CHAPTER-4

EVAPOTRANSPIRATION

Evaporation

Evaporation is defined as the rate of liquid water transformation to vapors into the atmosphere from open water, bare soil and vegetation.

Units (mm/day)

Factors affecting Evaporation

(1) Solar Energy (Latent heat of vaporization)
    (1) Temperature
(2) Ease with which water vapors can diffuse into the atmosphere
    (1) Wind Velocity
    (2) Humidity
    (3) Vapor Pressure / Atmospheric Pressure
(3) Water Body Characteristics
    (1) Size of the evaporation Surface
    (2) Depth of water
    (3) Soluble Salts (reduce 2-3% evaporation rate in oceans)

Significance of Evapotranspiration

(1) At global scales, evapotranspiration rate on land is about 60% of the total precipitation.

(2) To make water budgets at catchment scales (GW estimates).

(3) To estimate reservoir evaporation (may be 1/3rd of the total annual inflow in arid regions).

(4) Evaporation losses in Irrigation System.

(5) To estimate crop water requirements.

(6) To classify climate zones (Arid, humid, semi arid)

Standard Evaporation Rates

(1) Potential Evaporation Rate

(2) Reference Crop Evaporation Rate

(1) Potential Evaporation Rate, E_o (mm/day)

The quantity of water evaporated per unit area, per unit time from an idealized, extensive free water surface under existing atmospheric conditions.

(2) Reference Crop Evaporation Rate, E_{rc} (mm/day)

Rate of evaporation from an idealized grass crop with a fixed crop height of 12 cm and an albedo of 0.23, completely shading the ground and not short of water.

Physics of Evaporation & Transpiration

(1) Surface exchanges
   - (i) Latent heat
   - (ii) Water molecule movement b/w water surface and air
   - (iii) Saturated vapor content of air
   - (iv) Sensible heat

(2) Radiation Balance at Land surface
   - (i) Net short wave radiation
   - (ii) Net long wave radiation
   - (iii) Net radiation

(3) Energy Budget for a unit area

(4) Diffusion through air
   - (i) Molecular diffusion
   - (ii) Turbulent diffusion

Latent Heat Flux

Amount of heat absorbed / released by a unit mass of substance without change in temperature while passing from liquid to vapor state.

$$\lambda = 2.501 - 0.002361\ T_s \qquad \text{(MJ/Kg)}$$

Where

λ = latent heat of vaporization

T_s = surface temperature of water (degree celcius)

It means 2.5 MJ are required to evaporate 1Kg of water.

Water Molecule Movement b/w Water Surfaces and Air

- A molecule must have a minimum energy if it is to leave the surface
- Nos. of such molecules are related to the surface temperature.

EVAPORATION

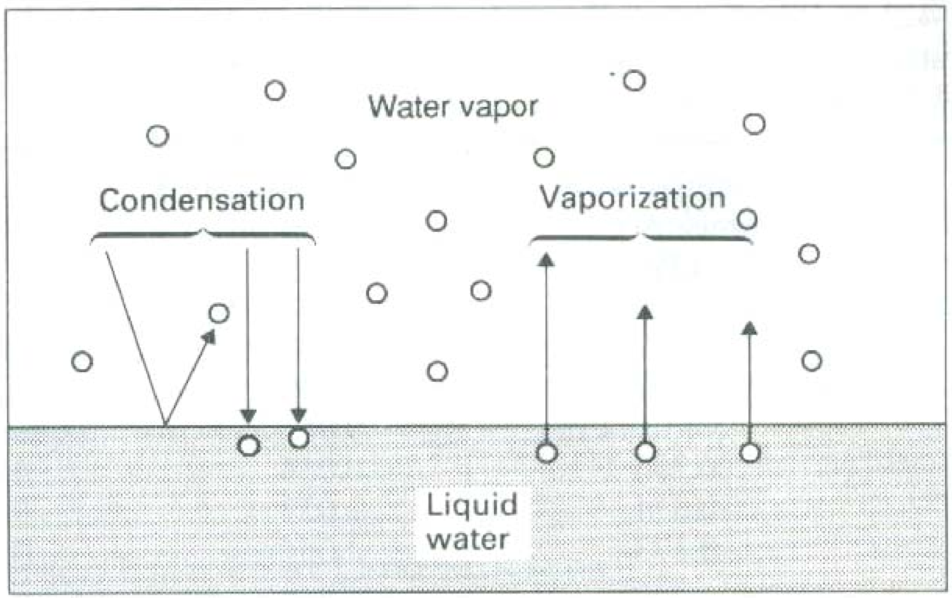


FIGURE 4.2.1 Molecular exchange between liquid water and water vapor. Not all the molecules hitting the surface are captured, but some condense at a rate which is proportional to the vapor pressure of the moist air: molecules with enough energy vaporize at a rate determined by the surface temperature.

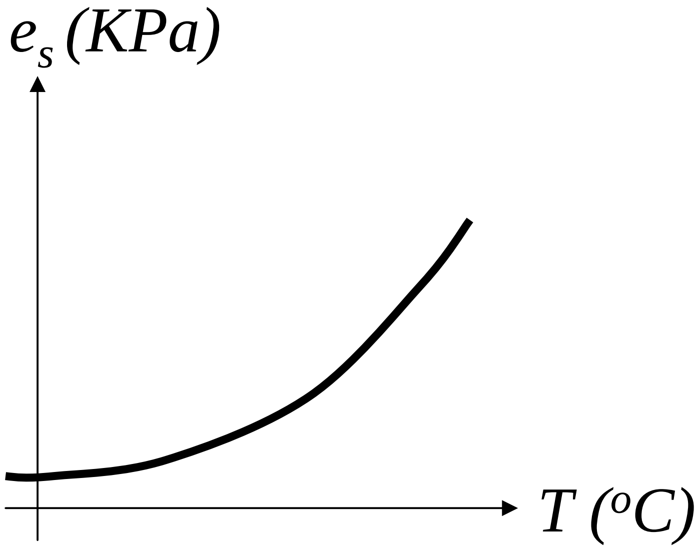
Saturated Vapor Content of Air

Evaporation = Difference between vaporization rate determined by temperature and condensation rate determined vapor pressure.

If difference is positive → evaporation continues.

If air is thermally insulated & enclosed, vapor pressure increases untill the rate of vaporization and condensation are equal and there is no more evaporation.

$$e_s = 0.6108 \ \exp\left(\frac{17.27 \ T}{237.3 + T}\right)$$



Where

e_s = saturated vapor pressure (KPa)

T = Temperature (degree celcius)

$$\Delta = \frac{d(e_s)}{dT} = \frac{4098 \ e_s}{(237.3 + T)^2} \quad KPa / C^O$$

Δ = gradient of e_s

Sensible Heat

Portion of radiant energy input to the earth surface is not used for evaporation, rather it warms the atmosphere in contact with the ground and then moves upward. It changes air temperature, a property which can be measured or sensed.

$$Temp\ change\ \alpha\ (c_p \rho_a)$$

Where

ρ_a = density of air (Kg/m^3)

c_p = specific heat of air at constant pressure = 1.01 Kj Kg^{-1} K^{-1}

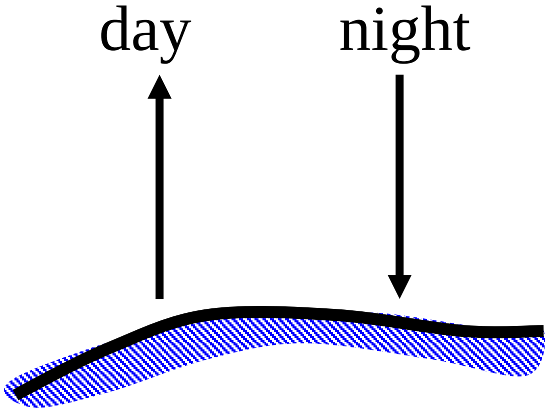
ρ_a can be determined from ideal gas law, but can be adequately estimated as

$$\rho_a = 3.486 \left(\frac{P}{275 + T} \right)$$

Where

P = Atmospheric pressure in (KPa)

T = Air Temperature in degree celcius



Sensible heat flux is commonly upward from ground during the day and usually downward at night to support radiant energy loss.

