Government of India & Government of The Netherlands

Technical Assistance
HYDROLOGY PROJECT

DHV CONSULTANTS &
DELFT HYDRAULICS with
HALCROW, TAHAL, CES,
ORG & JPS

VOLUME 3
HYDRO-METEOROLOGY

DESIGN MANUAL

Table of Contents

1 INTRODUCTION

1.1 GENERAL

The branch of Geophysics, which deals with the occurrence and movement of water in terms of quantities and quality on and below the surface of the earth except the oceans, in vapour, liquid or solid state, is termed Hydrology. For hydrological design and water resources assessment purposes proper estimates of rainfall and evapo(transpi)ration are required, which is the domain of hydro-meteorology. Areal rainfall amounts are estimated from point rainfall data. Potential evapo(transpi)ration is either estimated from pan evaporation measurements or derived from energy considerations, vapour transport or a combination of the two. For the latter procedures data are required on solar and longwave radiation, atmospheric pressure, temperature, humidity and wind.

In the Hydrological Information System with respect to hydro-meteorology three types of observation stations have been discerned:

1. **SRG station**, accommodating the standard non-recording raingauge
2. **ARG station**, accommodating a recording and a non-recording raingauge, and
3. **Full-climatic station** (see Figure 1.1), where in addition to raingauges also equipment is installed to observe the variables needed to estimate evaporation.

Figure 1.1: Full climatic station

The measurement of the hydro-meteorological quantities made at the observation stations is dealt with in this Volume 3 “Hydro-meteorology” of the “Manual on Hydrological Field Measurements and Data Processing”. This volume includes **how** measurements are made, **with what** equipment, **where** and **when**. Volume 3 consists of three parts:

1. **Design Manual**, in which the basic principles and procedures are put in context
2. **Reference Manual**, for details on specific topics, and
3. **Field Manual**, dealing with operational procedures at the observation station.

This part of Volume 3 covers the **Design Manual: ‘Hydro-meteorology’**. It is set up as follows:

- Chapter 1 deals with definitions and units.
- The physics of the rainfall and evaporation processes and statistics of relevant climatic variables are dealt with in Chapter 2.
- In Chapter 3 the design and optimisation of rainfall and climatic observation networks are discussed. Network densities are related to required accuracy, which is determined by the measurement objectives and spatial variation of the phenomena and cost of installation and operation.

- Once the network density has been specified the sites for the measurement of rainfall and climatic variables have to be selected. Criteria for site selection are discussed in Chapter 4.
- Next, in Chapter 5 the observation frequency to be applied for the various meteorological quantities in view of the measurement objectives and temporal variation of the observed processes are treated.
- The measurement techniques for observation of hydro-meteorological variables and related equipment are dealt with in Chapter 6.
- Since the buyers of the hydro-meteorological equipment are often neither sufficiently familiar with the exact functioning of (parts of) the equipment nor with the background of the specifications, remarks on the equipment specifications have been added in Chapter 7. The equipment specifications proper are covered in a separate and regularly updated volume: “Surface Water Equipment Specifications”.
- Guidelines on station design and equipment installation are presented in Chapter 8.

In the Field Manual operational practices in running the network stations are given in full, as well as field inspections, audits and last but not least, the topic of equipment maintenance and calibration, including maintenance and calibration schedules.

Notes

1. The content of this part of the manual deals only with hydro-meteorological measurements in the States of Peninsular India. The equipment discussed is used or appropriate for use in the Hydrological Information System of these States. Hence, the manual does not provide a complete review of all techniques and equipment applied elsewhere.
2. The procedures dealt with in this manual are conformable to BIS and ISO standards. It is essential that the procedures described in this manual be closely followed to guarantee a standardised approach in the entire operation of the Hydrological Information System.

1.2 DEFINITIONS AND UNITS

Quantity	Symbol	Unit	Quantity	Symbol	Unit
Density					
Density of dry air	ρ_d	kg.m^{-3}	Soil heat flux density,	G	[W.m^{-2}]
Density of moist air	ρ_a	kg.m^{-3}	Global solar radiation flux density, global radiation or short-wave radiation	$S^{\downarrow}$	[W.m^{-2}]
Mixing ratio	r	-	Net solar radiation flux density	S_n	[W.m^{-2}]
Pressure					
Air pressure	p_a	kPa			
Vapour pressure	e	kPa	Albedo	α	[-]
Saturation vapour pressure	e_s	kPa	Net terrestrial flux density or net long-wave radiation	L_n	[W.m^{-2}]
Slope of saturation water vapour pressure curve	s	kPa.^{o}C^{-1}	Net radiation flux density or net incoming radiant energy	R_n	[W.m^{-2}]
Saturation deficit	Δe	kPa			
Humidity			**Rainfall**		
Specific humidity	q_v	-	Gross rainfall or rainfall	P	mm.Δt^{-1}
Absolute humidity	ρ_v	kg.m^{-3}	Interception	E_i	mm.Δt^{-1}
Relative humidity	r_h	-	Net rainfall	P_n	mm.Δt^{-1}
Temperature			**Evaporation**		
Dew-point	T_d	or K	Open water evaporation	E_0	mm.Δt^{-1}
Wet-bulb temperature	T_w	^{o}C or K	Pan evaporation	E_{pan}	mm.Δt^{-1}
Virtual temperature	T_v	^{o}C or K	Soil evaporation,	E_s	mm.Δt^{-1}
			Transpiration	E_t	mm.Δt^{-1}
Pressure and temp.			Actual evapotransp.	E	mm.Δt^{-1}
Psychrometric constant	γ	kPa.^{o}C^{-1}	Potential evapotransp.	E_p	mm.Δt^{-1}
Energy-balance			Aerodynamic resistance to water vapour	r_a	s.m^{-1}
Latent heat of vaporisation	λ	J.kg^{-1}	Canopy resistance	r_c	s.m^{-1}
Latent heat flux density	λE	W.m^{-2}			
Sensible heat flux density	H	W.m^{-2}			
Bowen ratio	β	-			

Table 1.1: Overview of relevant quantities, symbols and units used in hydro-meteorology

In this section definitions, symbols and units of relevant quantities and parameters when dealing with rainfall and evaporation processes are given. A summary of all quantities and parameters is presented in Table 1.1.

Density

Consider a volume of (moist) air V having a mass m_a. The volume V is a mixture of dry air with mass m_d and water vapour with mass m_v so $m_a = m_d + m_v$. Then the following definitions apply.

Density of dry air ρ_d, [kg.m^{-3}] is the mass of dry air m_d per unit volume of air V:

$$\rho_d = \frac{m_d}{V} \tag{1.1}$$

Density of water vapour or **absolute humidity** ρ_v, [kg.m^{-3}] is the mass of water vapour per unit volume of air V:

$$\rho_v = \frac{m_v}{V} \tag{1.2}$$

Density of moist air ρ_a, [kg.m^{-3}] is the mass of (moist) air per unit volume of (moist) air, i.e. the sum of the mass of dry air and the mass of water vapour per unit volume the mixture of air and water vapour V:

$$\rho_a = \frac{(m_d + m_v)}{V} = \rho_d + \rho_v \approx \frac{p_a}{0.287(T_a + 275)} \tag{1.3}$$

where: p_a = air pressure [kPa]
T_a = air temperature [^{o}C]

Note that 0.287 is the specific gas constant for dry air R_a (= 0.287 kJ.kg^{-1}.^{o}C^{-1}) and (T_a + 275) is an approximation for the virtual temperature. Under standard conditions (P_a = 101.3 kP$_a$) the variations of the density of moist air as a function of the air temperature is shown in Figure 1.2.

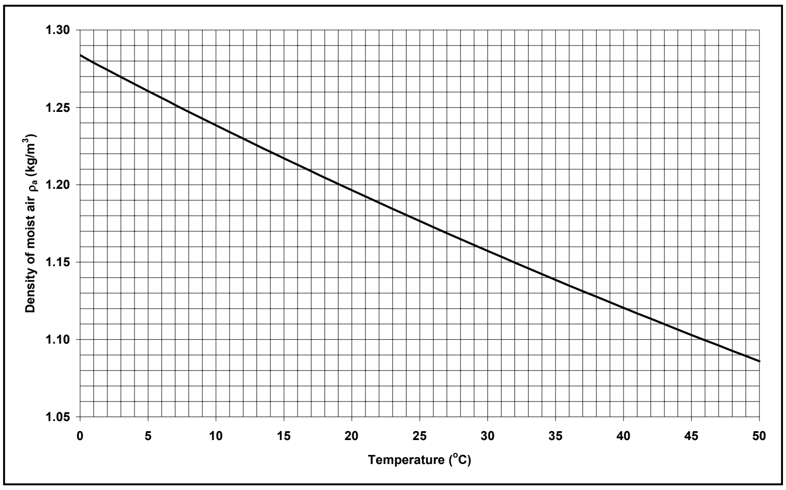


Figure 1.2:
Density of moist air (kg/m^3) under standard conditions (p_a = 101.3 kPa) as a function of air temperature T_a (^{o}C)

From the above definitions the following ratio's are to be distinguished:

Specific humidity, q_v [-] which is the mass of water vapour per unit mass of moist air, i.e.

$$q_v = \frac{m_v}{m_d + m_v} = \frac{\rho_v}{\rho_a} \tag{1.4}$$

Mixing ratio, r [-] is the ration of the mass of water vapour and the mass of dry air:

$$r = \frac{m_v}{m_d} = \frac{\rho_v}{\rho_d} \tag{1.5}$$

Pressure

Air pressure, p_a [kPa] is the total pressure exerted by all molecules of the air mass. The air pressure is related to altitude according to:

$$p_a = 101.3\left(\frac{T_A - 0.0065H}{T_A}\right)^{5.256} \tag{1.6}$$

where: T_A = average air temperature [K], $T_A = T_a + 273.15$
H = elevation relative to m.s.l. [m]

Air pressure, as a function of altitude and temperature is shown in Figure 1.3.

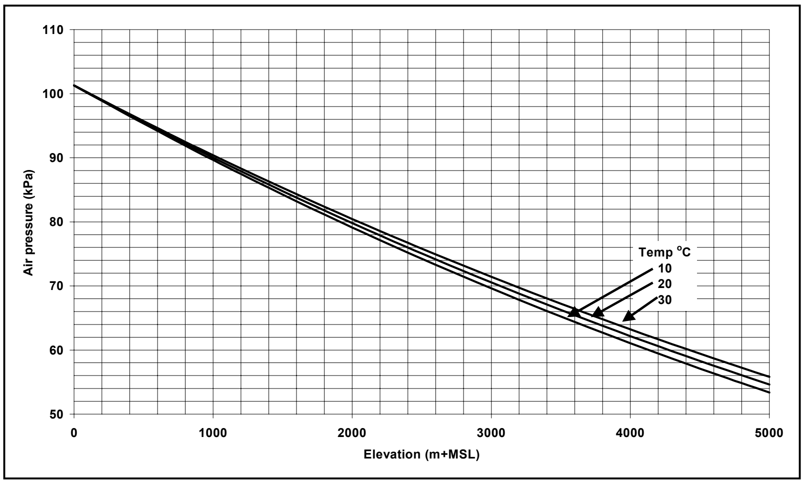


Figure 1.3:
Air pressure (kPa) as a function of altitude (m+MSL) and air temperature T_a (°C)

Vapour pressure, e_a [kPa] is the partial pressure of the water vapour molecules at a given temperature.

Saturation vapour pressure, e_s [kPa] is the vapour pressure at which the water vapour is in equilibrium with a plane water (or ice) surface of the same temperature and pressure. The saturation water vapour pressure as a function of temperature is well approximated by (for 0<T<50 °C error in e_s: $\delta_{es} < \pm 0.06\%$ compared to the Goff-Gratch equation for saturation vapour pressure):

$$e_s(T_a) = 0.6108 \exp\left(\frac{17.27T_a}{T_a + 237.3}\right) \tag{1.7}$$

The saturation vapour pressure is presented graphically in Figure 1.4

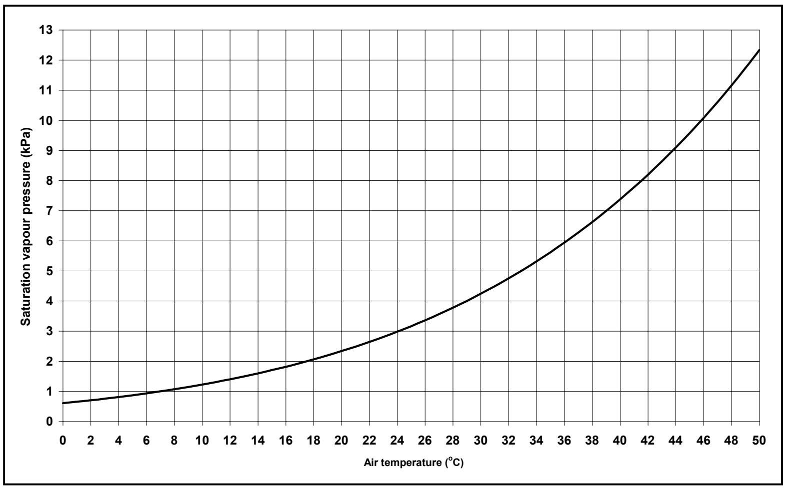


Figure 1.4:
Saturation vapour pressure (kPa) as function of air temperature T_a (^oC)

Slope of saturation water vapour pressure curve, s [$kPa.^oC^{-1}$] is the derivative of the saturation water vapour pressure to the temperature:

$$s = \frac{de_s}{dT_a} = \frac{4098\ e_s}{(237.3 + T_a)^2} \tag{1.8}$$

Since e_s is a function of the air temperature, so is s, as is shown in Figure 1.5:

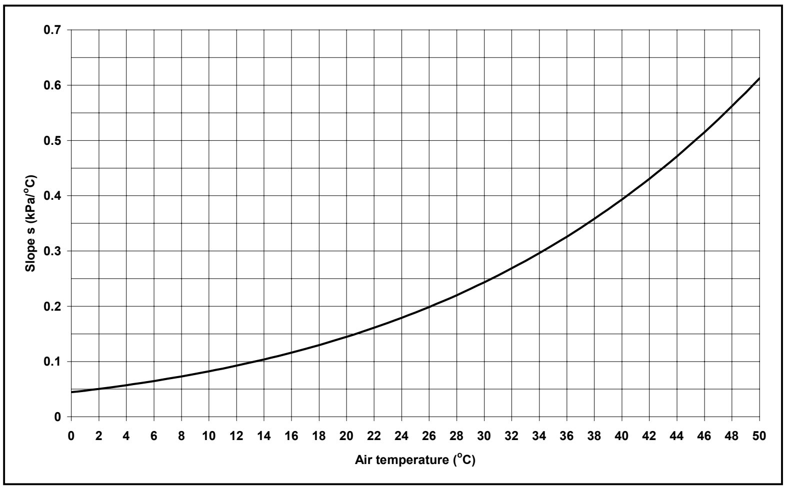


Figure 1.5:
Slope of saturation vapour pressure curve s (kPa/^oC) as a function of air temperature T_a (^oC)

Saturation deficit, Δe [kPa] is the difference between the saturation vapour pressure e_s and the actual vapour pressure e at the same temperature:

$$\Delta e = e_s - e_a \tag{1.9}$$

Humidity

Absolute humidity ρ_v and specific humidity q_v have been defined above, see respectively (1.2) and (1.4).

