Civil Engineering

Engineering Hydrology

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

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Engineering Hydrology

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Abstraction from Precipitations

INTRODUCTION

When precipitation comes to the earth's surface, it produces runoff. The runoff is important for study to design the hydraulic structure, estimating flood, etc. All the precipitation that comes to the earth's surface does not contribute to runoff, some part of it disappear. The loss of it occurs due to evaporation, transpiration, interception, depression storage and infiltration. These are also called as abstraction from precipitation.

3.1 Evaporation

Evaporation is the process in which a liquid changes to the gaseous state at the free surface, below the boiling point through the transfer of heat energy.

The molecule of water in a water body are in constant motion with a wide range of instantaneous velocities. If heat is given to a water molecule it increases kinetic energy of the water molecule. As the kinetic energy of the water particle increases, they tend to leave the surface of water body. And some water particles tend to come in water body from air (if present). If the net particle is going outward of body then it is called evaporation and if the net particle is going inward of water body then it is called condensation.

NOTE: Evaporation is a cooling process such that the latent heat of vaporization (at about 585 cal./g of evaporated water) is taken away from the water body by the escaping water molecule.

A number of meteorological and physical factors affect the rate of evaporation. Some of them are as:

(i) The vapour pressure at the water surface and air above
(ii) The air and water temperatures
(iii) Wind speed
(iv) Atmospheric pressure
(v) Quality of water
(vi) Size of water body
(vii) Humidity

(i) The Vapour Pressure: The rate of evaporation is proportional to the difference between the saturation vapour pressure (e_w) at the water temperature and the actual vapour pressure in the air (e_a).

$$E_L = C(e_w - e_a)$$

Here, E_L = Rate of evaporation (mm/day), C = constant, e_w = saturation vapour pressure in mm of mercury and e_a = actual vapour pressure in mm of mercury.

Evaporation will take place till $e_w \geq e_a$ and if $e_w < e_a$ then *condensation* takes place.

NOTE

Saturation vapour pressure: Water vapours are generally present in the atmosphere. The pressure exerted by the vapour present in the air is known as vapour pressure and if the air is fully saturated with these vapour it is called as saturation vapour pressure.

(ii) **Temperature:** By keeping the other factors same, the rate of evaporation increases with an increase in water temperature. Regarding air temperature, in general, increase in evaporation rate with increasing temperature, but a high correlation between evaporation rate and air does not exist.

It is possible that evaporation will be different in a different month if the mean monthly temperature is same in all these months.

(iii) **Wind:** Evaporation from a free water surface into a still layer of air, will continuously slow down as the air layer get saturated with moisture. If the wind remove this still layer of air which is saturated, the scope for evaporation will increase. However, if the wind velocity is large enough to remove all the evaporated water vapour, any further increase in wind velocity does not influence the evaporation. Thus, the rate of evaporation increases with the speed up to a critical speed beyond which any further increase in the wind speed has no influence on the evaporation rate.

This critical wind speed value is a function of the size of the water surface. For large water bodies high speed turbulent wind are needed to cause maximum rate of evaporation.

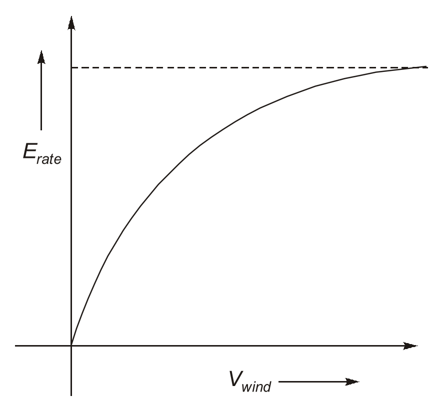

Fig. 3.1 *Evaporation vs. wind velocity*

(iv) **Atmospheric Pressure:** Keeping other factors same, a decrease in the atmospheric pressure increases the evaporation as seen in high altitude where the atmospheric pressure reduces.

(v) **Soluble Salt:** If a salt is dissolved in water, the vapour pressure of the solution is less than that of pure water and hence causes the reduction in the rate of evaporation.

In general, the evaporation decreases 1 per cent for every 1 per cent increase in salinity. As the sea water is more saline so they have 2-3% less evaporation.

(vi) **Water body size:** For a large water surface, the evaporation rate is majority influenced by the depth of water.