Radiation Balance at Land surface

Net Short wave radiation

- ☐ Radiation having short wave lengths (0.3 to 3 μ m)
- ☐ The sun is the main source of radiant energy.
- ☐ It is equivalent to a radiator of about 6000 °C.

S_o = extra terrestrial short wave radiation
S_t = Total short wave energy input (0.25 – 0.75 S_o)
S_d = Diffused short wave radiation reaches the surface (15 – 100 % S_t)

S_t is effected by

(i) Adsorption by atmospheric gases
(ii) Water vapors
(iii) Air molecules
(iv) Scattering by dust particles
(v) clouds

Radiation Balance at Land surface (contd.)

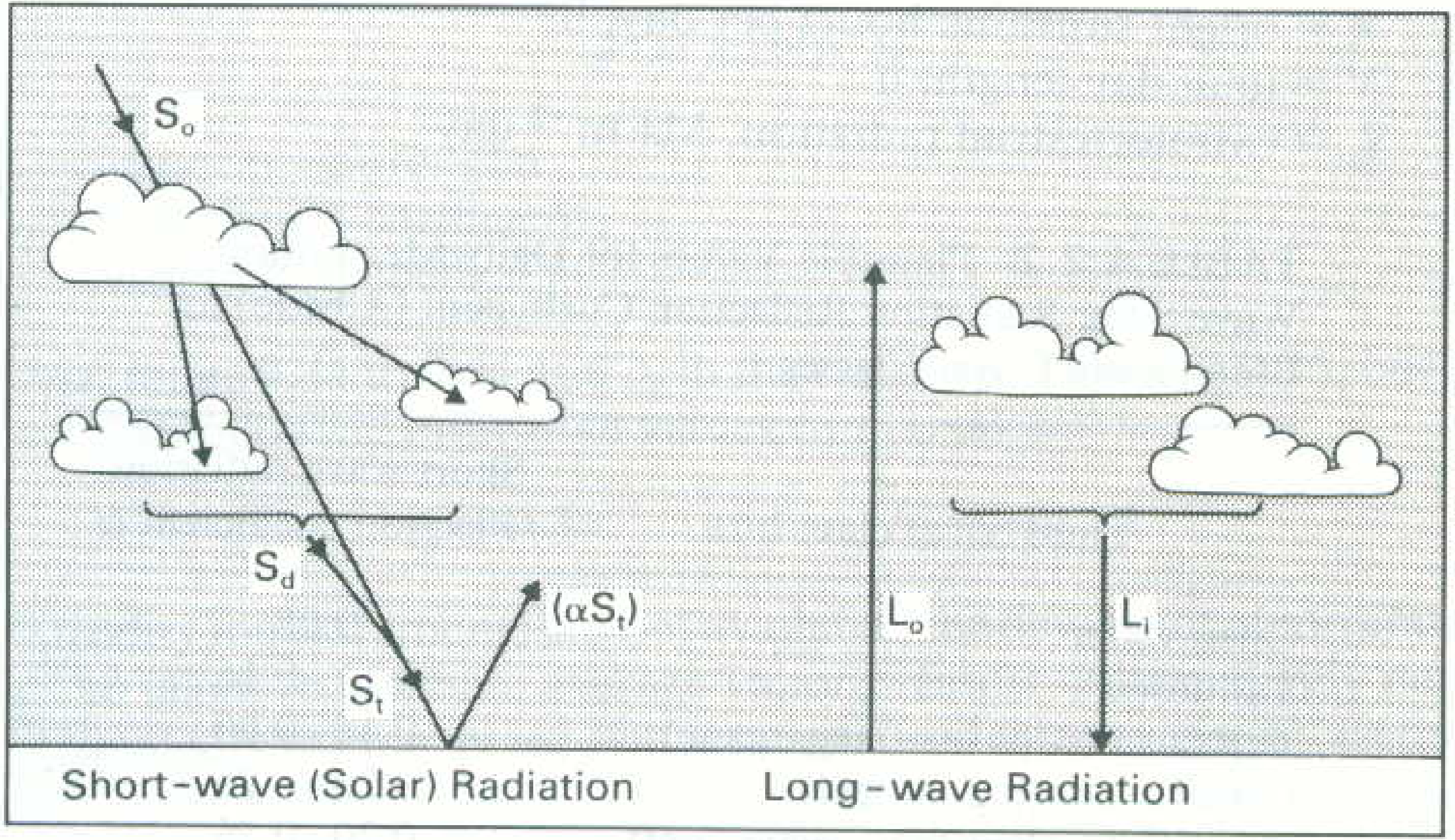


FIGURE 4.2.2 Radiation balance at the earth's surface. A proportion S_t of the solar radiation incident at the top of the atmosphere S_0 reaches the ground, some S_d indirectly after scattering by air and cloud. A proportion α, the albedo, is reflected. Outward long-wave radiation L_0 is partly compensated by incoming long-wave radiation L_i. S_t is typically 25 to 75 percent of S_0, while S_d can vary between 15 and 100 percent of S_t: both these proportions are influenced by cloud cover. α is typically 0.23 for land surfaces and 0.08 for water surfaces.