Relative humidity, r_h [-] is the ratio of the actual vapour pressure and the saturation vapour pressure at the same temperature:

$$r_h = \frac{e_a}{e_s} \tag{1.10}$$

Temperature

Dew-point, T_d [°C or K] is the temperature to which a certain quantum of moist air has to be cooled at constant pressure and mixing ratio r to reach saturation (can be obtained from (1.7)).

Wet-bulb temperature, T_w [°C or K] is the temperature that moist air obtains if it is flowing over a wet surface, when the ambient air solely delivers the latent heat of vaporisation.

Virtual temperature, T_v [°C or K] is the temperature that dry air must get to have the same density as moist air at the same pressure:

$$T_v = (1+0.61q_v)T_a \tag{1.11}$$

Pressure and temperature

Psychrometric constant, γ [kPa.°C^{-1}] is the difference between the saturation vapour pressure at the wet bulb temperature and the actual vapour pressure divided by the difference of the dry bulb (ambient air temperature) and wet bulb temperatures:

$$\gamma = \frac{e_s(T_w) - e_a(T_a)}{T_a - T_w} = \frac{c_p . p_a}{\varepsilon\lambda} \tag{1.12}$$

where: c_p = specific heat of air (=1.005 [kJ.kg^{-1}. °C^{-1}])
p_a = air pressure [kPa]
ε = ratio of molecular masses of water vapour and dry air [-], ε = 0.622
λ = latent heat of vaporisation [kJ.kg^{-1}], see (1.13)

The value of the γ is about 0.067 (kP$_a$/ °C) under standard atmospheric conditions as shown in Figure 1.6.

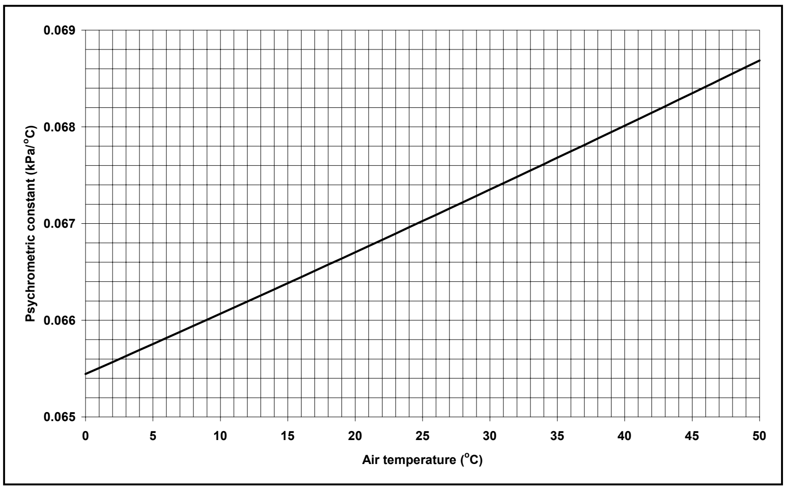


Figure 1.6:
Psychrometric constant γ (kPa/°C) as a function of air temperature T_a (°C) for standard atmospheric conditions (p_a = 101.3 kPa)

Energy-balance

Latent heat of vaporisation, λ [kJ.kg^{-1}] is the energy, which is required to vaporise one unit of mass of liquid water without change in temperature (isothermal). The energy is required to break the hydrogen bonds. Since at higher temperature more bonds are already broken the required energy for vaporisation will be somewhat less, hence λ varies with temperature (T °C):

$$\lambda_v = 2501 - 2.361T \qquad (1.13)$$

Latent heat flux density, λE [W.m^{-2}] i.e. the evaporation expressed as mass flux multiplied with the latent heat of vaporisation is the energy per unit of time and of surface used for evaporation.

Sensible heat flux density, H [W.m^{-2}] is the energy per unit of time and of surface, which is absorbed by the atmosphere used to heat up the air.

Bowen ratio, β [-] is the ratio of the sensible and latent heat flux densities as delivered by the surface of the earth to the atmosphere:

$$\beta = \frac{H}{\lambda E} \qquad (1.14)$$

Soil heat flux density, G [W.m^{-2}] is the energy per unit of time and of surface absorbed by the soil.

Global solar radiation flux density, global radiation or **short-wave radiation,** $S^{\downarrow}$ [W.m^{-2}] the sum of the direct and diffuse short-wave radiation (wave length < 3 μm) received from the hemisphere on a horizontal plane per unit of time and of surface.

Albedo, α [-] is the fraction of incoming short-wave radiation which is reflected by the surface of the earth:

$$\alpha = \frac{S^{\uparrow}}{S^{\downarrow}} \qquad (1.15)$$

Typical values for Albedo for various land covers are presented in Table 1.2. The values in the table are daily mean short wave solar radiation reflection coefficients. Note that the Albedo can vary widely with time of the day, season, latitude and cloud cover.

Land cover class	**Short-wave radiation reflection coefficient**
Open water (solar angle 60°-10°)	0.05-0.35
Tall forest	0.11-0.16
Tall farm crops (e.g. sugarcane)	0.15-0.16
Cereal crops (e.g. wheat)	0.20-0.26
Short farm crops (e.g. sugar beets)	0.20-0.26
Grass and pasture	0.20-0.26
Bare soil	0.10 (wet) – 0.35 (dry)
Snow	0.40 (old) – 0.80 (fresh)

Table 1.2: Daily mean short wave solar radiation reflection coefficients

Net solar radiation flux density, S_n [W.m^{-2}] is the difference between the incoming $S^{\downarrow}$ and the reflected outgoing short-wave radiation $S^{\uparrow}$per unit of time and per unit of surface (wavelength 0.3 – 3 μm):

$$S_n = S^{\downarrow} - S^{\uparrow} = (1-\alpha)(a + b\frac{n}{N})R_A \tag{1.16}$$

where: α = surface albedo or reflection coefficient [-]
a = fraction of extraterrestrial radiation on overcast days [-]
a+b = fraction of extraterrestrial radiation on clear days [-]
n/N = actual to maximum bright sunshine duration [-]
R_A = extraterrestrial radiation, or Angot value [W.m^{-2}]

Net terrestrial flux density or net long-wave radiation, L_n [W.m^{-2}] is the difference between the incoming long-wave radiation (from atmosphere to ground) $L^{\downarrow}$ and the outgoing long-wave radiation (from ground to atmosphere) $L^{\uparrow}$ (wavelength: 3-100 μm):

$$L_n = L^{\downarrow} - L^{\uparrow} = -\sigma T_A^4 (0.34 - 0.139\sqrt{e_a})(0.1 + 0.9\frac{n}{N}) \tag{1.17}$$

where: σ = Stefan-Boltzmann constant (=5.6745x10^{-8} Wm^{-2}K^{-4})
T_A = mean air temperature [K], where $T_A{}^4 = (T_{A\,max}{}^4 + T_{A\,min}{}^4)/2$
e_a = actual vapour pressure [kPa]
n/N = actual to maximum bright sunshine duration [-]

Net radiation flux density or **net incoming radiant energy,** R_n [W.m^{-2}] is the difference between the incoming and outgoing short-wave and long-wave radiation per unit of time and unit area. It is the difference between the incoming and reflected solar radiation S_n plus the difference between the incoming and outgoing long-wave radiation L_n:

$$R_n = S_n + L_n \tag{1.18}$$

Hence R_n is computed from equation (1.16) and (1.17).

Rainfall

Gross rainfall or shortly **rainfall,** P [mm.hr^{-1}, mm.day^{-1}, etc.] is the average rainfall intensity above the surface of the earth.

Interception, E_i [mm.hr^{-1}, mm.day^{-1}, etc.] is that part of the rainfall, which is intercepted by vegetation and structures and subsequently evaporates.

Net rainfall, P_n [mm.hr^{-1}, mm.day^{-1}, etc.] is the difference between gross rainfall and interception:

$$P_n = P - E_i \tag{1.19}$$

Evaporation

Open water evaporation, E_0 [mm.day^{-1}, etc.] is the theoretical evaporation flux from a smooth shallow water surface (with no storage of energy) when subjected to the ambient meteorological conditions.

Pan evaporation, E_{pan} [mm.day^{-1}, etc.] is the evaporation flux from an evaporation pan.

Soil evaporation, E_s [mm.day^{-1}, etc.] is the evaporation flux from the soil.

Evaporation [mm.day^{-1}, etc.] is the evaporation flux from intercepted water and from the soil, i.e it is $E_i + E_s$

Transpiration, E_t [mm.day^{-1}, etc.] is molecular diffusion of water vapour through the stomatal aperture of leaves.

Actual evapotranspiration, E [mm.day^{-1}, etc.] is the total evaporation flux of a cropped surface.

$$E = E_i + E_s + E_t \tag{1.20}$$

Potential soil evapotranspiration, E_{ps} [mm.day^{-1}, etc.] is the theoretical evaporation flux from the soil if the soil would sufficiently be supplied with water, when the soil is subjected to the ambient meteorological conditions, which remain unchanged during the evaporation process

Potential transpiration, E_{pt} [mm.day^{-1}, etc.] is the theoretical transpiration of plants, which are sufficiently supplied with water, when the plants are subjected to the ambient meteorological conditions.

Potential evapotranspiration, E_p [mm.day^{-1}, etc.] is the sum of the potential soil evaporation E_{sp} and transpiration E_{pt}:

$$E_p = E_{sp} + E_{pt} \tag{1.21}$$

Aerodynamic resistance to water vapour, r_a [s.m^{-1}] is the resistance to the transport of water vapour in the air layer between the canopy/soil and the height at which measurements are taken.

Canopy resistance, r_c [s.m^{-1}] is the apparent diffusive resistance to the transport of water vapour through the stomata to the surface of the leaves.

2 DESCRIPTION OF RAINFALL AND EVAPORATION PROCESSES

2.1 GENERAL

In the Hydrological Information System interest is focussed on the temporal and spatial variation of rainfall and evaporation/evapotranspiration, both important water balance components. Rainfall is measured by a network of recording and non-recording rain-gauges. Evaporation pans are used to measure open water evaporation, but evapotranspiration is cumbersome to measure directly. Indirect methods are being applied to estimate it. For these indirect methods data have to be available on air pressure, sunshine duration, temperature, humidity and wind speed and direction. In this chapter an introduction is presented on rainfall and evaporation and on the climatic variables determining evaporation, to get some insight in their spatial and temporal variation. These characteristics are of importance to appreciate the data collected in the field.

The following is presented in the next sections:

- In Section 2.2 the rainfall process and its characteristics over Peninsular India is discussed.
- The evaporation process and its related parameters are dealt with in Sections 2.3 and 2.4.

An overview of monthly and annual statistics of climatic variables for selected locations in Peninsular India is presented in Volume 3, Reference Manual, Hydro-meteorology.

2.2 RAINFALL

The term "precipitation" denotes all forms of water in solid or liquid form that reach the earth from the atmosphere and it is expressed as the depth (in mm) to which it would cover a horizontal area at the ground level in liquid form.

Physics of precipitation

For precipitation to form, a sequence of four processes must occur (see e.g. Dingman, 2002):

- atmosphere must have sufficient water vapour present, which is cooled to dewpoint,
- condensation of water vapour on cloud condensation nuclei
- growth of water droplets, and
- importation of water vapour.

Re 1. Cooling to dewpoint

Though there are several mechanisms active in the atmosphere which cool air, only the process of adiabatic cooling due to vertical uplift is able to produce precipitation of any significance. Three types of lifting mechanisms are available, lifting moist air to a level where condensation of water vapour does take place:

- convective,
- cyclonic, and
- orographic.

Under the **convective** process the lifting occurs due to differential heating of a region when the warmer moist air rises in relation to colder surroundings. Rainfall intensity varies from light to very heavy depending upon cloud height and its duration (a few hours). Most of the summer rain in India is of this type and generally occurs in afternoons.