At the start of summer season, the temperature of the entire body of water of shallow lake (which have lesser depth) will rise, and hence normal evaporation will take place. But in a deep lake (which have greater depth), the temperature of water will remain much less than that of the air above, which will reduce the evaporation from deep lakes.

This occur due to two reasons:

(a) When the temperature of water is less, the saturation vapour is less, hence lesser evaporation will occur.

(b) When the temperature of water is less than that of the air above, the film of air in contact with water is colder and therefore heavier and more stable water will reduce the effect of wind. The vapour will therefore find more difficulty in dispersion and hence reducing evaporation.

It is clear that the increase of depth of water reduce the rate of evaporation from the surface of water body in summer season.

In the winter season, the temperature of the surrounding air falls but the temperature of water in deep lake does not fall so easily and thus the water remains warmer in comparison to a shallow lake. We know that if the temperature of water is more than evaporation is more.

In winter season evaporation will increase with the increase of the depth of water body.

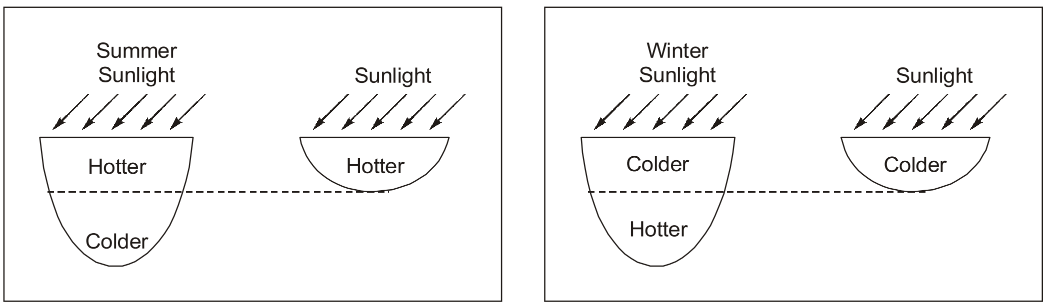

Fig. 3.2 *Effect of water body on evaporation*

(vii) **Humidity:** If the humidity of the atmosphere is more, the evaporation will be less. Because during the process of evaporation, water vapour move from the point of higher moisture content to the point of lower moisture content and the rate of this movement is governed by the difference of their moisture contents. So if the humidity is more than evaporation will be less.

Do You Know?

- **Humidity:** The term humidity is used in order to obtain an idea of the amount of moisture present in the air.

  The amount of moisture present in the air, when expressed as mass per unit volume is known as *absolute humidity*.

- **Relative Humidity:** It is defined as the ratio of the *actual vapour pressure* to the *saturation vapour pressure* at the same temperature.

  It tells us of the extent to which the air is saturated.
  Humidity is measured by the psychrometer or ***hydrometer***.

The evaporation from free water surface mainly depend on all the above factor but the evaporation of soil moisture depends on some other factors. These factor are as:

(i) **Soil Moisture Content:** Experiment have shown that, the evaporation from saturated soil is more than the evaporation of same surface water body.

Means, if a pond have the surface area A and evaporation is E and a soil body which is completely saturated have surface area A, then the evaporation from soil body will be more than E.

(ii) **Soil Capillary Characteristics:** Capillary supply the water to the surface so they enhance the evaporation.

(iii) **Depth of Water Table:** Experiments have shown that the soil evaporation is at a maximum when the water table is at the surface and decreases quiet rapidly as the water table goes down.

(iv) **Colour of Soil:** Soil colour also affects evaporation. A darker soil absorbs more heat and increases the temperature, so enhances evaporation.

3.1.1 Evaporation Measurement

Estimation of evaporation is of very much importance in many hydrologic problem like planning and operation of reservoirs and irrigation system. The amount of water is estimated from a water surface by the following methods:

A. Evaporimeter data B. Empirical Evaporation equation C. Analytical method

A. Evaporimeter Data

Evaporimeter are water containing pans which are exposed to atmosphere, and the loss of water by evaporation in them is measured. In practice so many evaporimeter are used. Some of them are:

(i) **Class A Evaporation Pan:** The pan is made up of unpainted galvanized iron sheet and moral metal is used where corrosion poses a problem. It is mainly used by US weather bureau.