Albedo for broad land cover classes

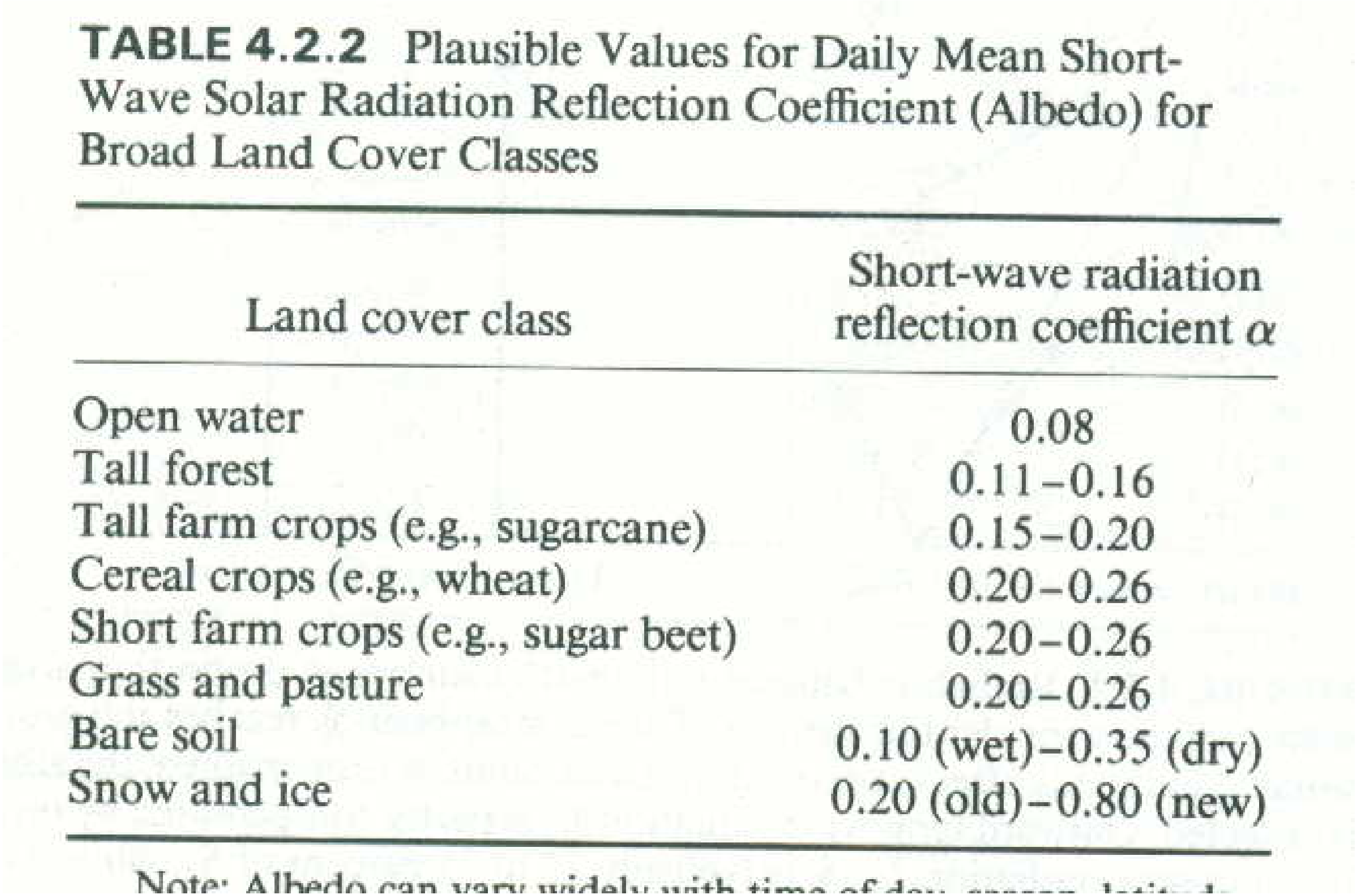


TABLE 4.2.2 Plausible Values for Daily Mean Short-Wave Solar Radiation Reflection Coefficient (Albedo) for Broad Land Cover Classes

Land cover class	Short-wave radiation reflection coefficient α
Open water	0.08
Tall forest	0.11–0.16
Tall farm crops (e.g., sugarcane)	0.15–0.20
Cereal crops (e.g., wheat)	0.20–0.26
Short farm crops (e.g., sugar beet)	0.20–0.26
Grass and pasture	0.20–0.26
Bare soil	0.10 (wet)–0.35 (dry)
Snow and ice	0.20 (old)–0.80 (new)

Note: Albedo can vary widely with time of day, season, latitude

Net Short Wave Radiation

$$S_n = S_t - \alpha\, S_t = S_t(1-\alpha)$$

Where

Sn = Net short wave radiation (MJ m^{-2} day^{-1})

St = incident short wave radiation (by Radiometer) (MJ m^{-2} day^{-1})

The total incoming short wave radiation can be estimated from measured sun shine hours (Pyranometer) as:

$$S_t = \left(a_s + b_s \frac{n}{N}\right) S_o$$

Where

a_s and b_s are Angstrom Coefficients

a_s = fraction of extra terrestrial radiation So on over cast days (n=0)

b_s = fraction of extra terrestrial radiation So on clear days

n/N = cloudiness factor

n = bright sun shine hours per day (hours) using Pyranometer

N = total day length (hours)

S_o = extra terrestrial radiation (MJ m^{-2} day^{-1})

When no actual solar radiation data are available, the following values are recommended for average climates.

$$a_s = 0.25,\ \ b_s = 0.5$$

Net Long Wave Radiation

- Radiation at larger wave lengths (3 to 100 μ m)
- Both the ground and the atmosphere emit black body radiation.
- Since the surface is on average warmer than atmosphere, there is usually a net loss of energy as thermal radiation from the ground

$$L_n = L_i - L_o = -f \ \varepsilon' \ \sigma \ (T + 273.2)^4$$

Where

L_n = Net long wave radiation (MJ m^{-2} day^{-1})
L_o = out going long wave radiation (MJ m^{-2} day^{-1})
f = adjustment for cloud cover = cloudiness factor
ε' = Net emissivity between the atmosphere & ground
σ = Stefan-Boltzmann constant (4.903 x 10^{-9} MJ m^{-2} K-4 day^{-1})
T = Mean air Temperature

$$\varepsilon' = a_e + b_e \sqrt{e_d}$$

e_d = vapor pressure (KPa)
a_e = Correlation coefficient (0.34-0.44)
b_e = Correlation coefficient (-0.14--0.25)

Net Long Wave Radiation (contd.)

When humidity measurements are not available, the dew point at minimum temperature can be taken to estimate average vapor pressure by

$$\varepsilon' = -0.02 + 0.261\ \exp\left(-7.77\ X\ 10^{-4}\ T^{2}\right)$$

$$f = a_c\left(\frac{S_t}{S_{to}}\right) + b_c$$

Where

S_t = measured solar radiation

S_{to} = solar radiation for clear skies (n/N = 1)

a_c & b_c = long wave radiation coefficients for clear skies (sum =1)

a_c & b_c are calibration parameters

$$a_c = 1.35,\ b_c = -0.35\ (For\ Arid\ areas)$$

$$a_c = 1.00,\ b_c = 0.0\ (For\ humid\ areas)$$

Based on sun shine hours data

$$f = 0.9\left(\frac{n}{N}\right) + 0.1$$

Net Radiation

Net input of radiation at the surface i.e. the difference between the incoming & reflected solar radiation plus the difference between incoming long wave radiation and outgoing long wave radiation.

$$R_n = S_n + L_n$$

R_n = Net radiation (MJ m^{-2} day^{-1})

R_n is comparatively simple to measure using instrumentation and indirect measurement is possible using Satellite data.

When only sunshine, temperature & humidity data are available, net radiation can be estimated by following equation:

$$R_n = \left(0.25 + 0.5\frac{n}{N}\right) S_o - \left(0.9\frac{n}{N} + 0.1\right)\left(0.34 - 0.14\sqrt{e_d}\right) \sigma\, T^4$$

Radiometer

Pyranometer

Energy Budget for a Unit Area

Consider a volume of defined vertical extent & unit area in horizontal plane.