Lifting in a **cyclonic** process occurs due to convergence of moist air into a low pressure area. These low pressure systems could be frontal or non-frontal. Frontal precipitation is associated with extra tropical cyclones with a warm front in advance followed by a cold front. A warm front (warm air displacing cold air at the surface) has a flat surface with gentle slopes causing light to moderate precipitation spreading over larger areas (a few thousand square kilometres). A cold front (cold air displacing warm air at the surface) has steeper slopes thereby causing the warmer moist air to rise faster and develop into massive thundercloud yielding storming-showery weather of shorter duration (a few hours). Non frontal systems are monsoon depressions and more intense tropical revolving cyclones. These systems usually produce heavy to very heavy rain and floods.

Orographic rain occurs due to mechanical lifting of moist air on mountain slopes. Maximum vertical velocity is generated, when the lower level moist wind is perpendicular to the mountain ranges. Torrential rains, popularly called cloudbursts, occur. This type of precipitation is common during the monsoon season along the lower and middle ranges of the Himalayas, Khasi-Jayanti hills, Western Ghats all along the west coast and Eastern ghats along the east coast of India.

Re 2. Condensation of water vapour

Cloud condensation nuclei, which vary in size from 10^{-5} to 10^{-1} mm, are required to condense water vapour at dew point. Typical cloud condensation nuclei are meteoric dust, windblown clay and silt, volcanic material, sea salt and combustion products. Natural concentrations of cloud condensation nuclei vary from 100 to 300 cm^{-3}, but may locally become 10 to 100 times larger due to human activities.

Re 3. Growth of water droplets

Before precipitation is occurring cloud droplets sized from 0.001 to 0.2 mm have to grow to 0.4 to 4 mm in diameter to reach a fall velocity that exceeds the rate of uplift. Cloud droplets may grow at temperatures above 0 ^{o}C by droplet collision due to differences in fall and lift velocities caused by the differences in droplet size. Below zero cloud droplets evaporate and condense on ice-crystal to grow. This so called Bergeron-Findeisen process is induced by the lower saturation vapour pressure of an ice surface compared to a liquid-water surface at the same temperature.

Re 4. Importation of water vapour

The water content of a 10 km thick cloud would produce rainfall amounts of about 5 mm. Hence, for any substantial rainfall to occur influx of moist air is continually required. This inflow of moist air is provided by winds that converge on the precipitation-producing clouds.

Climatic seasons

The climate is derived from the long-term behaviour of rainfall and other meteorological variables. The climate of the Indian subcontinent covers two major seasons separated by two transitional periods:

- South-west monsoon (June-September)
- Transition-I, Post monsoon (October-November)
- Winter season (December-February), and
- Transition-II, Summer (March-May)

Weather Systems

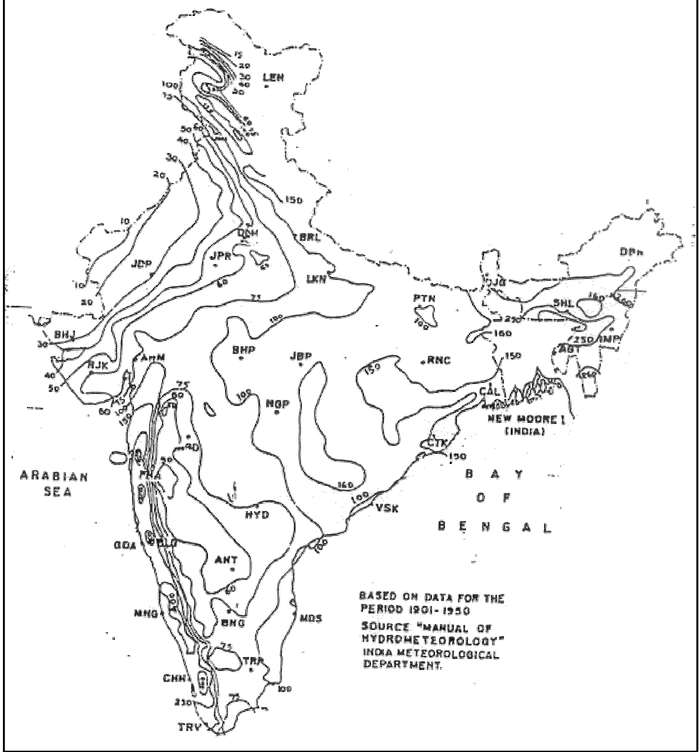
Western Disturbances as popularly known are extra tropical cyclones. These systems form over the Mediterranean Sea and move eastwards. By the time the Indian longitude is reached, they become occluded. Gujarat, the northern parts of Maharashtra and Madhya Pradesh receive light to moderate rain occasionally during winter.

Tropical Cyclones: These systems form over the central Bay of Bengal during April-May and October- November. After intensification, these move westwards across Andhra Pradesh, Tamil Nadu, Karnataka and at times Kerala. A few emerge into the Arabian Sea, intensify again and move north hitting the Gujarat or Maharashtra coast. These system cause heavy to very heavy widespread rain over several thousand square kilometre area. During the monsoon months (June to September) these systems form over the northern Bay of Bengal and being close to the coast, they remain as depressions (less severe than cyclones). After intensification, these move in north-westerly direction causing heavy and widespread rain over Orissa, Madhya Pradesh and at times Gujarat.

Monsoons: Southwest and Northeast. Some 70 to 80 % of the annual rainfall over Peninsular India occurs during the monsoon months. The Southwest monsoon onsets on 1st June over Kerala and covers other States by 7th July. The withdrawal starts from 1st September from Gujarat and the Southwest monsoon reverses to Northeast monsoon in October. It causes rainfall over Tamil Nadu and adjoining States and finally withdraws by 1st December.

Rainfall Distribution

In India, the rainfall distribution is highly variable, both in space and time. The coastal areas receive high rainfall and it decreases over the interiors. The entire west coast covering the coastal areas of Maharashtra, Karnataka and Kerala receive annual rainfall of the order of 2500 mm near the coast increasing rapidly to 4000 mm all along the western ghats, see Figure 2.1. The rainfall decreases abruptly on the lee-side of the western ghats stretching over the plateau areas on the eastern side to about 500 mm. Further eastwards, the annual rainfall increases again to about 1000 mm along the east coast of Tamil Nadu and Andhra Pradesh. The States of Orissa, Madhya Pradesh and coastal areas of south Gujarat receive annual rainfall of the order of 1500 mm, whereas the interior portion of Gujarat receives about 750 mm decreasing further to 400 mm over the extreme west. Except Tamil Nadu, all States in Peninsular India receive 80% of the annual rainfall during the Southwest Monsoon season (June to September), whereas Tamil Nadu receives 50 % of its annual rainfall during Northeast Monsoon season (October to November). In regions where annual rainfall is high, the annual coefficient of variation (Cv) of rainfall is about 10 to 20 %, whereas in regions of low annual rainfall, the Cv is high of the order of 40 to 60 %. The interiors of Gujarat and Andhra Pradesh are regions of high Cv, where the monthly Cv is about 80 %.



BASED ON DATA FOR THE PERIOD 1901-1950
SOURCE "MANUAL OF HYDROMETEOROLOGY" INDIA METEOROLOGICAL DEPARTMENT.

Figure 2.1:
Long term annual rainfall in India (in cm)

Rainfall Intensity

India Meteorological Department has brought out maps showing 50 year-short duration maximum rainfall for the country:

- the map depicting 50 Year – 1-hour maximum rainfall shows that the value of 1hour max rainfall varies from 60 to 100 mm in Peninsular India.

- 50 Year – 24-hour rainfall map, however, shows wide variations:
  - the values vary from 140 to 200 mm over the interiors of Gujarat, Maharashtra, Andhra Pradesh and north Karnataka
  - the values are 300 to 400 mm all along the coastal areas, and
  - between 200 to 300 mm over Madhya Pradesh, Chhattisgarh and adjoining areas of Gujarat, Orissa, Andhra Pradesh and Maharashtra.

2.3 EVAPORATION

Factors affecting evaporation

Evaporation occurs when water in liquid form is converted into water vapour. Evaporation from a surface depends on:

- meteorological factors, including
  - energy supply, and
  - aerodynamic parameters
- surface factors:
  - whether at the surface free water is present, or
  - if not, whether water can be transported to the surface.

At the evaporating surface energy is required to break the hydrogen bonds between the water molecules to let them escape from the surface. The energy is mainly delivered by net radiation. Occasionally, some energy is advected from the surroundings. Part of the supplied energy is used for evaporation (latent heat). Another part warms up the air (sensible heat) or is conducted into the soil or water body. Some 2% only is taken up by the plants and used for photosynthesis. Supply of energy however is not sufficient to sustain a high rate of evaporation. Aerodynamic factors like surface wind and vapour pressure difference between the surface and lower atmosphere control the conditions for transfer of water vapour away from the evaporating surface. The surface roughness affects the aerodynamic resistance to moisture transfer. Stomatal resistance apart from meteorological conditions and surface factors, largely controls transpiration from a plant surface. The latter is a function of the number and size of the stomata, and whether they are opened or closed. Stomatal resistance shows a diurnal pattern and also strongly depends on available soil moisture.

Estimating evaporation and evapotranspiration

Evaporation can be estimated directly from pan evaporation measurements, see Chapter 6. Due to exposure conditions an evaporation pan generally overestimates potential evaporation. Evaporation rates can be calculated from water balances, energy balances and by heat and mass transfer methods. By combining the energy balance and the mass transfer method Penman developed a procedure to estimate open water evaporation from measurement of simple climatic variables at 2 m above the evaporating surface. Monteith and Rijtema generalised the Penman method by including transpiration and eliminating a number of empirical factors. To obtain a proper insight into the factors affecting evaporation and evapotranspiration the Penman-Monteith approach will be dealt with. It is currently accepted as the best-performing combination method (Smith, 1990). Potential and actual evapotranspiration estimates can be computed provided aerodynamic and canopy resistances can be determined.

Penman and Penman-Monteith approach

The following evaporating surfaces are considered:

1. free water surface, and
2. cropped surface

Evaporation from a free water surface or from a wet cropped surface

Starting with the free-water surface the Penman approach considers the energy balance for an evaporating body, which reads:

$$\frac{dQ}{dt} = R_n - G - \lambda E - H + A \tag{2.1}$$

where: dQ/dt = change in stored energy per unit of time [Wm^{-2}]
R_n = net incoming radiant energy [Wm^{-2}]
G = soil energy flux density [Wm^{-2}]
λE = latent heat flux density [Wm^{-2}]
H = sensible heat flux density [Wm^{-2}]
A = air and water advected energy flux density [Wm^{-2}]

If the change in stored energy and the advected energy flux is small compared to R_n then (2.1) reduces to:

$$R_n - G = \lambda E + H \tag{2.2}$$

The latent and sensible heat fluxes are respectively given by:

$$\lambda E = \frac{\lambda \varepsilon \rho_a}{p_a} \frac{e_0 - e_2}{r_a} \quad \text{and} \quad H = c_p \rho_a \frac{T_0 - T_2}{r_a} \tag{2.3}$$

with: ε = ratio of molecular masses of water vapour and dry air (ε = 0.622 [-])
r_a = aerodynamic resistance [s/m]
p_a = atmospheric pressure [kPa]
ρ_a = density of moist air [kgm^{-3}]
e_0, e_2 = vapour pressures at the evaporating surface (z=0) and at 2 m above the ground
T_0,T_2 = temperatures taken at the same levels as the vapour pressure is considered
c_p = specific heat of dry air at constant pressure [$Jkg^{-1}{}^{\circ}C^{-1}$]

The rate of transfer of water vapour and sensible heat away from the surface by turbulent diffusion is controlled by the aerodynamic resistance r_a, which is inversely proportional to the wind speed and changes with height of the surface roughness:

$$r_a = \frac{\ln[(z_u - d)/z_{0m}]\ln[(z_e - d)/z_{0v}]}{\kappa^2 u_z} \tag{2.4}$$

where: z_u = height at which the wind velocity is measured [m]
z_e = height at which the humidity is measured [m]
d = displacement height [m]
z_{0m} = roughness length for momentum [m]
z_{0v} = roughness length for water vapour [m]
κ = Von Karman constant [-], κ = 0.41
u_z = wind velocity measured at height z = 2 m above the evaporating surface [m/s]

Note that at height z = d + z_0 the wind velocity is zero.

