporated water from the lake during that one week

A	250	Ha
Tw	20	c
RH	40	%
W1m	16	km/hr
Km	0.36	
u9	21.89981	km/hr
ew	17.54	mmhg
ea	0.4*17.54	7.016
EL=	0.36*(17.54-7.016)*(1+(21.89981/16))	
	8.974296	mm/day
evaporated volume in 7 days		
156975	m3	

EVAPOTRANSPIRATION AND ITS ESTIMATION

- Potential Evaporation (*Ep) and Potential Transpiration* (*Tp)*: Rate of evaporation that would occur from a uniformly wet, large area of soil covered with vegetation with access to unlimited water supply
- Actual Evaporation (*Ea) and Actual Transpiration (Ta):* takes into account water supply limitations at the soil surface

EVAPOTRANSPIRATION AND ITS ESTIMATION

Lysimeters :-it is a special water tight tank containing a block of soil and set in a field of growing plants.(the plants put in the lysimeter are similar to the surrounding plants)

- The ET is measured by calculating the amount of water required to maintain the plant. either volumetrically of gravimetrically.
- The study using lysometer is time consuming

EVAPOTRANSPIRATION AND ITS ESTIMATION

Bare Soil Lysimeter

Weighing lysimeters measure changes in soil weight to determine evaporated water.

Vegetated Lysimeter

Non-weighing lysimeters measure ET by difference of rainfall and percolation.

Field plots: uses water budget equation in a known time interval

ET=P+I-RO-increase in soil storage-GW

Estimation of evapo-transpiration

- **Governing factors**

Energy supply and vapor transport (**Aerodynamic**)

Supply of moisture at evaporative surfaces

- Methods
  - Combination theory   penman –monteith method
  - Empirical formulations based on temperature – e.g Hargreaves method
  - Empirical formulations based on radiation – e.g. Blaney –Criddle Formula
  - Empirical formulation based on pan evaporation
- Combined consideration of governing factors
  - The Energy balance (radiation/ Temperature)
  - The aerodynamic (Wind)

Penman- Monteith method

- Obtained by combining energy balance and mass balance equations.

$$E_{tr} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34 U_2)}$$

where:

E_{tr} = reference crop evaporation (mm/day)

R_n = net radiation ar crop surface ($MJ/m^2/d$)

G = soil heat flux ($MJ/m^2/d$)

T = average temperature (^oC)

U_2 = wind speed measured at 2 m height (m/s)

$(e_s - e_a)$ = vapor pressure deficit (kPa)

Δ = slope of vapor pressure curve (kPa/^oC) γ = hygrometric constant (kPa/^oC)

G = 0.4 ($T_{\text{month n mean temperature}}$ ^0C - $T_{\text{month n-1 mean temperature}}$ ^oC)

900 = conversion factor

$$R_n = (1-\alpha)(0.35 + 0.61\frac{n}{N})S_o - (0.9\frac{n}{N} + 0.1)(0.34 - 0.14\sqrt{e_d})\ \sigma T^4$$

Γ=psycometric constant=0.49 mm of Hg/c

Penman- Monteith method

γ = psychrometric constant = 0.49 mm of mercury/ °C

The net radiation is the same as used in the energy budget [Eq. (3.8)] and is estimated by the following equation:

$$H_n = H_a(1-r)\left(a + b\frac{n}{N}\right) - \sigma T_a^4 (0.56 - 0.092\sqrt{e_a})\left(0.10 + 0.90\frac{n}{N}\right) \quad (3.14)$$

where H_a = incident solar radiation outside the atmosphere on a horizontal surface, expressed in mm of evaporable water per day (it is a function of the latitude and period of the year as indicated in Table 3.4).

a = a constant depending upon the latitude ϕ and is given by $a = 0.29 \cos\phi$

b = a constant with an average value of 0.52

n = actual duration of bright sunshine in hours

N = maximum possible hours of bright sunshine (it is a function of latitude as indicated in Table 3.5)

r = reflection coefficient (albedo). Usual ranges of values of r are given below.