Let R_n = net incoming radiation

λE = outgoing energy as evaporation

H = outgoing sensible heat flux

G = outgoing heat conduction into the soil

S = energy temporarily stored within the volume (often neglected except for forest)

P = energy absorbed by bio-chemical processes in plants (2% of Rn)

A_d = loss of energy associated with horizontal air movement $A_d = A_d^o - A_d^i$

A = available energy for vaporization (MJ m^{-2} day^{-1})

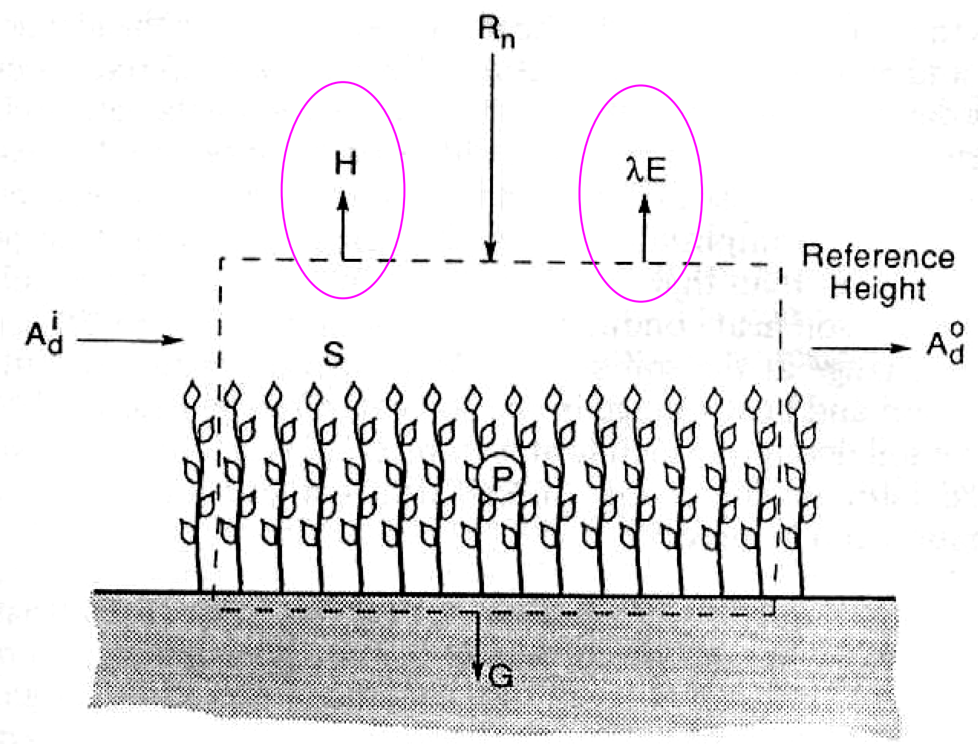


FIGURE 4.2.3 The components of the energy balance for a volume extending from just below the soil surface to the height at which the net radiation balance is determined.

$$A = \lambda E + H$$

$$A = R_n - G - S - P - A_d$$

$$\lambda E + H = R_n - G - S - P - A_d$$

Energy Budget for a Unit Area (contd.)

Heat Conduction (G)

- Conduction is the main mechanism for heat transfer in soils
- Heat flow is maximum when the r.o.c.o. soil surface temperature is maximum
- G can be large (30% of net radiation)
- With dense vegetation, little radiation reaches to the ground and heat storage can be neglected

Heat Conduction estimation

(1) Heat Conductance for hourly temperature variation

$$G = C_s \ d_s \left(\frac{T_2 - T_1}{\Delta t} \right)$$ (MJ m^{-2} day^{-1})

(2) Heat Conduction for daily temperature variations

$$G = 0.38 \ \left(T_{day2} - T_{day1} \right)$$ (MJ m^{-2} day^{-1})

(3) Heat Conduction for monthly temperature variation

$$G = 0.14 \ \left(T_{month2} - T_{month1} \right)$$ (MJ m^{-2} day^{-1})

Where

G = Soil conductance

T_2 = Temperature at the end of period (^oC)

T_1 = Temperature at the beginning of perid

Δt = length of period (days)

C_s = Soil heat capacity (2.1 MJ m^{-3} C^{-1}) for avg moist soil

d_s = estimated effective soil depth (m), 0.18 m for daily and 2 m for monthly temperatures

Heat Transfer in a Water Body

Heat transfers to depth in a water body is by:

1) Conduction
2) Thermal convection
3) Penetration of radiation below the surface

- Calculation is complex
- Easy to measure from temperature profile surveys

$$A_h = 4.19 X 10^{-3} \left(q_i \, T_i - q_o \, T_o + P \, T_p \right)$$

A_h = Advection rate / unit lake area

q_i & q_o = rate of inflow and out flow per unit area of lake

P = rate of precipitation (mm)

$T_{i,}$ T_o & T_p = Temperatures (°C) of inflow, outflow & precipitation water

Estimation of Evaporation

Evaporation estimation methods:

(1) Using Evaporimeters data ($E_L = K_P E_P$)
  - (i) Surface Pans
  - (ii) Sunken Pans
  - (iii) Floating Pans

(2) Empirical Evaporation Equations
  - (i) Meyer's Formula
  - (ii) Rohwer's Formula

(3) Analytical Methods
  - (i) Water Budget Method
  - (ii) Energy Balance Method
  - (iii) Mass-Transfer Method

Evaporation Pans/Evaporimeters

Pan Coefficients

S.No	Type of Pan	Avg Value	Range
1	Class A Land Pan	0.70	0.60-0.80
2	ISI Pan	0.80	0.65-1.10
3	Colorado Sunken Pan	0.78	0.75-0.86
4	USGS Floating Pan	0.80	0.70-0.82

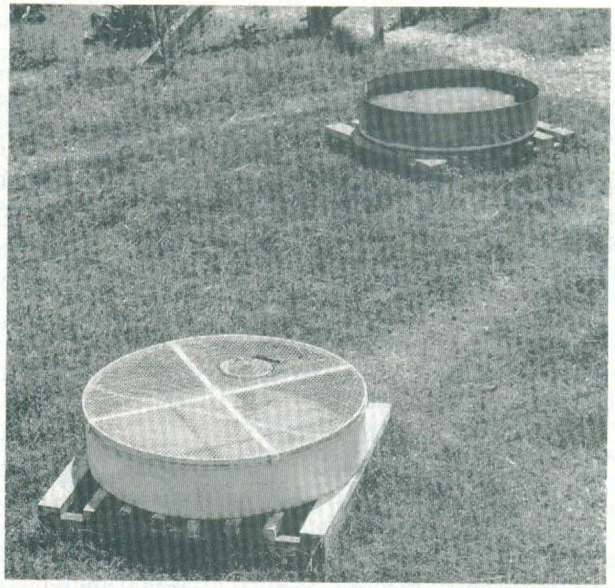


FIGURE 4.3.1 U.S. Weather Bureau Class A evaporation pans with screen in the foreground, and without screen in the background.

Empirical Evaporation Equations

Most of the formulae are based on Dalton type equation

$$E_L = K \; f(u) \; (e_w - e_a)$$

(i) Meyer's Formula (1915)

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

(ii) Rohwer's Formula (1931)

$$E_L = 0.771 \; (1.465 - 0.000732 \; p_a) \; (0.44 + 0.0733 \; u_o) \; (e_w - e_a)$$

Where

E_L = Lake evaporation in mm/day

e_w = Saturated vapor pressure at water surface temperature in mm of Hg

e_a = Actual vapor pressure of overlaying air at a specified height in mm of Hg

$f(u)$ = Wind speed correction factor

K = Coefficient

u_9 = Monthly mean wind velocity in Km/hr at about 9 m above the ground

K_M = Coefficient (0.36 for large deep water, 0.50 for small shallow waters

p_a = mean barometric reading in mm of Hg

u_0 = Mean wind velocity in km/hr at ground level (0.60 m above G.L.)