Now the essence of the Penman method is the replacement of the surface temperature T_0 in the expression for the sensible heat, which is generally unknown. Consider the Bowen ratio (1.14) and the equations (2.3) and (1.12):

$$\beta = \frac{H}{\lambda E} = \frac{c_p \rho_a}{\varepsilon \lambda} \frac{T_0 - T_2}{e_0 - e_2} = \gamma \frac{T_0 - T_2}{e_0 - e_2} \tag{2.5}$$

Since the evaporating surface z = 0 considered here is a free-water surface, e_0 is the saturation vapour pressure $e_{s,0}$. The saturation vapour pressure at z = 2 m is denoted by $e_{s,2}$. The slope of the saturation vapour pressure curve taken at T_2 reads:

$$s = \frac{de_{s,2}}{dT_2} \approx \frac{e_{s,0} - e_{s,2}}{T_0 - T_2} \tag{2.6}$$

Hence:

$$T_0 - T_2 = \frac{e_{s,0} - e_{s,2}}{s} \tag{2.7}$$

So, the Bowen ratio becomes:

$$\frac{H}{\lambda E} = \frac{\gamma}{s}\left(\frac{e_{s,0} - e_{s,2}}{e_{s,0} - e_2}\right) = \frac{\gamma}{s}\left(1 - \frac{e_{s,2} - e_2}{e_{s,0} - e_2}\right) = \frac{\gamma}{s}\left(1 - \frac{\lambda E_a}{\lambda E}\right) \text{ where: } \lambda E_a = \frac{\lambda \varepsilon \rho_a}{p_a} \frac{(e_{s,2} - e_2)}{r_a} \tag{2.8}$$

The quantity E_a is called the isothermal evaporation. Now substituting (2.8) in (2.2) results in Penman equation for open water, which is also valid for wet crops:

$$\lambda E = \frac{s}{s+\gamma}(R_n - G) + \frac{\gamma}{s+\gamma}\lambda E_a \quad \text{or} \quad E = \frac{1}{\lambda} \frac{s(R_n - G) + c_p \rho_a (e_{s,2} - e_2)/r_a}{s+\gamma} \tag{2.9}$$

By writing equation (2.9) as:

$$\lambda E = c_1 (R_n - G) + c_2 \lambda E_a \quad \text{with: } c_1 = \frac{s}{s+\gamma} \quad \text{and: } c_2 = \frac{\gamma}{s+\gamma} = 1 - c_1$$

It is observed that the evaporation is described as a function of the net radiation (corrected for the soil energy flux) and of the saturation deficit at the measuring height above the surface. The value of the coefficient c_1 is shown in Figure 2.2.

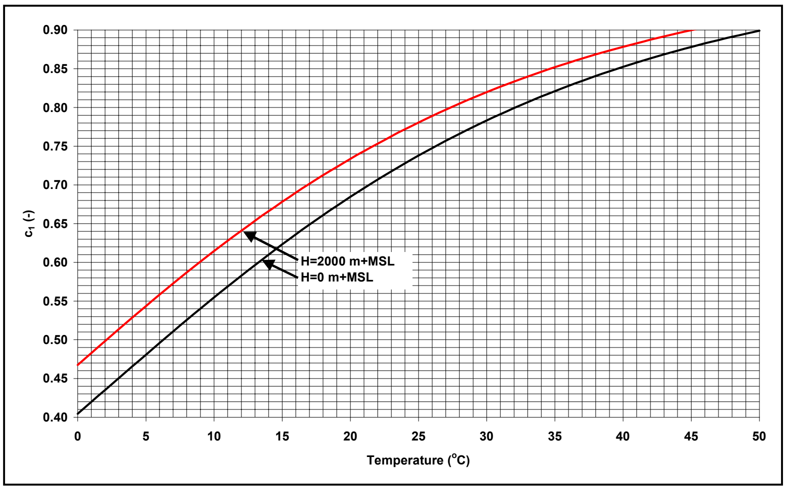


Figure 2.2:
$c_1 = s/(s+\gamma)$ as a function of temperature at 0 and 2000 m elevation under standard conditions (p_a = 101.3 kPa at MSL)

Note that c_1 is generally larger than c_2 except at low temperatures. It implies that even with 100% humidity, i.e. when $\lambda E_a = 0$, there is still considerable evaporation possible as it is the vapour pressure difference between layers rather than the saturation deficit at a layer that controls the evaporation. This may also be seen from the sensible heat flux density H for which it follows:

$$H = c_2(R_n - G - \lambda E_a)$$

Hence, though with $\lambda E_a = 0$ the energy used to heat up the air increases, still usually the larger part of the net radiation input is used for evaporation as generally $c_1 > c_2$.

Note that equation (2.9) is a generalisation of the original Penman formula. All empirical factors have been removed from the original equation. Two situations are distinguished:

- for open water, $E = E_0$ and r_a is computed with $d = 0$ and $z_0 = z_{0m} = z_{0v} = 2 \times 10^{-4}$ m
- for a wet cropped surface, $E = E_p$; here r_a is computed with $d = 0.67$ h, where h is the height of the crop, $z_{0m} = 0.123$ h and $z_{0v} = 0.1\ z_{0m}$.

The aerodynamic resistance as a function of wind speed for open water and vegetation height is presented in Figure 2.3.

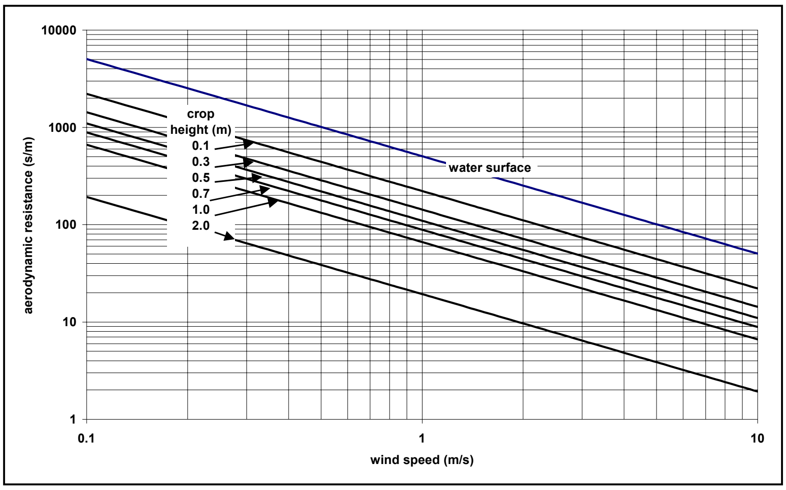


Figure 2.3:
Aerodynamic resistance as a function of wind speed for open water and vegetated surfaces.

It is observed that the aerodynamic resistance above a smooth water surface is larger than above a crop. So, for the same wind speed, temperature and humidity, the isothermal evaporation E_a for the latter surface will generally be larger. Whether this means that the potential evaporation from a densely cropped surface is larger than from open water depends also on the net radiation input (albedo) and the energy loss to the subsurface.

The values of E_0 and E_p emanating from (2.9) are in [$\text{kgm}^{-2}\text{s}^{-1}$]. To convert this to evaporation in mm/day note that $\rho_w = 1000\ \text{kgm}^{-3}$. Hence 1 kg corresponds with $10^{-3}\ \text{m}^3$. So:

$$1\frac{\text{kg}}{\text{m}^2\text{s}} = 1\frac{10^{-3}\text{m}^3}{\text{m}^2\text{s}} = 1\frac{\text{mm}}{\text{s}} = 3600\frac{\text{mm}}{\text{hr}} = 86400\frac{\text{mm}}{\text{day}}$$

According to Shuttleworth (1992) the magnitude of the daily soil heat flux over 10 to 30-day periods is relatively small and is therefore often neglected in hydrological studies. Heat transfer to depth in a water body is by conduction and thermal convection, and by the penetration of radiation below the surface. Where the temperature shows a large variation through the year this factor may be of importance.

Van Bavel (1966) showed that the Penman equation gives reliable estimates of daily evaporation when based on **measured** daily radiation and average daily values for temperature, humidity and wind speed. Use of empirical radiation equations was found to lead to substantial errors if not properly calibrated on the local situation.

EXAMPLE 2.1
Computation of potential evapotranspiration with the Penman equation (2.9)

The potential evapotranspiration is determined for a field crop of 0.30 m height at latitude 20°N on 21 June at midday for a clear sky. At 2 m above the surface the air temperature is 30°C, the wind speed is 3 m/s and the relative humidity amounts 50%. The albedo for the cropped surface is 0.25. The air pressure = 100 kPa.

1. Determination of the model parameters and vapour pressure.
    - Saturation vapour pressure e_s is calculated from equation (1.7) with air temperature T_a = 30°C:

$$e_s = 0.6108\exp\left(\frac{17.27T_a}{T_a + 237.3}\right) = 0.6108\exp\left(\frac{17.27x30}{30 + 237.3}\right) = 4.243\ \text{kPa}$$

    - Actual vapour pressure ea is found from equation (1.10) applying a relative humidity rh =0.5:

      $e_a = r_h$ x e_s = 0.5 x 4.243 = 2.122 kPa

    - Slope of the saturation vapour pressure curve s follows from equation (1.8):

$$s = \frac{4098e_s}{(237.3 + T_a)^2} = \frac{4098x4.243}{(237.3 + 30)^2} = 0.243\ \text{kPa}/^oC$$

    - Density of moist air ρa can be estimated from equation (1.3) with pa = 100 kPa and Ta=30oC:

$$\rho_a \approx \frac{p_a}{0.287(T_a + 275)} = \frac{100}{0.287(30 + 275)} = 1.142\ \text{kg/m}^3$$

    - Latent heat of vaporisation λ follows from equation (1.13) with T_a=30°C:

$$\lambda = 2501 - 2.361T = 2501 - 2.361x30 = 2430\ \text{kJ / kg}$$

    - Psychrometric constant γ, calculated from equation (1.12) with c_p = 1.005 kJ/kg/°C, p_a = 100 kPa and λ = 2430 kJ/kg:

$$\gamma = \frac{c_p p_a}{\varepsilon\lambda} = \frac{1.005x100}{0.622x2430} = 0.0665\text{kPa}/^oC$$

    - Weights of the radiation and isothermal evaporation components in the Penman equation: s/(s+γ) and γ/(s+γ):

$$\frac{s}{s+\gamma} = \frac{0.243}{0.243 + 0.0665} = 0.785 \text{ and } \frac{\gamma}{s+\gamma} = 1 - \frac{s}{s+\gamma} = 1 - 0.785 = 0.215$$

2. Determination of the net radiation component, assuming that the soil energy flux density G ≈ 0.
    - The net radiation flux density R_n is computed by (1.18) as the sum of the net solar radiation flux density S_n and the net terrestrial flux density or net long wave radiation L_n:

      $R_n = S_n + L_n$ = = 789 – 66 = 747 W/m^2 = 0.723 kW/m^2 as elaborated below.

    - Since no direct measurements of the net solar radiation flux density S_n is available it is calculated from equation (1.16), with albedo α = 0.25 and n/N = 1 in view of the clear sky. The coefficients a and b in (1.16) are estimated by a = 0.29 cosϕ, where ϕ = latitude, and b=0.52. The extraterrestrial radiation will be equal here to the solar constant R_A=1367 W/m^2 as the sun is almost sheer above the crop at noon on 21 June at latitude 20°N (Tropic of Cancer = 23.5°N), adjusted for eccentricity of the earth rotation around the sun, which is for that date 0.967. It follows:

$$S_n = (1 - \alpha)(a + b\frac{n}{N})R_A = (1 - 0.25)(0.29x\cos(20) + 0.52x1)x0.967x1367 =$$

$$= 0.75x(0.276 + 0.52)x0.967x1367 = 789\text{W/m}^2$$

    - The net long-wave radiation L_n is computed from (1.17), with T_A = 273.15 + Ta, e_a and n/N given above:

$$L_n = -\sigma T_A^4(0.34 - 0.139\sqrt{e_a})(0.1 + 0.9\frac{n}{N})$$

$$L_n = -5.6745x10^{-8}(30 + 273.15)^4(0.34 - 0.139\sqrt{2..122})(0.1 + 0.9x1) = -66\text{W/m}^2$$

3. Determination of the isothermal evaporation λEa, according to (2.8).

   - The aerodynamic resistance is calculated from (2.4), with d = 0.69h, z_{0m}=0.123h and z_{ov}=0.1z_{0m} and h is the crop height, h = 0.30 m:

$$r_a = \frac{\ln(\frac{z_u - d}{z_{0m}})\ln(\frac{z_u - d}{z_{0v}})}{k^2 u_z} = \frac{\ln(\frac{2-0.67x0.30}{0.123x0.3})\ln(\frac{2-0.67x0.30}{0.1x0.123x0.3})}{0.41^2 x3} = 48s/m$$

   - The isothermal evaporation then follows from:

$$\lambda E_a = \frac{\lambda\varepsilon\rho_a}{p_a}\frac{(e_{s,2} - e_2)}{r_a} = \frac{2430x0.622x1.142}{100}\frac{(4.243 - 2.122)}{48} = 0.763kW/m^2$$

4. The potential evapotranspiration in mm/hr at midday is finally computed from (2.9), with G ≈ 0:

$$\lambda E = \frac{s}{s+\gamma}(R_n - G) + \frac{\gamma}{s+\gamma}\lambda E_a = 0.785x(0.723 - 0) + 0.215x0.763 = 0.732kW/m^2$$

$$E = \frac{\lambda E}{\lambda} = \frac{0.732}{2430}\square\frac{kW/m^2}{kJ/kg} = 3.01x10^{-4}\frac{kJ/(s.m^2)}{kJ/kg} = 3.01x10^{-4}\frac{kg}{s.m^2} = 3.01x10^{-4}\frac{mm}{s} = 1.08\frac{mm}{hr}$$

Evapotranspiration from dry cropped surface

Montheith extented equation (2.9) to include also transpiration from a crop by introducing another resistance factor: the canopy resistance. The concept of the approach is that the vapour follows two paths in series:

- from the sub-stomatal cavity (see Figure 2.4) to the leaf surface, where the vapour encounters canopy resistance r_c, and
- from the leaf surface to the external air where the measurements are taken at z = 2 m, where the vapour encounters the aerodynamic resistance r_a as before.