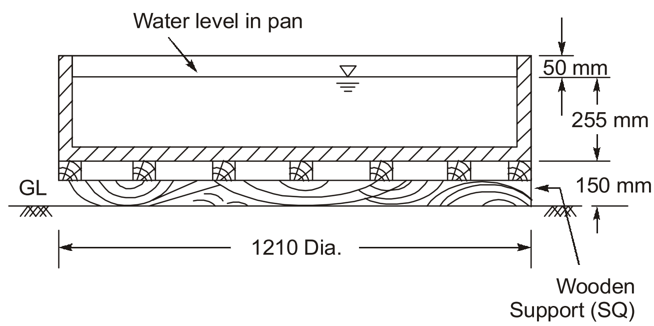

Fig. 3.3 *US Class A Evaporation Pan*

(ii) **ISI Standard Pan:** This pan evaporimeter is also known as *modified class A pan*. This pan is made of copper sheet, tinned inside and painted white outside. The top of the pan is covered fully with a hexagonal wire netting of galvanized iron to protect the water in the pan from birds. The presence of a wire mesh makes the water temperature more uniform during day and night. The evaporation from this pan is 14% less than class A evaporation.

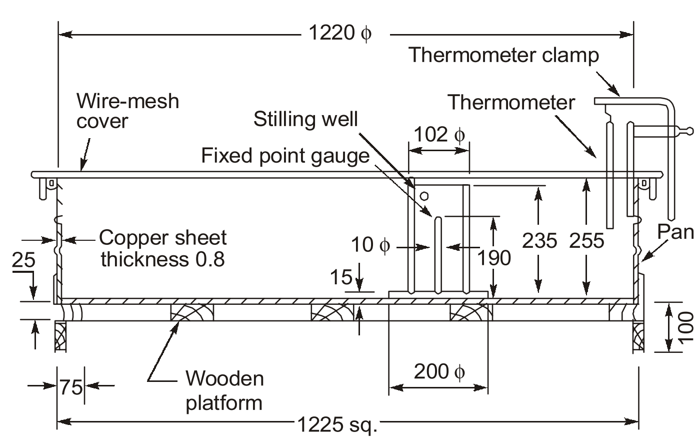

Fig. 3.4 *ISI Evaporation Pan*

(iii) **Colorado Sunken Pan:** This pan is made up of unpainted galvanized iron sheet and buried into the ground within 100 mm of the top. The chief advantage of sunken pan is that radiation and aerodynamic character are similar to those of lake. But it has some disadvantage too.

(a) It is very difficult to detect the leak.

(b) Extra care is needed to keep the surrounding area free from dust and any obstacle to air as sunlight.

(c) It is very expensive to install.

(iv) **US geological Survey Pan:** This type of pan are kept free in water body, whose evaporation is found. This way we can simulate the characteristic of large water body and pan. It has some disadvantages also

(a) High cost of installation and maintenance.

(b) Very difficult to take measurement.

Pan Coefficient (C_p): Since the evaporimeter are not exact models of large reservoir, the evaporation observed from a pan has to be corrected to get the evaporation from a lake under similar climatic and exposure conditions.

$$\text{Lake evaporation} = C_p \times \text{Pan evaporation}$$

This C_p value is always less than 1 due to following reason:

(i) The heat transfer characteristics of the pan material is different from that of the reservoir.

(ii) The evaporimeter and water body differ in heat storing capacity.

S.No	Types of pan	Average Value	Range
1.	Class A Land Pan	0.70	0.60 – 0.80
2.	ISI Pan (modified Class A)	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

Evaporation Station Density: The WMO recommends the minimum number of evaporimeter in a particular region.

(i) Arid zones— one station for every 30,000 km^2

(ii) Humid temperate estimates—one station for every 50,000 km^2

(iii) Cold region—one station for every 10,00,00 km^2

***Table :** WMO Criteria for Hydrometry Station Density*

S.No.	Region	Minimum density (km^2/station)	Tolerable density under difficult conditions (km^2/station)
1.	Flat region of temperate, mediterranean and tropical zones	1,000 – 2,500	3,000 – 10,000
2.	Mountainous regions of temperate, mediterranean and tropical zones	300 – 1,000	1,000 – 5,000
3.	Arid and polar zones	5,000 – 20,000	

B. Empirical Equations

A large number of empirical equations are available to estimate the lake evaporation using commonly available metrological data. Most of the formulae from them are based on Dalton's law.