Empirical Evaporation Equations (contd.)

For up to height of a 500 m above the G.L., the I/7th root law may be used to compute wind velocity at any height h.

$$\frac{u_h}{U} = C\left(\frac{h}{H}\right)^{1/7}$$

Where

u_h = Wind velocity at a height h above the ground

C = Constant

Analytical Methods for Evaporation Estimation

(i) Water Budget Method

- Simplest method (Law of Conservation of mass)
- Least reliable
- Based on Hydrological Continuity Equation
- Considering daily average values for a lake

Where

$$P + V_{is} + V_{ig} = V_{os} + V_{og} + E_L + \Delta S + T_L$$

P = Daily Precipitation (in m^3 or mm)

V_{is} = Daily surface inflow into the lake

V_{ig} = Daily Ground water inflow

V_{os} = Daily surface outflow from the lake

V_{og} = Daily seepage outflow

E_L = Daily Lake evaporation

ΔS = Change in lake storage in a day

T_L = Daily Transpiration Loss

$$E_L = P + (V_{is} - V_{os}) + (V_{ig} - V_{og}) - T_L - \Delta S$$

(i) Water Budget Method (cond.)

- P, V_{is}, V_{os} & ΔS can be measures
- V_{ig}, V_{og} & T_L is not possible to measure (so estimated)
- Transpiration losses can be considered as insignificant in reservoirs
- Better accuracy can be achieved for coarser time scales

(ii) Energy Budget Method

- Law of conservation of energy
- Incoming minus outgoing energy is equal to change in storage

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

$$H_n = H_c(1-r) - H_b$$

Where

H_n = Net heat energy received by the water surface (calories/mm^2/day)

$H_c(1-r)$ = incoming solar radiation into a surface of reflection coefficient

H_b = Back radiation (long wave) from water body

H_a = Sensible heat transfer from water surface to air

H_e = Heat energy used up in evaporation

$H_e = \rho\ L\ E_L$

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 energy)

(ii) Energy Budget Method (contd.)

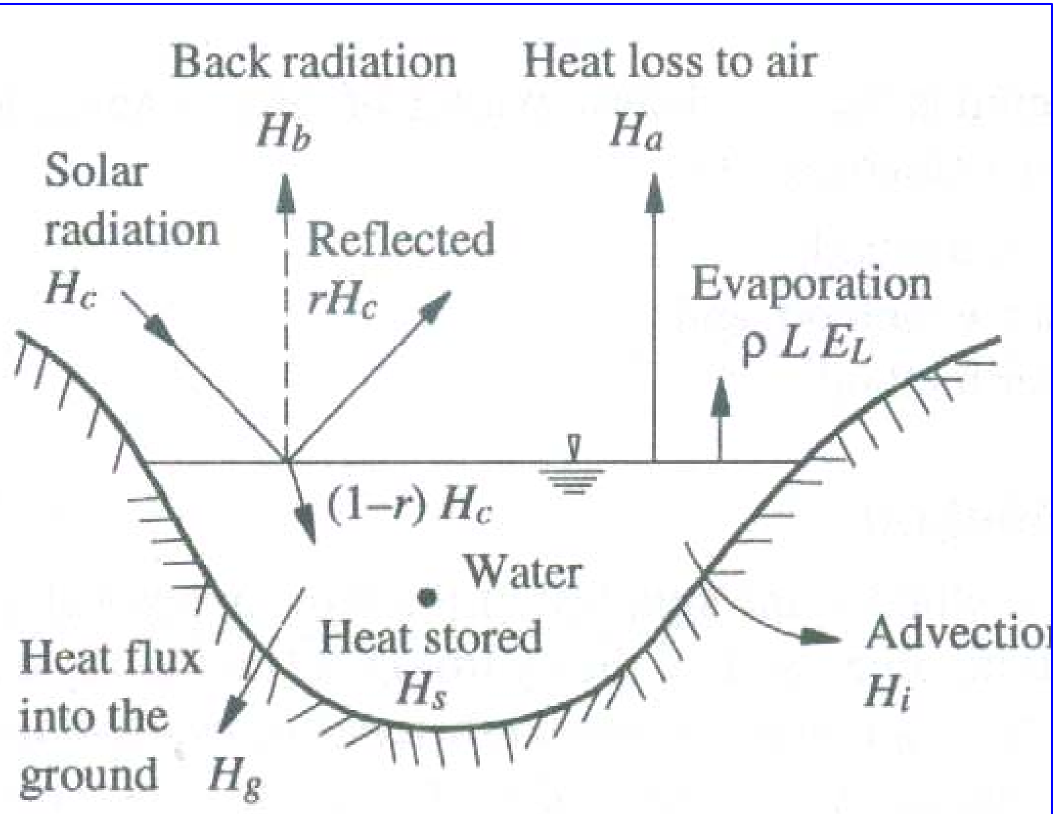


Fig. 3.4 Energy balance in a water body

(ii) Energy Budget Method

- ❑ **If the time period is short, the Hs and Hi can be neglected**
- ❑ **All terms except Ha can be measured or evalauted**
- ❑ **The sensible heat term Ha is estimated using Brown's ratio**

$$\beta = \left(\frac{H_a}{\rho \ L \ E_L} \right) = 6.1 X 10^{-4} X \ \ p_a \left(\frac{T_w - T_a}{e_w - e_a} \right)$$

Where

T_w = Temperature of water surface in °C

T_a = Temperature of air in °C

The equation for Lake evaporation can be written as

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

- ❑ **Method gives satisfactory results (errors 5%)**

(iii) Mass-Transfer Method

- ☐ Based on Turbulent Mass Transfer theories in Boundary Layer
- ☐ Calculates mass water vapor transfer from the surface to atmosphere
- ☐ Sophisticated instrumentation is required
- ☐ Expensive method

Reservoir Evaporation

- Analytical methods provide better results
- Empirical equations can give approximate values
- The volume of water lost due to evaporation from a reservoir in a month is calculated as:

$$V_E = A\ E_{pm}\ K_P$$

Where

V_E = Volume of water lost in evaporation in a month (m^3)

A = Average reservoir area during the month

E_{pm} = Pan evaporation loss in the month (m) [pan evap in mm/day x no. of days in the month x 10^{-3}]

K_P = Relevant pan coefficient

- Water loss from water surface in reservoirs can be as high as 1600 mm / year.

Methods to reduce Evaporation in Reservoirs

(i) Reduction of Surface Area
(ii) Mechanical Covers
(iii) Chemical Films

(i) Reduction of Surface Area

- Evaporation is proportional to surface area of lake
- Where ever feasible, reduce surface area
- Deep reservoirs
- Elimination of shallow areas

(ii) Mechanical covers

- Permanent roofs over the reservoir
- Temporary roofs
- Floating roofs (rafts & light weight floating particles)
- Suitable for small water bodies

(iii) Chemical Films

- Applying a thin chemical film on the water surface
- The only feasible method available (upto moderate size)
- Certain chemicals are applied
  - (1) Cetyl Alcohol (Hexa decanol)
  - (2) Stearyl Alcohol (Octa decanol)
- These apply mono-molecular layers on water surface
- These layers act as evaporation inhibitors and prevent water molecules to escape
- The thin film formed has the following desire-able features

(1) The film is strong and flexible and cannot break due to wave action

(2) If punctured due to impact of raindrops, birds, insects, the film closes back soon after.