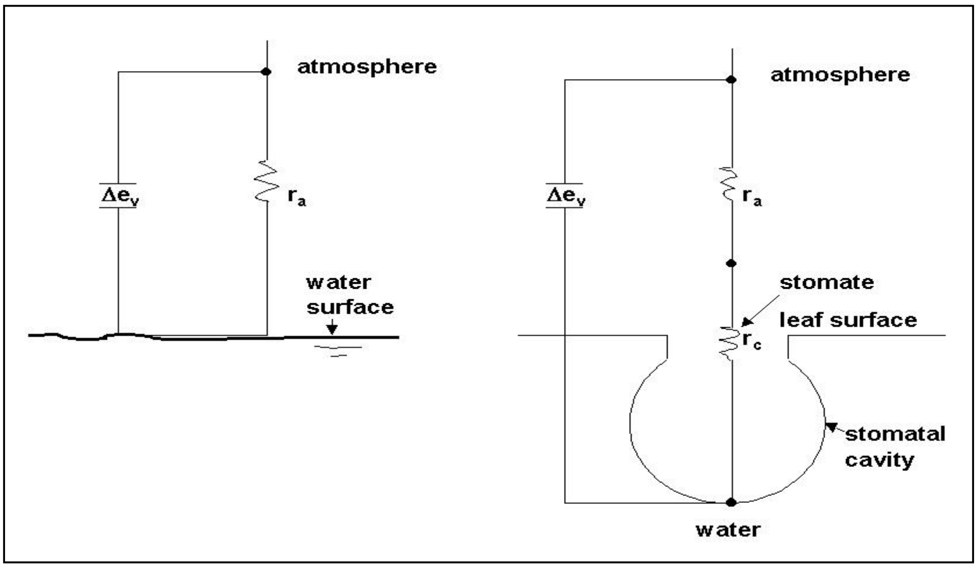


Figure 2.4: Canopy and aerodynamic resistance (adapted from Dingman, 2002)

Hence, instead of a transport resistance of r_a in the case of a saturated surface the total vapour transport resistance becomes now $r_c + r_a$. The air within the cavities is considered to be saturated at the leaf surface temperature $e_{s,ols}(T_s)$. Vapour escapes via the stomata through the outer leaf surface, where a lower pressure e_{ols} exists, which is assumed to be approximately equal to the saturation vapour pressure at T_2. Then λE in (2.3) can be extended as follows:

$$\lambda E = \frac{\lambda\varepsilon\rho_a}{p_a}\frac{(e_{s,ols} - e_{ols})}{r_c} = \frac{\lambda\varepsilon\rho_a}{p_a}\frac{(e_{ols} - e_2)}{r_a} = \frac{\lambda\varepsilon\rho_a}{p_a}\frac{(e_{s,ols} - e_2)}{r_c + r_a} \quad (2.10)$$

Substitution of (2.10) in the Bowen ratio (2.5) gives:

$$\beta = \frac{H}{\lambda E} = \frac{c_p p_a}{\varepsilon\lambda}\frac{r_c + r_a}{r_a}\frac{T_{ols} - T_2}{e_{s,ols} - e_2} = \gamma^* \frac{T_{ols} - T_2}{e_{s,ols} - e_2} \quad \text{where :} \quad \gamma^* = \gamma(1 + \frac{r_c}{r_a}) \quad (2.11)$$

Note that the level of the outer leaf surface “ols” replaces the “0” level used in (2.5). The rest of the derivation runs along similar lines as presented above. So, finally the following general Penman-Monteith evapotranspiration formula is obtained:

$$E = \frac{1}{\lambda}\frac{s(R_n - G) + c_p\rho_a(e_{s,2} - e_2)/r_a}{s + \gamma(1 + r_c/r_a)} \quad (2.12)$$

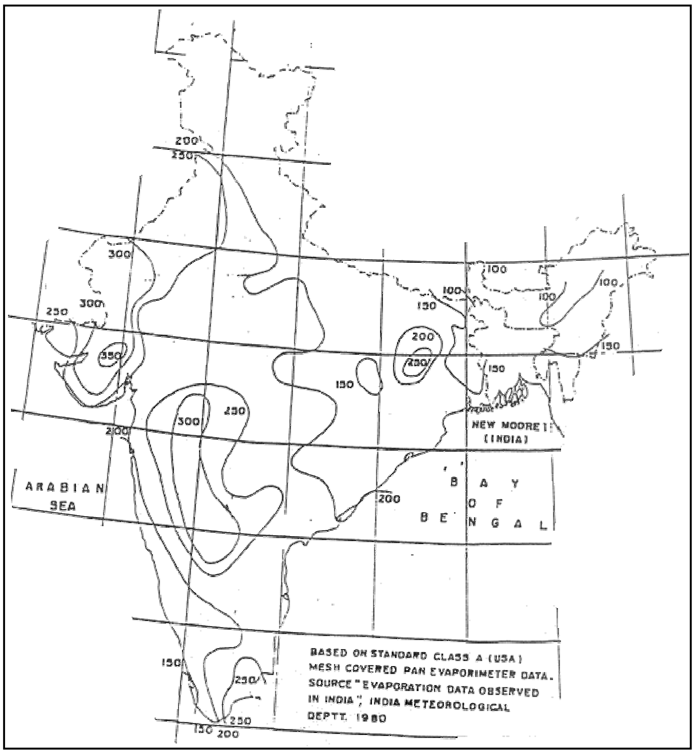
From (2.12) it is observed that with r_c =0 equation (2.9) for a evaporation from a free-water surface or a wetted crop is obtained. Feddes et. al., (1994) mention that the canopy resistance for a dry crop, completely covering the ground, has a non-zero minimum value if the water supply from the root-zone is optimal (potential evapotranspiration conditions!). For arable crops this minimum value is r_c = 30 s/m; that for a forest is about 150 s/m. The canopy resistance is a complex function of incoming solar radiation, water vapour deficit and soil moisture. With (2.12) in principle potential as well as actual evapotranspiration can be determined.

The **reference crop evapotranspiration** is now defined as “the evapotranspiration from a hypothetical crop fully covering the ground, no short of water, with an assumed crop height of 12 cm, a fixed canopy resistance of 70 s/m, and a canopy reflection coefficient of 0.23”. For a standard measuring height it then follows:

$r_a = 208/u_2$ and $r_c/r_a = 0.337u_2$.

Potential evapotranspiration from other cropped surfaces could be calculated with minimum values of r_c.

The spatial variation of evaporation in India is observed from Figure 2.5. It is noted that this refers to pan-evaporation. Hence, potential evapotranspiration values will be in the order of 70% of the values displayed in the figure.



BASED ON STANDARD CLASS A (USA) MESH COVERED PAN EVAPORIMETER DATA. SOURCE "EVAPORATION DATA OBSERVED IN INDIA", INDIA METEOROLOGICAL DEPTT. 1980

Figure 2.5:
Average annual pan-evaporation (in cm)

2.4 CLIMATIC VARIABLES FOR EVAPORATION ESTIMATION

Radiation

The main source of energy of the earth's surface and the atmosphere is the solar radiation. One part of the sun's radiation is direct and the other part is diffuse. The sum total is the short wave radiation. On the day when the sky is clear, major part of the reflected radiation (long wave) escapes through the atmosphere. The net radiation (incoming – outgoing) is maximum during summer months and minimum during winter months. In the Indian region net annual radiation varies from 9250 kW/m^2/day to 6920 kW/m^2/day if one moves from 5^o N to 40^o N.

Temperatures

The mean maximum temperature during summer months (March to May) ranges between 32 to 35 degree Celsius over coastal areas. It increases gradually over the interiors ranging from 40 to 45 ^oC. Extreme temperatures exceeding 45 ^oC are occasionally experienced in Andhra Pradesh, Madhya Pradesh, Maharashtra and Gujarat. The mean minimum temperature during winter months (December-February) ranges from 10 to 15 ^oC over Gujarat, Madhya Pradesh, interiors of Maharashtra and Orissa. It ranges between 15 to 20 ^oC Andhra Pradesh, Karnataka and coastal Orissa and Maharashtra. It is about 22.5 ^oC over Tamil Nadu and Kerala.

Humidity

During summer (March to May) the humidity varies from 40 to 60 % over the coastal areas and 20 to 40 % over the interiors. During the monsoon months (June to September and for Tamil Nadu- October November) the humidity ranges between 70 to 80 % over the interiors and 90 to 100 % over the coast. During winter (January to February) the humidity ranges between 60 to 80 % in the morning hours and gradually decreasing to 40 - 60 % by afternoon.

Surface Wind

During winter the surface wind generally remains light easterly to north-easterly. During summer it is light variable in the morning, changing to westerly along the west coast and easterly along the east coast and interiors. During monsoon months the surface wind is generally westerly to south-westerly and quite strong. It is north-easterly over Tamil Nadu (October-November).

Variation of potential evapotranspiration

As is observed from Figure 2.5 annual pan-evaporation varies from 1500 in the Western Ghats to 3500 mm in parts of Gujarat. This implies that potential evapotranspiration varies between 1000 and 2500 mm, using a pan coefficient of 0.7. The potential evapotranspiration value is highest during April-May and lowest during the monsoon season.

3 NETWORK DESIGN AND OPTIMISATION

3.1 INTRODUCTION

General considerations

A monitoring network is based upon two considerations, namely:

- the monitoring objectives, and
- the physical characteristics of the systems to be monitored.

The identification of the monitoring objectives is the first step in the design and optimisation of monitoring systems. Related to this is the identification of the potential data users and their future needs. If there is more than one objective, priorities need to be set. Identification of monitoring objectives is also important because they determine the scale of changes to be detected in the data, the kind of information to be extracted from the data and therefore the way the data are analysed.

The analysis of the data, obtained from the network, is also determined by the dynamics of the measured processes. The physical basis of the relevant processes must be known in order to be able to make preliminary guesses of the scale of the variability with respect to space and time.

To enable an optimal design of a monitoring network, a measure is required, which quantifies the effectiveness level. Which measure is adequate depends on the monitoring objectives. Often, this measure is related to statistical concepts like errors in areal estimates, interpolation error, trend detectability, etc., and can be formulated as a function of:

- sampling **variables** (what),
- sampling **locations** (where),
- sampling **frequencies** (when), and
- sampling **accuracy** (with what) (i.e. technique/equipment).

These aspects also determine the cost of establishing and running of the network, like the costs related to land acquisition, station construction, equipment procurement and installation, station operation, maintenance, data processing and storage and staffing of field stations and data centres. Once the relationship between the chosen effectiveness measure and costs have been established, the optimal network can be found, in principle, by weighing the two in a cost – effectiveness analysis.

It is stressed that once the network is operational, it has to be evaluated regularly to see whether (revised) objectives still match with the produced output in a cost-effective manner. A network, therefore, is to be seen as a **dynamic system** and should never be considered as a static entity. This requires some flexibility in establishing new stations and closing down others.

Types of networks

It is necessary to distinguish between the following network levels:

- **basic** or **primary** network, with a low network density, where measurements are continued for a long period of time,
- **secondary** network, with a density supplementary to the basic network to meet accuracy demands, and where stations are kept operational for a shorter period of time,
- **dedicated** networks, put in place for a certain project, where the project objectives determine the network density and period of operation, and
- networks for **representative basins**, to study certain phenomena in detail.

Despite the necessary flexibility in the network layout as stipulated above, part of the network should have a permanent character, to ensure that some basic information be gathered continuously. The network used/maintained by IMD can be considered as the primary or basic network. This network has a large coverage, though the density is limited and it is in operation for a long period of time.

In addition to that network, stations may be established to better cope with the spatial variability of the observed variable. Once sufficient data have been collected from the secondary network to be able to establish relations with the primary stations, the added value of keeping the secondary stations operational should be re-examined. This is particularly so, if one is interested in reliable long term mean monthly, seasonal or annual values rather than in each individual value. Spatial correlation reduces the information content in a set of data from the network taken at a particular moment in time. For variables like rainfall, where any temporal correlation is fairly non-existing, one more year of data adds on much more information to the data set to compute some long-term average than one extra station does in case of non-zero spatial correlation.

The concept of representative basins is particularly useful when phenomena have to be studied in detail. The representativeness in this case particularly refers to the hydro-meteorological boundary conditions. Small basins may be selected to study e.g. the spatial and temporal variability of short duration rainfall for design purposes.

Integration of networks

In the Hydrological Information System the following networks are operational:

- hydro-meteorological network of rainfall and full climatic stations,
- hydrometric network,
- surface water quality network,
- geo-hydrological network, and
- groundwater quality network.

These networks are operated by various State and Central agencies. To avoid duplication of work and to reduce cost, the networks operated by the various agencies have to be integrated, technically and organisationally.

The hydro-meteorological network has to be considered in conjunction with the surface water and groundwater networks. The former should have sufficient spatial coverage so that all discharge stations in the hydrometric network are fully covered. This means that dependent on the objectives, rainfall-runoff computations can be made or water balances can be established. Similar water balance and resource assessment considerations apply also for the hydro-meteorological network in relation to the groundwater network.

Organisational integration of the networks implies that the networks are complimentary and that regular exchange of field data takes place to produce authenticated data of high quality. Review of the networks is also to be done in close collaboration.

Steps in network design

The sequence of steps to be carried out for network review and redesign include:

Institutional set-up: review of mandates, roles and aims of the organisations involved in the operation of the HIS. Where required, communication links should be improved to ensure co-ordination/integration of data collection networks.

Data need identification: with the aid of the questionnaire ‘Data needs assessment’ presented in the Part III of Volume I, Field Manual, Hydrological Information System, the existing and potential future data users have to be approached to review their data needs.

Objectives of the network: based on the outcome of the previous step a Hydrological Information Need (HIN) document is to be prepared which lists out a set of objectives in terms of required network output. The consequences of not meeting the target are to be indicated.

Prioritisation: a priority ranking among the set of objectives is to be made in case of budget constraints.