(i) Meyer's Formula

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

u_9 = monthly mean wind velocity in km/hr of about 9 m above ground level

k_m = 0.36 for large deep water and 0.50 for small shallow water

e_a is measured at same height at which wind speed is measured. If the wind velocity data would be available at an elevation other than the needed, then we find out the velocity

$$U_h = Ch^{1/7} \quad \text{this called 1/7th power law.}$$

(ii) Rohwer's Formula

This is an another empirical equation to find out the evaporation.

$$E_L = 0.771(1.465 - 0.000732\, P_a)\,(0.44 + 0.0733\, u_0)(e_w - e_a)$$

E_L = lake evaporation in mm/day

e_w = saturated vapour pressure in mm of mercury

e_a = actual vapour pressure in mm of mercury

p_a = mean barometric reading in mm of mercury

u_0 = mean wind velocity in km/h at ground level (this velocity can be taken as velocity at 0.6 m from ground surface)

Example 3.1

(a) A reservoir with a surface area of 250 hectares had the following average values of climate parameters during a week; water temperature = 20°C, Relative humidity = 40%, wind velocity at 1.0 m above ground surface = 16 km/h and e_w = 17.54 mm (Hg).
Estimate the average daily evaporation from the lake by using Meyer's formula.

(b) An ISI Standard evaporation pan at the site indicated a pan coefficient of 0.80 on the basis of calibration against controlled water budgeting method. If this pan indicated an evaporation of 72 mm in the week under question, (i) estimate the accuracy if Meyer's method relative to the pan evaporation measurements. (ii) Also, estimate the volume of water evaporated from the lake in that week.

Solution:

(a) e_w = 17.54 mm of Hg, $e_a = 0.4 \times 17.54 = 7.02$ mm of Hg

$$u_9 = \text{wind velocity at a height of 9.0 m above ground}$$
$$= u_1 \times (9)^{1/7} = 21.9 \text{ km/h}$$

By Meyer's formula

$$E_L = 0.36(17.54 - 7.02)\left(1 + \frac{21.9}{16}\right) = 8.97 \text{ mm/day}$$

(b) (i) Daily evaporation as per Pan evaporimeter = $\left(\frac{72.00}{7}\right) \times 0.8 = 8.23 \text{mm}$

Error by Meyer's formula = (8.23 – 8.97) = –0.74 mm. Hence, Meyer's method overestimates the evaporation relative to the pan.

(ii) Considering the Pan measurements as the basis, volume of water evaporated from the lake in 7 days = 7 × (8.23/1000) × 250 × 10^4 = 144025 m^3

[The lake area is assumed to be constant at 250 ha throughout the week]

Example 3.2 A reservoir with a surface area of 300 hectares has the following average meteorological values during a given week.

water temperature = 30°C
relative humidity = 50%
wind velocity at 1 m above ground =12 km/h
mean barometer reading = 750 mm of Hg, e_s = 31.82 mm (Hg)

Estimate the average daily evaporation from the lake reservoir, and the volume of water evaporated from the lake during this week. Make use of Meyer's formula as well as Rohwer's formula to compare the results.

Solution:

(a) Using Meyer's Formula

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

Where, K_m = 0.36 for large deep water, e_s = saturation vapour pressure at 30°C = 31.82 mm of Hg, e_a=?

Also $\frac{e_a}{e_s}$ = 50 % (Relative Humidity)

∴ e_a = 50%, e_s = 0.5 × 31.82 = 15.91 mm of Hg

u_9 = ?

V_1 = 12 km/hr

$$\frac{u_9}{V_1} = \left(\frac{9}{1}\right)^{0.143}$$

∴ $u_9 = (9)^{0.143} \times 12$ km/hr = 16.43 km/hr

Substituting values, we get

$$E = 0.36(31.82 - 15.91)\left(1+\frac{16.43}{16}\right) = 11.61 \text{ mm/day}$$

∴ Total evaporation volume in 7 days (1 week) from 300 hectares of surface area

$$= \frac{11.61}{1000}\frac{\text{m}}{\text{day}} \times 7 \text{ days} \times (300 \times 10^4 \text{m}^2) = 243810 \text{ m}^3$$