(3) It is pervious to oxygen and CO_2, so the water quality does not effect.

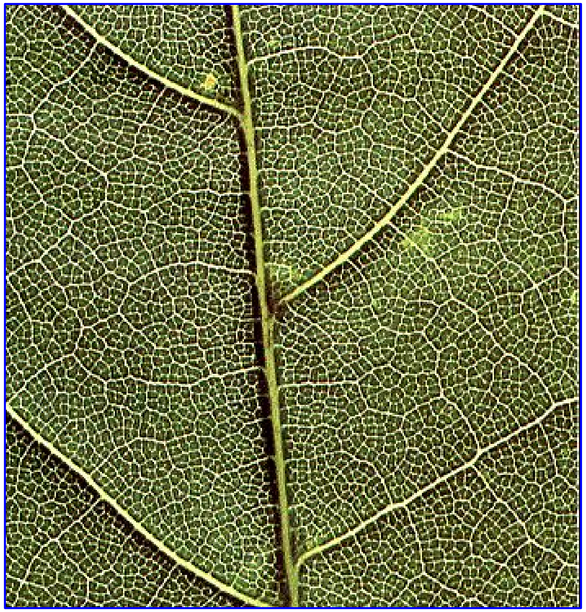
(4) It is colorless, odorless and non toxic

Cetyl Alcohol

- Cetyl Alcohol is the most suitable chemical for evaporation.
- It is white, waxy, crystalline solid & is available as lumps, flakes or powder
- It can applied to the water surface in the form of powder, emulsion or solution
- Roughly 3.5 N/hectare/day of Cetyl Alcohol is needed for effective action
- Use of Cetyl Alcohol reduces evaporation about 60% in Laboratory
- Use of Cetyl Alcohol reduces evaporation about 20-50% in field conditions
- Heavy winds may break the film

Transpiration

Transpiration is the evaporation of water from plants. It occurs chiefly at the leaves while their stomata are open for the passage of CO_2 and O_2 during photosynthesis



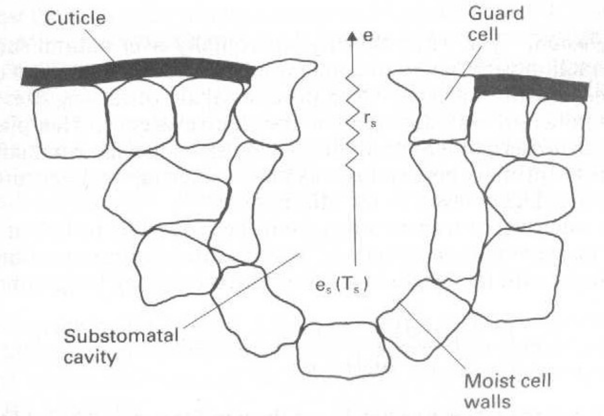
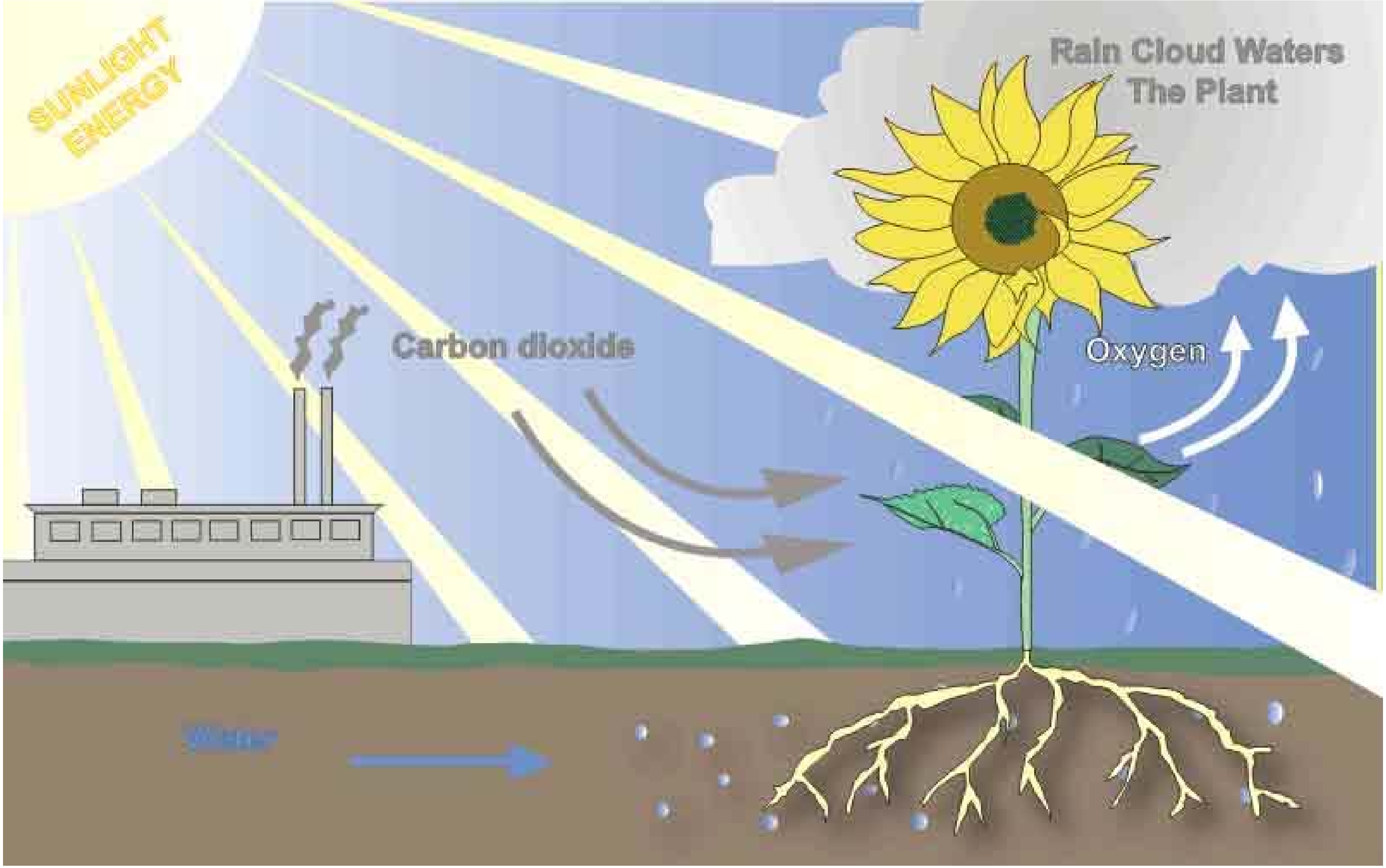
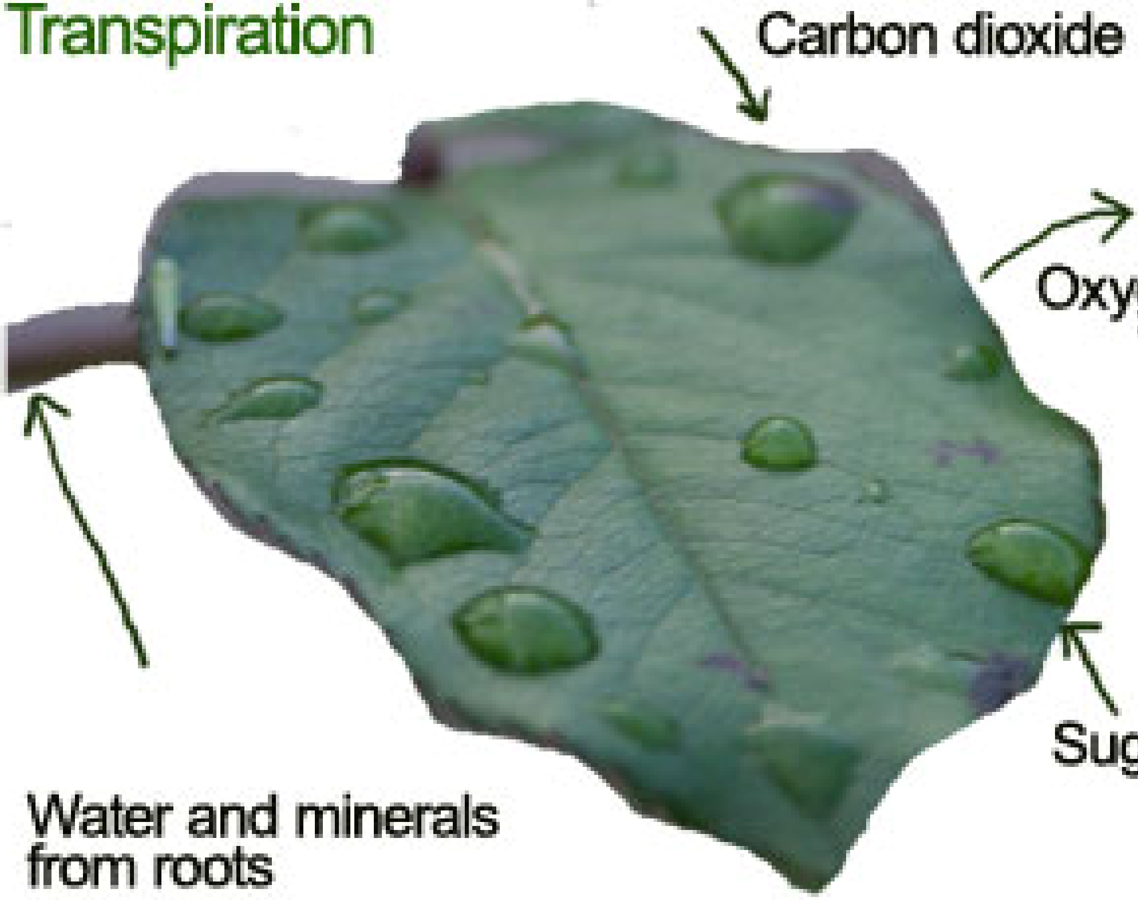