Network density: based on the objectives, the required network density is determined using an effectiveness measure, taking in view the spatial (and temporal) correlation structure of the variable(s).

Review of existing network: reviewed are the existing network density versus the required one as worked out in the previous step, the spreading of the stations in conjunction with the hydrometric and groundwater network, the available equipment and its adequacy for collecting the required information, and the adequacy of operational procedures and possible improvements. Deficiencies have to be reported upon.

Site and equipment selection: if the existing network is inadequate to meet the information demands, additional sites as well as the appropriate equipment have to be selected.

Cost estimation: costs involved in developing, operating and maintaining the existing and new sites as well as the data centres have to be estimated.

Cost-effectiveness analysis: cost and effectiveness are compared. The last four steps have to be repeated in full or in part if the budget is insufficient to cover the anticipated costs.

Implementation: once the network design is approved, the network is to be implemented in a planned manner, where execution of civil works, equipment procurement and installation and staff recruitment and training is properly tuned to each other. The use of HIDAP is a necessity.

The network has to be **reviewed** after 3 years or at a shorter interval if new data needs do develop. The above listed procedure should then be executed again.

3.2 RAINFALL NETWORK

3.2.1 MEASURING OBJECTIVES

The major uses of rainfall data are generally for:

- water resources planning,
- design,
- management, and
- research.

Water resources planning requires generally long historical series of areal monthly, seasonal or annual data. Often, one is only interested in the long-term mean value of areal rainfall. For assessment of dependable amounts of rainfall its variability is also required, either for a particular month or season in the year or for sequential months/seasons. For network design, it is of importance to know, which statistical parameter(s) has (have) to be estimated and with what accuracy. Given the variability in space and time, this determines the number of stations required in the network and the duration of the measurements.

For design of structures, generally, statistics of short duration rainfall (e.g. quarterly, hourly or daily) have to be estimated. Rather than focussing on the average amounts, here the interest is particularly on the extremes and on the areal extent of extreme rainfall. The spatial correlation structure of short duration rainfall (minutes, hours or days) differs generally much from the same of long duration rainfall data as discussed for planning. This feature has important consequences not only for the required network density, but also for the type of equipment to be used for rainfall measurement.

Management requires less historical data. Here the interest is particularly in data on a real time basis for operational purposes, like reservoir operation and flood forecasting. Historical data are here required for the design of rule curves and operational strategies and for model development. The provision of real-time data is not yet an objective of the Hydrological Information System.

Research needs intensive data, to improve the understanding of certain processes or phenomena. The research generally concentrates on small river or water resources management systems. The type of data required for research varies from study to study, but is often comparable with the requirements for design.

From the above it follows, that different objectives lead to different information needs, and, given the variation of the spatial correlation structure of rainfall with duration, to different network densities as will be shown in the next few sub-sections, unless concessions are made towards the required accuracy.

3.2.2 MEASURE OF EFFECTIVENESS

Based on the analysis presented in the previous sections, the objective of the rainfall network should be to give reliable estimates of areal rainfall for areas commensurate with the hydrometric network. The latter condition stems from the need of integration of the networks. The stream gauge density in the plains is approximately one gauge per 2,000 km^2 and one per 1,000 km^2 in the hilly areas. Upstream of every stream gauging station sufficient rain gauges should be available to estimate the areal rainfall with a specified accuracy.

With respect to areal rainfall the interest is in:

- individual areal estimates, and/or
- long term mean values.

Due to the presence of spatial correlation among the point rainfall stations and (near) absence of serial correlation, (see sketch below) these objectives will lead to different networks and duration of operation. If spatial correlation would be absent then each point rainfall data in time or in space would equally contribute to the improvement of the long term mean areal rainfall estimate, provided the rainfall field is homogeneous. However, correlation reduces the effective number of data, since information in one is to some extent already included in others. Hence, due to the spatial correlation data points in time are more effective then data points in space to improve the long term areal mean. Or in other words: a less dense network operated for a longer period of time is more cost-effective than a denser network providing the same number of point rainfall data points. A reduction in the density of the network, however, adversely affects the quality of the individual areal estimates possibly to an unacceptable level. The latter is better served with a higher density, though this in turn may be sub-optimal for estimating the long term mean but is certainly not harmful.

$\longrightarrow$ number of stations N

$$\begin{array}{lllll}
h_{1,1} & h_{1,2} & h_{1,3} \ldots\ldots\ldots h_{1,N} & & \text{year 1} \\
h_{2,1} & h_{2,2} & h_{2,3} \ldots\ldots\ldots h_{2,N} & & \text{year 2} \\
h_{3,1} & h_{3,2} & h_{3,3} \ldots\ldots\ldots h_{3,N} & & \text{year 3} \\
h_{n,1} & h_{n,2} & h_{n,3} \ldots\ldots\ldots h_{n,N} & & \text{year n}
\end{array}$$

Figure 3.1:
Data matrix nxN of n years of data at N stations

(data $h_{i,1}$ to $h_{i,N}$, spatially correlated)
(data $h_{1,j}$ to $h_{n,j}$, serially not correlated)

For most hydrological purposes the objective of the rainfall network should be to provide reliable estimates of **individual** events of areal rainfall of a **particular duration**, like a duration of an hour, day, month or season. It implies that the uncertainty in each element of the areal rainfall series, estimated from point rainfall data, should not exceed a certain value. This is particularly so for the network in use for the Hydrological Information System, where various users have to be served with different objectives. A measure for the quality of the areal rainfall data is the mean square error of the estimate. Hence, the **root mean square error in estimating the areal rainfall of a particular duration**, expressed as a percentage of the average rainfall in an area is an appropriate **measure for the effectiveness** of the network.

3.2.3 SPATIAL CORRELATION OF RAINFALL

The required network density depends a.o. on the spatial correlation between point rainfall data. The spatial correlation structure of rainfall data in spatially homogeneous areas is usually well described by an exponential relation of the following type:

$$r(d) = r_0 \exp(-d/d_0) \qquad (3.1)$$

where: $r(d)$ = correlation coefficient as a function of distance
d = distance
r_0 = correlation coefficient at d = 0
d_0 = characteristic correlation distance: if $d = d_0$, $r(d_0) = r_0e^{-1} = 0.368\ r_0$

The parameters r_0 and d_0 are determined from the correlation coefficients between the point rainfall series available in the basin for that particular duration or interval (e.g. series of August rainfall of sequential years). The estimation of the correlation coefficients is discussed in Chapter 3 of Volume 2, Design Manual, Sampling Principles. The correlation coefficients are presented as a function of the distance between the various sites. Hence, equation (3.1) represents the average correlation structure of the rainfall for the considered duration over the number of years considered, and the structure for an individual event (hourly, daily or monthly totals, etc.) may deviate from this.

The parameter r_0 is generally less than 1 due to random errors in the point rainfall data and microclimatic irregularities in the region. If the true rainfall at a point is h^* and the measured value h then the random error in the point rainfall ε is defined by:

$$\varepsilon = h - h^* \quad \text{with} \quad E[\varepsilon] = 0 \quad \text{and} \quad \sigma_\varepsilon^2 = E[(h - h^*)^2] \qquad (3.2)$$

Note that $E[\varepsilon]=0$ implies unbiased estimates, which means that ε does not represent the systematic errors in the rainfall data due to wind, etc; the series are assumed to be corrected for this. The following relation for r_0 as a function of the error variance σ_ε^2 and the variance of the point rainfall process σ_h^2 can be derived (de Bruin, 1977):

$$r_0 = 1/(\sigma_\varepsilon^2 / \sigma_h^2 + 1) \approx 1 - \sigma_\varepsilon^2 / \sigma_h^2 \tag{3.3}$$

The right hand side approximation in equation (3.3) is valid only for $\sigma^2_\varepsilon / \sigma^2_h < 0.25$. In practice, for r_0 generally values in the range of $0.8 < r_0 \leq 1$ are found.

The characteristic correlation distance d_0 for convective storms is much smaller than for frontal systems. Further, for short duration rainfall the spatial extent of correlation tends to be larger for heavier storms (Upadhyay, 1995). Generally, d_0 increases if the time interval becomes larger; e.g. d_0 for monthly series is larger than for daily series, and, in general, for annual series d_0 is larger than for monthly series.

An example of spatial correlation structures for monthly and annual series is shown in Figure 3.1, where data of the Tel basin, a sub-basin of Mahanadi in Orissa, is displayed. The figure shows r_0 values ranging from 0.85 to 0.975, whereas d_0 for the monthly values ranged from 125 to 150 km and d_0 for annual data amounted 200 km. (For details reference is made to Volume 3, Reference Manual, Hydro-meteorology)

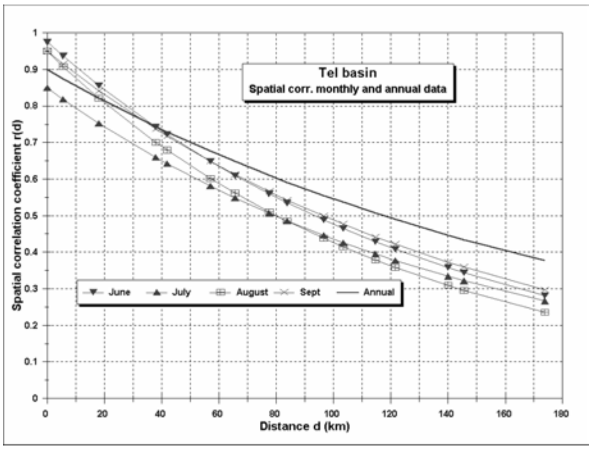


Figure 3.1: Spatial correlation functions for monthly and annual rainfall data in Tel basin

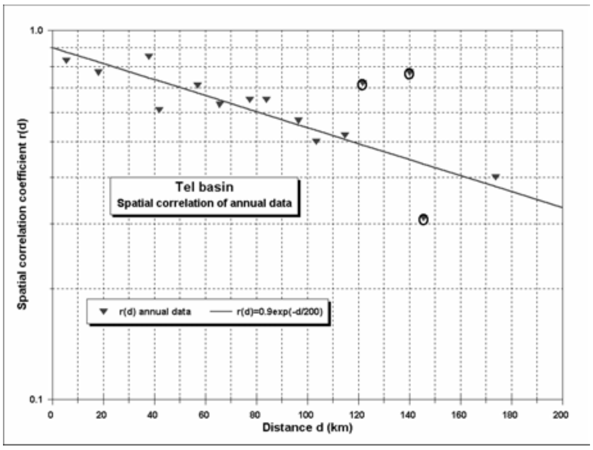


Figure 3.2: Example of correlation function fitting

Some **practical aspects** in estimating the spatial correlation function are mentioned here:

- The individual correlation coefficients, plotted as a function of distance, generally show a large scatter. To create some order in the scatter, average correlation coefficients for distance-intervals are determined.
- To estimate the parameters r_0 and d_0 either a manual approach is used by plotting the entries on semi-log paper, drawing a straight line through the points and read r_0 and d_0 from the plot at d=0 and r(d)=0.37, respectively, or a least squares approach is applied on ln(r(d)) versus distance d.
- In estimating the parameters r_0 and d_0 often entries have to be discarded from the data set, particularly when the least squares approach is used, as outliers may disturb the estimation too much. An example is given in Figure 3.2, where the encircled data points were left out of the analysis.

- Spatial homogeneity in the rainfall field has been assumed. Orographical effects or other types of inhomogeneity have first to be eliminated from the point rainfall data series. For this, reference is made to the Data Processing Manual.

3.2.4 STANDARD ERROR OF AREAL RAINFALL ESTIMATE

Let the true areal rainfall in a basin be denoted by h^*_A and its estimate, based on N point rainfall values, by h_A, then the error R in estimating h^*_A reads:

$$R = h_A - h^*_A \tag{3.4}$$

If h_A is an unbiased estimate of h^*_A then the mean square error is the error variance σ^2_R:

$$\sigma^2_R = E[(h_A - h^*_A)^2] \tag{3.5}$$

Further, let the (time) average rainfall be denoted by h_{av}, then the root mean square error Z_{areal} in estimating the areal rainfall, expressed as a fraction of h_{av}, is defined by:

$$Z_{areal} = \frac{\sigma_R}{h_{av}} \tag{3.6}$$

This relative root mean square error is equivalent to the relative standard error. As will be elaborated below, the relative root mean square error is a function of:

- the coefficient of variation of the point rainfall **time** series,
- the **spatial** correlation structure of the rainfall field,
- the **size** of the basin for which an areal estimate has to be made, and
- the **number** of point rainfall data considered in estimating the areal rainfall.

Let there be N rain-gauge stations in a basin with area S, equally distributed over the basin. The rainfall in the basin is statistically homogeneous. The areal rainfall over S, h_A, is estimated as the arithmetic average of the observations at the N point rainfall stations:

$$h_A = \frac{1}{N}\sum_{i=1}^{N} h_i \tag{3.7}$$

where: h_i = point rainfall observed at gauge station i.