(b) Using Rowher's formula

$$E = 0.771(1.465 - 0.000732\, P_a)\,(0.44 + 0.0733\, V_{0.6})(e_s - e_a)$$

Where, e_s = 31.82 mm of Hg, e_a = 15.91 mm of Hg, P_a = 750 mm of Hg

$$\frac{V_{0.6}}{V_1} = \left(\frac{0.6}{1}\right)^{0.143}$$

or
$$V_{0.6} = \left(\frac{0.6}{1}\right)^{0.143} \times 12 \text{ km/h} = 11.15 \text{ km/h}$$

$$E = 0.771(1.465 - 0.000732 \times 750)(0.44 + 0.0733 \times 11.15) \times (31.82 - 15.91) \text{ mm/day}$$
$$= 14.13 \text{ mm/day}$$

Example 3.3 At the beginning of a certain week, the depth of water in an evaporation pan, 1.2 metre diameter, was 7.75 cm. During the week, the rainfall was 3.8 cm and 2.5 cm of water was removed from the pan to keep the depth of water in it within a fixed range. At the end of the week, the gauge indicated a depth of 8.32 cm of water in the pan. Using a suitable evaporation pan coefficient, estimate the evaporation during the week from the surface of a reservoir under similar atmospheric condition.

Solution:

Initial depth of water in the pan	= 7.75 cm
Rainfall	= 3.8 cm
Water removed	= 2.5 cm
Net addition of water in the pan	= 3.8 – 2.5 = 1.3 cm
Depth at the end of week, if there is no loss	= 7.75 + 1.3 = 9.05 cm
Actual depth at the end of week	= 8.32 cm
Evaporation lost from the pan	= 9.05 – 8.32 = 0.73 cm
Evaporation loss from the reservoir	= 0.7 × 0.73 = 0.511 cm
	(Assume a pan coefficient = 0.7)

Hence, the evaporation during the week from the surface of reservoir under similar atmospheric conditions is 5.11 mm.

C. Analytical Methods

Analytical method for determination of lake evaporation can be broadly classified as

(i) Water budget method (ii) Energy balance method (iii) Mass transfer method

(i) Water budget method: This method is simplest in all three method. In this by the hydrological continuity equation, we find out the evaporation from the lake.

The continuity is written down as:

$$P + V_{iS} + V_{iG} = V_{oS} + V_{oG} + E_L + \Delta S + T_L$$

Where, P = precipitation, V_{iS} = surface inflow
V_{iG} = ground water inflow, V_{oS} = surface outflow
V_{oG} = Seepage outflow, E_L = evaporation
ΔS = change in storage, T_L = daily transpiration loss

P, V_{iS}, V_{oS} and ΔS can be measured, but it is not possible to measure V_{iG}, V_{oG} and T_L and these quantities can only be estimated. Due to this reason, the result from this E_L is not accurate.

If time period is kept large for estimation of E_L, better accuracy is possible.

(ii) **Energy budget method:** The energy budget method is an application of the *law of conservation of energy*. The energy available for evaporation is determined by considering the incoming energy, outgoing energy and energy stored in water body over a known time interval.

Consider the water body, the energy balance to the evaporating surface in a period of one day is given by

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

r = reflection coefficient

H_n = net heat energy received by the water surface

$= H_c(1 - r) - H_b$

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

H_a = sensible heat transfer from water surface to air,

H_e = heat energy used in evaporation

$= \rho L E_L$

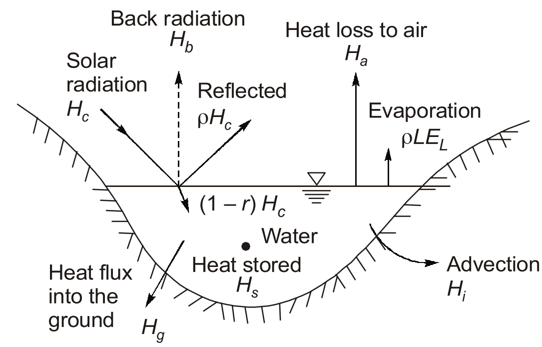

***Fig. 3.5** Energy Balance in a Water body*

ρ = density, L = latent heat of evaporation

E_L = evaporation in mm H_g = heat flux into the ground

H_i = net heat conducted out of the system by water flow.

All the energy term are in calories/sq.mm/day

If the time period are short, the term H_s and H_i can be neglected as they are negligibly small. Then

$$E_L = \frac{H_n - H_g - H_s - H_i}{\rho L(1+\beta)} \quad \text{where,} \quad \beta = \text{Bowen's ratio} = \frac{H_a}{H_e}$$

Estimated of evaporation in a lake by the energy balance method has been found to give satisfactory result, when applied for a short period less than a week.