FIGURE 4.2.4 Transpiration by molecular diffusion of water vapor through the stomatal aperture of dry leaves. Air inside the substomatal cavity is saturated at the temperature of the leaf, and the water vapor diffuses through the stomatal opening to the less saturated atmosphere against a stomatal resistance which, for the whole canopy, is called the surface resistance r_s.

- The volume of water lost in transpiration can be very high.
- It has been estimated that over the growing season, one acre of corn plants may transpire 400,000 gallons of water.
- As liquid water, this would cover the field with a lake 15 inches deep.
- An acre of forest probably does even better.


SUNLIGHT ENERGY
Rain Cloud Waters The Plant
Carbon dioxide
Oxygen

Transpiration

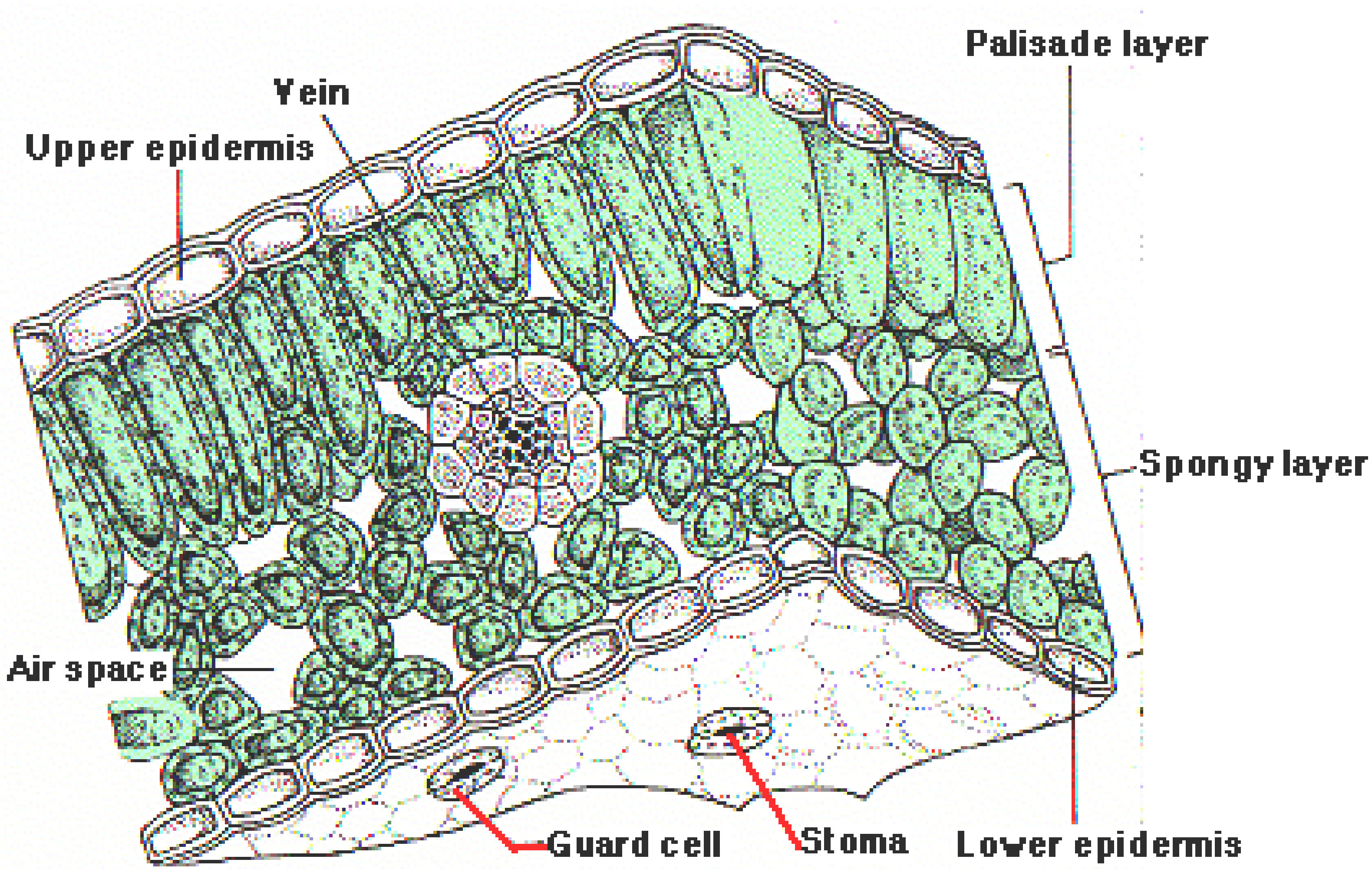


Carbon dioxide in

Oxygen and water vapour out

Sugars synthesised by leaves

Water and minerals from roots


Palisade layer
Vein
Upper epidermis
Spongy layer
Air space
Guard cell
Stoma
Lower epidermis

Factors affecting Transpiration

1. Light

Plants transpire more rapidly in the light than in the dark. This is largely because light stimulates the opening of the stomata. Light also speeds up transpiration by warming the leaf.