Kagan (1972) showed that the error variance σ^2_R in the areal rainfall estimate for the entire area S, when h_A is estimated by equation (3.7), follows from (see also Chapter 6 of Volume 2, Design Manual, Sampling Principles):

$$\sigma^2_R = \sum_{i=1}^{N} \frac{1}{N^2}\sigma^2_{R,i} = \frac{\sigma^2_h}{N}\left(1 - r_0 + \frac{0.23}{d_0}\sqrt{\frac{S}{N}}\right) \tag{3.8}$$

If the coefficient of variation of a rainfall series at any fixed point in S is denoted by Cv= σ_h/h_{av} then, by substituting equation (3.8) in (3.6), the standard error in the areal rainfall over S, expressed as a fraction of the (time) average rainfall, finally becomes:

$$Z_{areal} = \frac{\sigma_R}{h_{av}} = Cv\sqrt{\frac{1}{N}\left(1 - r_0 + \frac{0.23}{d_0}\sqrt{\frac{S}{N}}\right)} \tag{3.9}$$

By stating the permissible value of Z_{areal}, one obtains an estimate for the required minimum number of stations N in a basin with area S. Typical values for Z_{areal}, given as a percentage, are 5 or 10%. Note that when making water balances, the errors in the various components have to be judged. Errors in the river discharge are in the order of 5-10%, hence a similar error for rainfall should be acceptable. With respect to Z_{areal} some further remarks are made here:

- It should be recalled, that Z is the root of the **mean** square error and, in specific cases, errors twice and even three times as high as Z are possible.
- In the above derivation a **uniformly** spaced rainfall network was assumed. If the distribution is less even, the error variance will be somewhat larger and so will Z.

The error variance in case of a **non-uniformly** spaced network can be determined with block kriging, see Chapter 6 of Volume 2, Design Manual, Sampling Principles. If the stations are clustered, the error will be somewhat higher then in the case of a uniform distribution.

The effects of the various parameters Cv, r_0, d_0 and S on Z_{areal} and N are shown in the Figures 3.3 to 3.6:

- Figure 3.3 shows that the temporal variation of rainfall has a large impact on the required network density. Variation coefficients are high for short duration rainfall data and diminish gradually when the interval gets larger. Also pre-and post-monsoon monthly rainfall data show generally high coefficients of variation. In such cases either higher Z_{areal} -values have to be accepted or a denser network is to be applied.
- Figure 3.4 illustrates the effect of inaccurate measurements (relatively low values of r_0, see equation (3.3)) on the estimation error and the consequences for required density of the network. Accurate measurements pay off!!

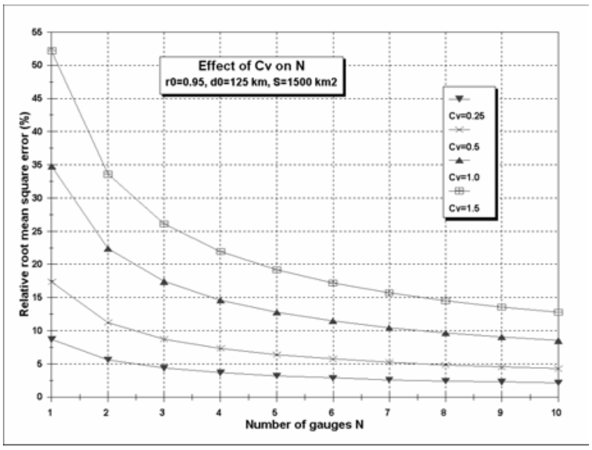


Figure 3.3: Estimation error as function of Cv and N

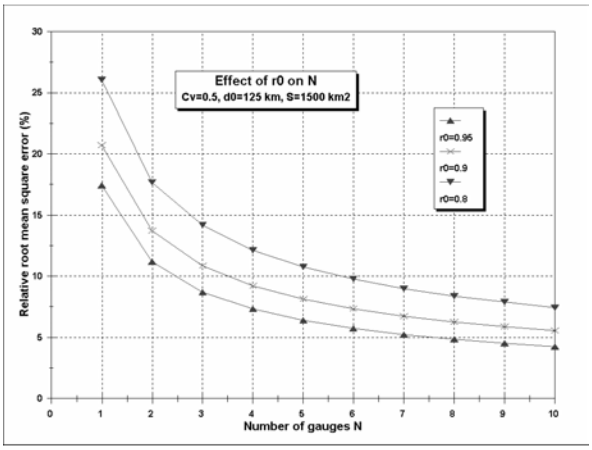


Figure 3.4: Estimation error as function of r_0 and N

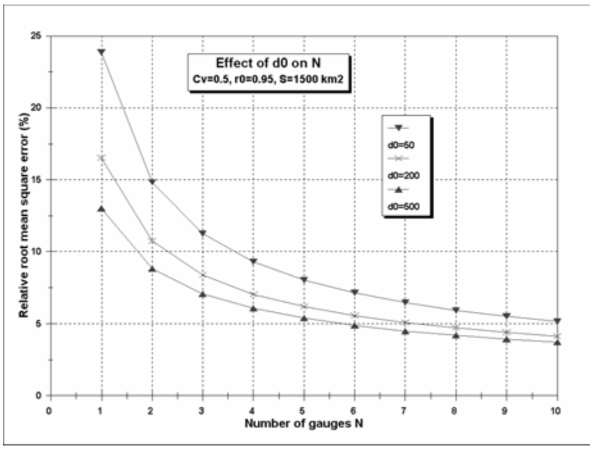


Figure 3.5: *Estimation error as function of d_0 and N*

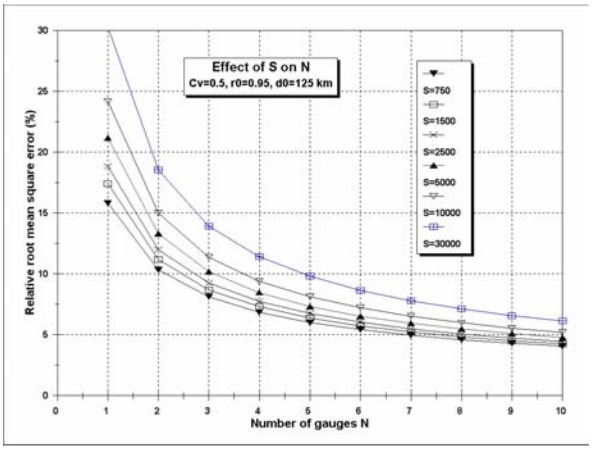


Figure 3.6: *Estimation error as function of S and N*

- In Figure 3.5 the effect of the characteristic correlation distance d_0 on Z_{areal} and N is given. It clearly shows, as one would expect, that a stronger spatial correlation reduces the network density requirement to reach the Z_{areal} -target. The distance d_0 generally increases with the duration, whereas Cv reduces when looking at a larger interval, but both with a similar effect on the required network density. This may be taken into consideration when deciding on the interval for which the network has to give a specified accuracy.
- Figure 3.6 shows the effect of the size of the basin on the required network density. The general tendency is that for the same accuracy a smaller catchment needs a denser network than a larger one. Figure 3.6 is to be fully understood, as one may be tempted to enter for S in equation (3.9) the entire catchment area, which leads to too optimistic results. Earlier, the importance of integration of the networks was indicated. Upstream of every stream gauging station sufficient rain gauges should be available to estimate the areal rainfall with a specified accuracy. The stream gauge density in the plains is approximately one gauge per 2,000 km^2 and one per 1,000 km^2 in the hilly areas. Hence those are the catchment sizes to be considered while applying equation (3.9).

Finally, all figures show that doubling the accuracy requirement (by halving the Z_{areal} -value from 10 to 5%) can only be achieved at the cost of a much denser network. It is therefore imperative that a cost-effectiveness analysis is carried out before a final decision is taken.

Summing up

Application of the theory, presented above, in which the relative root mean square error of areal rainfall estimates Z_{areal} is taken as the measure of effectiveness of the network, involves the following steps, (see also Part I of Volume 3, Field Manual, Hydro-meteorology):

1. Select the smallest duration or time interval Δt^* for which areal rainfall estimates have to be made and define the maximum acceptable value for Z_{areal} for a particular season in the year.
2. Collect the rainfall data of all stations in the region under study with a time interval of the data: $\Delta t \leq \Delta t^*$.
3. Validate the data thoroughly but do not fill in missing data, as this will generally affect the variability of the point processes and increase the correlation between the series and will lead to an inadequate network.
4. Derive the basic statistics of the point rainfall time series with interval Δt^*, i.e. mean, standard deviation and coefficient of variation per month or any other suitable homogeneous period in the year.
5. Based on topography, movement of weather systems and computed statistics, divide the region under study in homogeneous areas, if required by applying a suitable transformation.

6. Review the period for which the maximum acceptable value of Z_{areal} should be applicable based on the outcome of step 4.
7. Compute the correlation coefficient between the point rainfall time series for the same periods in the year for which the basic statistics have been determined, considering only non-zero data.
8. Plot the average correlation coefficient against average distance to reduce scatter on linear and semi-log paper.
9. Eliminate outliers from the plot, fit a straight line through the data points using a semi-log scale and estimate the parameters r_0 and d_0.
10. Determine the relative root mean square error as a function of the number of gauging sites N for a design area S (to be derived from the hydrometric network) and compute for each period the required gauge density for a series of values for Z_{areal}.
11. Apply a sensitivity analysis on the assumed design conditions and parameter values. Test the computed Z_{areal} -values with block-kriging.
12. Investigate the option to differentiate in the required network density to meet various objectives.
13. Make an estimate of the costs involved in development and operation of the network.
14. Analyse the consequences of not meeting the Z_{areal} -target.
15. Prepare a document in which the preferred network layout with a few variants is given inclusive of the financial consequences of all options.

The above listed steps are part of the overall network design process presented in Section 3.1.

In the list, particular attention is drawn in case the objectives have to meet network requirements for **design** purposes. For design, statistics of short duration rainfall data is often required. The time variation and areal extent of short duration rainfall is such that a dense network with recorders will be required. In such cases a cost-effective solution is to have in a few **representative basins** a dense network fulfilling the demands for design, whereas the network covering the whole region should have a density meeting the objectives for planning and management, say based on accuracy's for decadal, monthly or seasonal data.

3.2.5 EXAMPLE OF DESIGN PROCEDURE

To show how the procedure presented above is to be applied, the example of the network design for Tel basin, elaborated in full in the Reference Manual, is presented.

The Tel basin (see Figure 3.7) was subdivided in three homogeneous areas, viz. NW, SE and SW and in the example the data of the south-eastern region are presented. Possible orographic influence was investigated The altitude in the region is generally below 600 m. In tropical countries like India, orographic effects will be prominent above an elevation of 800 metres and so that influence can be considered non-existing in the selected Tel basin.

Since no Hydrological Data User need inventory was made at the time of the analysis, it was assumed that the network should be able to provide monthly and as an alternative seasonal or annual areal rainfall with a relative root mean square of not more than 10% on average.

Monthly and annual point rainfall series, derived from daily observations in the period 1970-1995 for all available rain gauge stations in the south-eastern part of the basin were used for the analysis. The stations included state-operated sites as well as IMD stations. A map was prepared with the station locations.

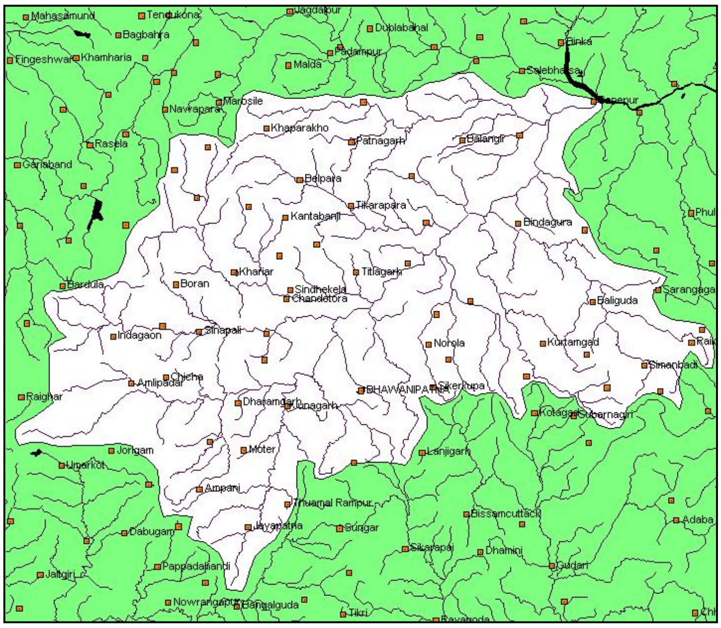


Figure 3.7:
Rain gauge network in Tel basin

Because no record was available on data validation, prior to the analysis the historical data were carefully screened using the techniques described in the Data Processing Manual. For the validation use was made of the HYMOS data processing software. It appeared that a great deal of the historical data was of dubious quality, which was henceforth left out. The exercise showed (with similar experience in the other areas) the need for thorough data validation to be carried before any further analysis takes place. If such validation can not be carried out at short notice, the WMO standards as presented in the following sub-section should be applied.