(iii) **Mass-Transfer Method:** This method is based on theories of turbulent mass transfer in boundary layer to calculate the mass of water vapour transfer from the surface to the surrounding atmosphere.

The volume of water lost due to evaporation from a water body is calculated as

$$V_E = AE_{pm}C_p$$

V_E = Volume of water lost in evaporation A = Average reservoir surface area

E_{pm} = Pan evaporation C_p = relevant pan coefficient

Typically, under Indian condition, evaporation loss from a water body is about 160 cm in a year. Value will increase in arid.

3.1.2 Methods to Reduce Evaporation Losses

There are various method to reduce the evaporation from surface of water body:

(i) **Reduction of Surface Area:** The volume of evaporated water is directly proportional to the surface area of the water body. So we try to reduce the surface by-making the water body more deeper.

(ii) **Mechanical Cover:** Evaporation occur when the sunlight reach to the surface of water body. So by providing the mechanical cover, we protect the surface of water body from direct sunlight. This is to be done by making a roof or shelter (it is normal in Gujarat) on the water body.

(iii) **Chemical Cover:** This method consists of applying a thin film on the water surface to reduce the evaporation. This film reduces movement of water particle, those which leaves the surface after settling energy.

Chemical such as *cetyl alcohol* (hexadecanol) and *stearyl alcohol* (octadeconal) form monomolecular layers on a water surface. This layer has following desirable features.

(i) The layer is strong and flexible and does not break easily due to wave action.

(ii) If punctured due to impact of raindrops or by birds, insects etc. the film repair itself very soon.

(iii) It is pervious to oxygen and carbon-dioxide, so the water quality is not affected by its presence.

(iv) It is colourless, odourless and nontoxic.

Cetyl alcohol is most suitable for use on a layer to reduce the evaporation. Evaporation reduction is more when the film pressure 4×10^{-2} N/m is maintained. Cetyl alcohol can *reduce the evaporation upto 60%*.

Heavy wind is the only factor which affects the efficiency of layer severely.

(iv) **Increase in Salinity:** As we know, if the salinity is more then evaporation is less, so by increasing salinity we can reduce the evaporation.

3.2 Interception

- When a rain falls, it is firstly intercepted by trees, plants, buildings etc., when they become completely wet, the water comes down to the earth surface.
- The initial water intercepted by trees, plants and buildings etc., is required to wet them and after that the water intercepted by them equals evaporation rate. So this complete amount of water is called interception loss. It is denoted by

$$x = a + bt$$

x = total interception (in cm)

a = water required for wetting (or interception storage capacity (in cm)

b = evaporation rate from the intercepting surface (in cm/hr)

t = duration of showers (in hr)

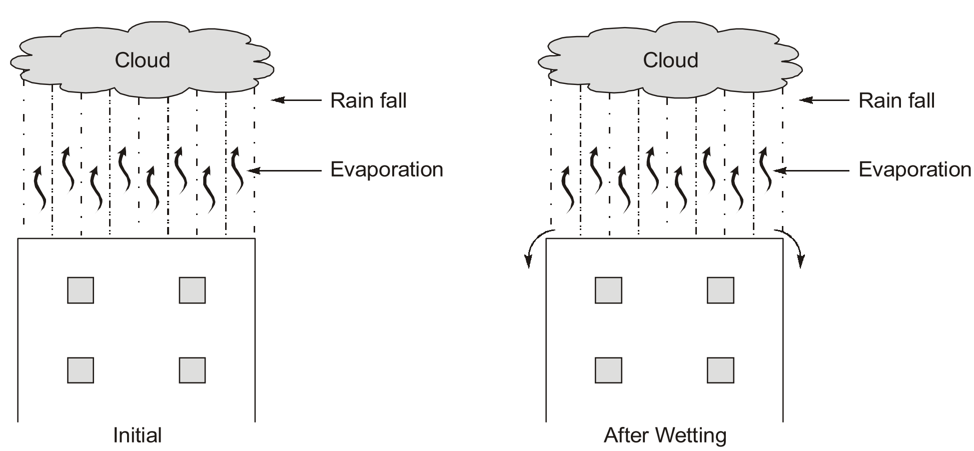

Fig. 3.6 *Interception loss*