Penman- Monteith method

Surface	range of r values
Close ground corps	0.15—0.25
Bare lands	0.05—0.45
Water surface	0.05
Snow	0.45—0.95

σ = Stefan-Boltzman constant = 2.01×10^{-9} mm/day

T_a = mean air temperature in degrees kelvin = 273 + °C

e_a = actual mean vapour pressure in the air in mm of mercury

The parameter E_a is estimated as

$$E_a = 0.35\left(1 + \frac{u_2}{160}\right)(e_w - e_a) \tag{3.15}$$

in which

u_2 = mean wind speed at 2 m above ground in km/day

e_w = saturation vapour pressure at mean air temperature in mm of mercury (Table 3.3)

e_a = actual vapour pressure, defined earlier

Useful tables…

TABLE 3.5 MEAN MONTHLY VALUES OF POSSIBLE SUNSHINE HOURS, *N*

North latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0°	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1
10°	11.6	11.8	12.1	12.4	12.6	12.7	12.6	12.4	12.9	11.9	11.7	11.5
20°	11.1	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
30°	10.4	11.1	12.0	12.9	13.7	14.1	13.9	13.2	12.4	11.5	10.6	10.2
40°	9.6	10.7	11.9	13.2	14.4	15.0	14.7	13.8	12.5	11.2	10.0	9.4
50°	8.6	10.1	11.8	13.8	15.4	16.4	16.0	14.5	12.7	10.8	9.1	8.1

Useful tables…

TABLE 3.4 MEAN MONTHLY SOLAR RADIATION AT TOP OF ATMOSPHERE, H_a IN mm OF EVAPORABLE WATER/DAY

North latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0°	14.5	15.0	15.2	14.7	13.9	13.4	13.5	14.2	14.9	15.0	14.6	14.3
10°	12.8	13.9	14.8	15.2	15.0	14.8	14.8	15.0	14.9	14.1	13.1	12.4
20°	10.8	12.3	13.9	15.2	15.7	15.8	15.7	15.3	14.4	12.9	11.2	10.3
30°	8.5	10.5	12.7	14.8	16.0	16.5	16.2	15.3	13.5	11.3	9.1	7.9
40°	6.0	8.3	11.0	13.9	15.9	16.7	16.3	14.8	12.2	9.3	6.7	5.4
50°	3.6	5.9	9.1	12.7	15.4	16.7	16.1	13.9	10.5	7.1	4.3	3.0

Example

Calculate the potential evapotranspiration from an area the month of November by Penman's fomula. The following data are available :

Latitude	:	$28° 4' N$
Elevation	:	*230 m (above sea level)*
Mean monthly temperature	:	$19° C$
Mean relative humidity	:	*75%*
Mean observed sunshine hours	:	*9 h*
Wind velocity at 2 m height	:	*85 km / day*
Nature of surface cover	:	*Close-ground green crop*

SOLUTION : From Table 3.3,

$$A = 1.00 \text{ mm/°C}$$

$$e_w = 16.50 \text{ mm of Hg}$$

From Table 3.4

$$H_a = 9.506 \text{ mm of water/day}$$

From Table 3.5

$$N = 10.716 \text{ h}$$

$$n/N = 9/10.716 = 0.84$$

From given data

$$e_a = 16.50 \times 0.75 = 12.38 \text{ mm of Hg}$$

$$a = 0.29 \cos 28° \, 4' = 0.2559$$

$$b = 0.52$$

$$\sigma = 2.01 \times 10^{-9} \text{ mm/day}$$

$$T_a = 273 + 19 = 292 \text{ K}$$

$$\sigma T_a^{\,4} = 14.613$$

r = albedo for close-ground green crop is taken as 0.25

From Eq.(3.14),

$$H_n = 9.506 \times (1 - 0.25) \times (0.2559 + (0.52 \times 0.84))$$

$$- 14.613 \times (0.56 - 0.092 \sqrt{12.38}) \times (0.10 + (0.9 \times 0.84))$$

$$= 4.936 - 2.946$$

$$= 1.990 \text{ mm of water / day}$$

From Eq.(3.15),

$$E_a = 0.35 \times \left(1 + \frac{85}{160}\right) \times (16.50 - 12.38)$$

$$= 2.208 \text{ mm / day}$$

From Eq.(3.13), noting the value of $\gamma = 0.49$

$$\text{PET} = \frac{(1 \times 1.990) + (2.208 \times 0.49)}{(1.00 + 0.49)} = 2.06 \text{ mm/day}$$