2. Temperature

Plants transpire more rapidly at higher temperatures because water evaporates more rapidly as the temperature rises. At 30°C, a leaf may transpire three times as fast as it does at 20°C.

3. Humidity

The rate of diffusion of any substance increases as the difference in concentration of the substances in the two regions increases.When the surrounding air is dry, diffusion of water out of the leaf goes on more rapidly.

4. Wind

When there is no breeze, the air surrounding a leaf becomes increasingly humid thus reducing the rate of transpiration. When a breeze is present, the humid air is carried away and replaced by drier air.

5. Soil water

A plant cannot continue to transpire rapidly if its water loss is not made up by replacement from the soil. When absorption of water by the roots fails to keep up with the rate of transpiration, loss of turgor occurs, and the stomata close. This immediately reduces the rate of transpiration (as well as of photosynthesis). If the loss of turgor extends to the rest of the leaf and stem, the plant wilts.

Evapotranspiration/Consumptive Use

"The combination of water-loss from the soil surface by evaporation and from the crop by transpiration is termed as evapotranspiration"

Potential Evapotranspiration (PET)

Actual Evapotranspiration (AET)

If water supply to the plant is adequate, the soil moisture will be at the field capacity.

AET=PET

If water supply is less than PET, the soil dries out

$AET < PET$

Evapotranspiration Equations

Reference Crop Evaporation

(1) Physically Based equation (based on equilibrium Resistant network)

- (i) Combination equations
- (ii) Radiation based equation
- (iii) Temperature based equations

(2) Empirical Equations

- (i) Blaney Criddle Method
- (ii) Radiation Method / Makkink formula
- (iii) Penman Method

Measurement of Evapotranspiration

(1) Using Lysimeters (2) Field Plots

(1) Using Lysimeters

- A device in which a volume of soil may be planted with vegetation is isolated hydrologically so that leakage $V_L = 0$.
- Thermal, hydrologic and mechanical properties should be same
- Vegetation sample (height and density) should be as surroundings

$$E = P - \frac{(V_R + V_S + V_L)}{A}$$

- Dia = 0.5 – 2 m
- It permits measurement of drainage V_R or makes it 0.
- In case of weighing lysimeter, the change in water storage is determined by weight difference.
- It is difficult
- Expensive
- Good for research applications
- Can be used for calibration of empirical equations

Lysimeter

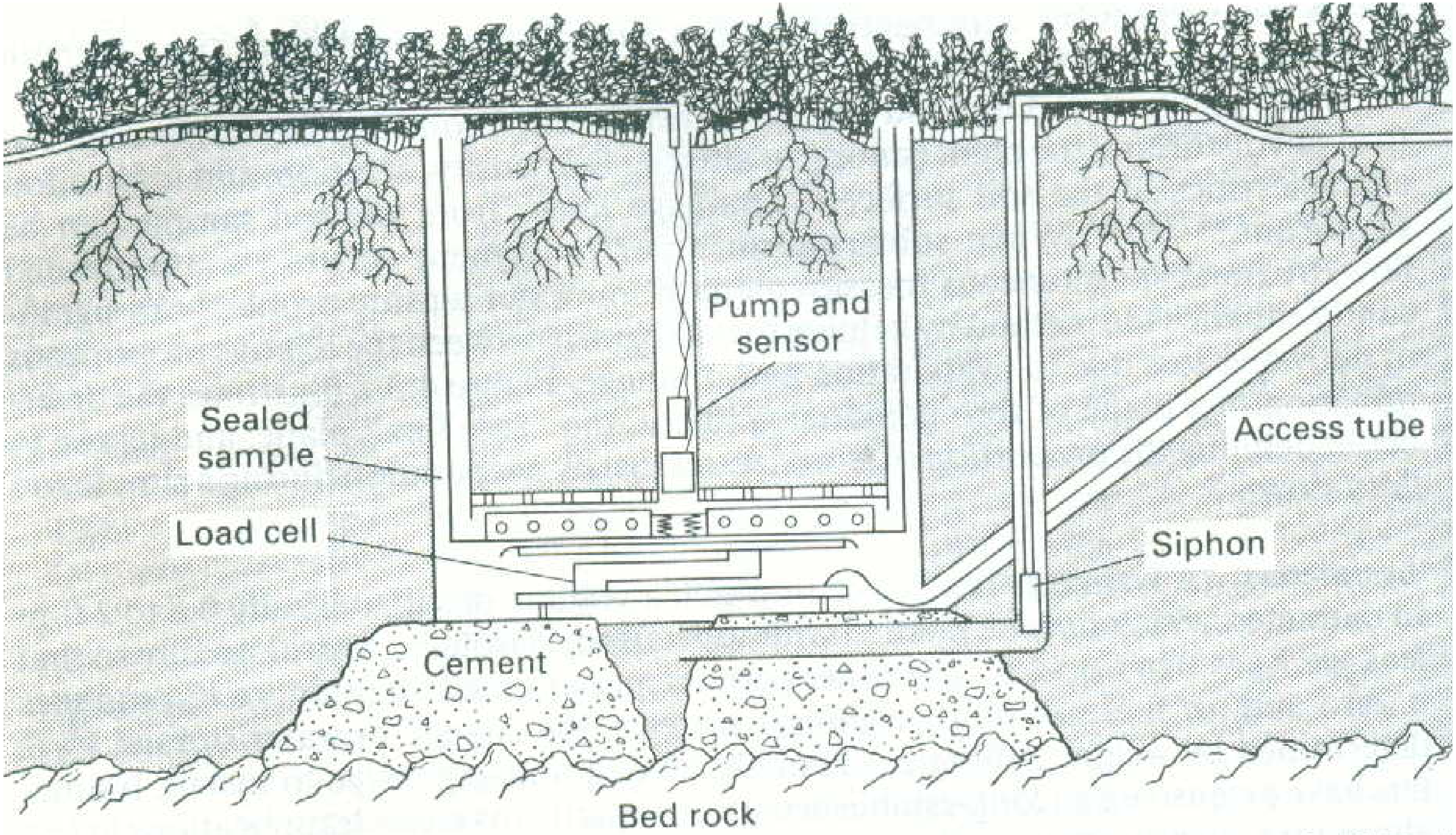


FIGURE 4.3.3 An example of a well-designed weighing lysimeter *(redrawn from Wright.*[133] *Used with permission.)* employing an undisturbed representative sample about 1 m in diameter, with the water status of the soil maintained similar to that of the surrounding area by pumping drainage water.

(2) Field Plots

- ❑ In special plots, all elements of the water budget in a known interval of time are measured.
- ❑ Evapotranspiration is computed using Hydrologic equation

Measured quantities are

Precipitation, Irrigation input, Surface Runoff, Soil moisture

$$ET = P + IRR - \left(R + \Delta S + GW\right)$$

Where

ET = Evapotranspiration

IRR = Irrigation input

R = Runoff

ΔS = Increase in soil moisture

GW = Ground water loss