Based on the previous validation 9 stations were finally selected to be used in the network design exercise. The characteristics of the monthly point rainfall series are displayed in Figure 3.8. Typically, the rainfall in the Tel basin is concentrated in the monsoon season, with July and August being the wettest months, both with a long-term average rainfall of approximately 400 mm. The annual rainfall in that area is 1435 mm. In the same figure the coefficient of variation of the monthly point-rainfall series is also displayed. It is observed, that the Cv-values for the monsoon months are lowest, and are approximately 0.5. The Cv-values in the non-monsoon season range from 1 to 3.5. To give an indication of the variability of the Cv-values for the individual rain gauge stations also the 90% reliable Cv-values (i.e. the Cv-values which are not exceeded at 90% of the stations) are shown. From Figure 3.8 it is observed, that apart from December the variation in the Cv-values is very small. Hence the conditions for the assumed homogeneity were justified. The Cv-value for the annual point-rainfall series is 0.29 (against 0.23 for the areal average series). It shows that the variation for the larger interval is about half the value of the monthly series. The Cv-statistics are summarised in Table 3.1

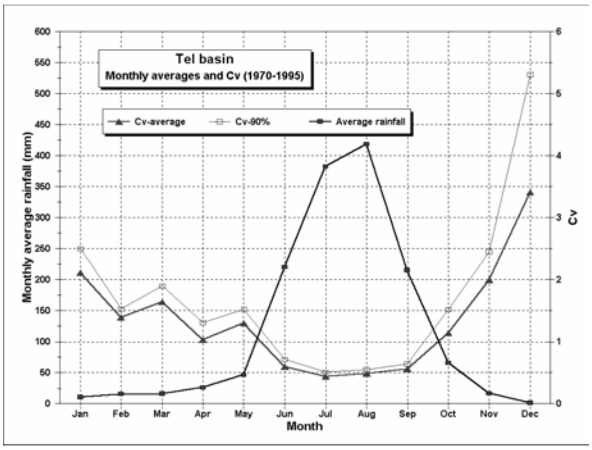


Figure 3.8:
Average monthly rainfall and Cv in Tel basin

Tel-basin	**Month**				**Year**
Design S=2000 km^2	**June**	**July**	**August**	**Sept**	
Cv-average	0.60	0.44	0.48	0.56	0.29
Cv-90%	0.71	0.51	0.55	0.64	0.33
r0	0.975	0.85 (0.90)	0.95	0.95	0.90
d0 (km)	140	150	125	150	200
Z_{areal}=0.1 (10%) : S/N in km^2/gauge	780	560 (800)	830	710	1670
Z_{areal} =0.05 (5%): S/N in km^2/gauge	270	150 (210)	270	220	480

Table 3.1: Summary of rainfall network design statistics and rain-gauge density requirements for different measures of effectiveness

Given that nearly all rainfall takes place in the period June to September, the analysis was concentrated only on these months. Annual data were considered as well. The correlation coefficients for the selected months and of the annual data between the 9 stations have been computed and to reduce the scatter were averaged over intervals of 10 km distance. An example is shown in Figure 3.9 for the month of August.

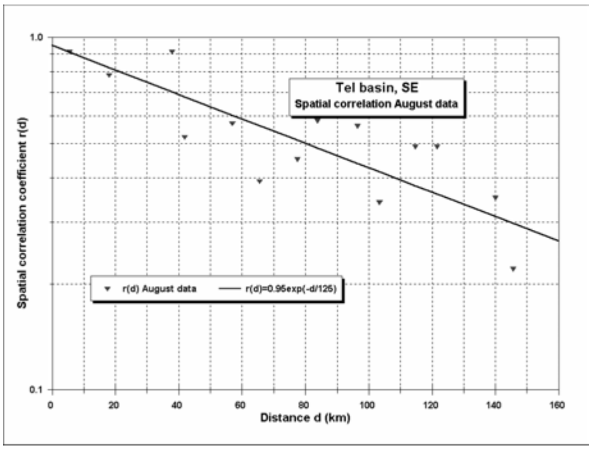


Figure 3.9: Spatial correlation structure of August data

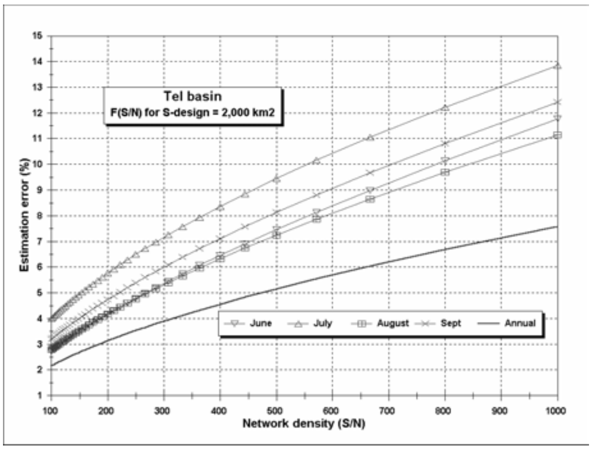


Figure 3.10: Network requirements for S=2,000 km^2

Outliers were eliminated in the computation of r_0 and d_0 from the data. The estimates for r_0 and d_0 for the monsoon months and annual data are presented in Table 3.1. July data appear to have a r_0 of 0.85, indicating large measuring errors or strong microclimatic variability. The d_0 values of the monsoonal monthly rainfalls are typically in the order of 125-150 km. The annual series show a larger spatial correlation, with d_0 = 200 km.

Using the Cv, r_0 and d_0 values as listed in Table 3.1 and assuming a design basin area of S = 2,000 km^2 in view of hydrometric network demands, the required network densities were computed for each month and for the annual series meeting a Z_{areal} -value of 10%. The results are presented in Figure 3.10 and Table 3.1. It is observed, that the month of July puts the largest pressure on the network. To estimate the areal rainfall in July for units of approximately 2,000 km^2 with on average an error less than 10% one gauge per 560 km2 would be required. This is primarily due to the low accuracy of the rainfall measurements in that month.

In Table 3.1 within brackets also the density requirement is indicated if the measurements of July would be improved to an error variance <10% of the series variance, (r_0=0.9). It is observed that this would reduce the required network density for that month with 30%. Hence, investment in better observation practice really pays off.

In Table 3.1 also the required network density for a Z_{areal} -value of 5% is indicated. It shows, that by doubling the accuracy a network would be required, which is almost 4 times as dense. Ergo, the Z_{areal} -value has to chosen carefully and the financial implications of different Z_{areal} -values have to be evaluated. Note that the WMO norm for plain areas is one gauge per 500 km^2, see Table 3.2. For Tel this density requirement nicely matches with the required density for monthly values if a 10% error in monthly areal rainfall estimates is considered to be acceptable.

3.2.6 MINIMUM NETWORK DENSITY

Based on world-wide experiences, WMO (1994) has presented a general guide for the required density of precipitation stations. An absolute minimum density for different physiographic units is given in Table 3.2. In their documentation no mentioning is made about the criteria applied in the preparation of this Table. According to Table 3.2 at least 10% of the network stations should be equipped with a recording raingauge.

Region	Minimum density in km^2/gauge	
	Non-recording (SRG)	Recording (ARG)
Hilly region	250	2,500
Semi-hilly region	500	5,000
Plains, high rainfall region	500	5,000
Plains, low rainfall region	900	9,000
Arid region	10,000	100,000

Table 3.2: Minimum density of precipitation stations (WMO, 1994)

From the example shown in the previous sub-section, WMO's minimum requirement will lead to reasonably (<10% error) accurate areal rainfall estimates for intervals of a month and larger if the Tel rainfall variability is considered representative for the rest of the country. **To start with**, the density requirements presented in Table 3.2 can be considered as adequate.

Application of the network density requirements in Table 3.2 and keeping in view the physiographic regions in the various states, in Table 3.3 the required rainfall network per state has been indicated. With respect to the network requirements per state the following additional remarks are made:

- The number rain gauges in the network according to Table 3.3 are to be considered as a minimum requirement and need to be used until measurement objectives are clearly formulated and rainfall data have been analysed.
- At least at 10% of the stations according to Table 3.3 recording gauges should be installed to get a proper impression about short term duration rainfall all over the state.
- In each state at least 2 to 3 small representative basins have to be equipped with recording rain gauges at a density as required for appropriate estimation of areal rainfall for short duration rainfall. This recording has to be continued for a period of at least 5 years to be able to estimate areal reduction factors and to establish rainfall-runoff relations, both for design purposes. Once sufficient data have been collected, the equipment may be transferred to other areas.

State	**Area** (km^2)	**Minimum number of SRG's**			**IMD** validity data
		Plain	**Hilly**	**Total**	
Andhra Pradesh	275,100	230	140	370	223
Chhattisgarh [1)]	135,000	203	135	338	45
Gujarat	195,900	163	100	263	168
Karnataka	192,000	288	182	470	260
Kerala	38,000	52	52	104	68
Madhya Pradesh [2)]	23,000	34	23	57	42
Maharashtra	308,000	257	308	565	189
Orissa	155,700	233	156	389	54
Tamil Nadu	130,200	195	132	327	157

[1)] without Ganga basin

[2)] without Narmada and Ganga basin

Table 3.3: Minimum rain gauge network per state

3.3 EVAPORATION NETWORK

3.3.1 MEASURING OBJECTIVES

Interest in evaporation data may concern:

- potential evaporation or potential evapotranspiration, and/or
- actual evaporation or actual evapotranspiration.

The data processed and stored in the Hydrological Information System refer only to **potential** evapo(transpi)ration, either as a directly measured quantity or indirectly by measuring radiation or sunshine duration, temperature, humidity and wind speed and direction.

The major use of potential evapo(transpi)ration data is generally for:

1. water resources planning,
2. agricultural and irrigation management, and
3. research.

The temporal and spatial characteristics of potential evapo(transpi)ration deviate remarkably from those of rainfall. Apart from the diurnal variation, the temporal variation of potential evapo(transpi)ration is much smaller than that of rainfall and varies little from year to year. Hence the variation coefficients of monthly potential evapotranspiration are small. The spatial correlation structure extents over a much larger area then for rainfall. These characteristics make that there is little interest in short duration evaporation data from a large number of stations.

Evaporation data are mainly used for water balance computations, assessment of water availability, for computation of reservoir evaporation and water use in irrigation systems. It typically refers to data of a larger time interval like day, decade and month. Only for research there is need for detailed temporal evaporation data, generally concentrated on representative basins or command areas.

Different from rainfall, with respect to evaporation interest is in estimates for very small areas (like reservoir surfaces) as well as for larger basins.

3.3.2 DESIGN PROCEDURE

Measure of effectiveness

For most hydrological purposes the objective of the evaporation network is to provide reliable estimates of **individual** events of:

- point evapo(transpi)ration for durations typically of a day to week (reservoirs, small plots), and
- areal evapo(transpiration) for areas commensurate with the hydrometric network and for durations of a decade, month or longer.

In the first case a proper measure of effectiveness is the interpolation error and in the second case the estimation error in the areal potential evapo(transpi)ration. The accuracy with which potential evaporation has to be known, is of the same order as that of rainfall and discharge; an error of 10% is generally acceptable.

Interpolation error

The relative root mean square interpolation error made in a **uniformly distributed** climatic network is a function of:

- the **time variability** of the climatic variable at a point, expressed in the coefficient of variation
- the **spatial correlation** structure
- network **density** S/N

Using the exponential correlation function (3.1) to describe the spatial correlation structure of evaporation, the maximum root mean square error in the estimated point evaporation expressed as a fraction of the time average point evaporation becomes (Kagan, 1972):

$$Z_{int} = Cv\sqrt{1/3(1-r_0)+0.52\frac{r_0}{d_0}\sqrt{\frac{S}{N}}} \quad \text{with} \quad Cv = \frac{\sigma_E}{E_{av}} \qquad (3.10)$$

with: σ_E = standard deviation of point evaporation
E_{av}= average of point evaporation
r_0,d_0,S,N are defined as before, see Section (3.2)

The error variance in case of a **non-uniformly** spaced network can be determined with point kriging.

Error in estimation areal potential evapotranspiration

The procedure for computation of the estimation error for areal potential evapotranspiration is similar to that presented for areal rainfall in Section 3 and reference is made to that section for computational details. Here, as for rainfall, a design area S has to be selected to be able to arrive at a required network density in view of the target set for Z_{areal}.

3.3.3 MINIMUM EVAPORATION NETWORK

The minimum evaporation network requirement recommended by WMO (1994) is one observatory per 50,000 km^2. In view of the larger variability of the weather systems in the tropical regions, IMD recommends a density of one station per 5,000 km^2. Based on the latter requirement the size of the networks for each of the states is presented in Table 3.4.

State	**Area** (km^2)	**FCS** N
Andhra Pradesh	275,100	55
Chhattisgarh [1)]	135,000	27
Gujarat	195,900	39
Karnataka	192,000	38
Kerala	38,000	8
Madhya Pradesh [2)]	23,000	5
Maharashtra	308,000	62
Orissa	155,700	31
Tamil Nadu	130,200	26

[1)] without Ganga basin

[2)] without Narmada and Ganga basin

Table 3.4: Minimum evaporation network per state

The values given in Table 3.4 are indicative. As soon as data are available for spatial correlation analysis, the procedures presented in Sub-section 3.3.2 should be applied to test the validity of the density given in the table.

4 SITE SELECTION

4.1 GENERAL

In the Hydrological Information System three types of hydro-meteorological stations have been discerned:

1. SRG-station, a rainfall station equipped with a standard or non-recording rain gauge,
2. ARG station, a rainfall station with a recording (and also a non-recording) rain gauge, and
3. FCS station, a full climatic station, where the following climatic variables are being observed:
    - for direct evaporation measurements: pan-evaporation,
    - for evaporation estimation:
        - sunshine duration
        - air temperature
        - humidity
        - wind speed and direction, and
        - atmospheric pressure (also used for groundwater studies).

In the previous chapter the required network density for each of the stations was discussed. The actual location of the station has yet to be determined. Several factors are to be taken into consideration, while making a proper choice for the site for setting up the observatory station to ensure long term reliable data.

The following aspects are to be considered:

technical aspects:

- what variable is to be measured where and with what accuracy and frequency
- integration with surface water and/or groundwater quantity and quality networks

environmental aspects:

- availability of suitable levelled ground
- exposure conditions
- future expansion near the site
- no water logging

logistical aspects:

- accessibility
- communication
- staffing

security aspects:

- security of instruments
- away from residential areas and play grounds

legal aspects:

- land acquisition
- right of passage

financial aspects, including costs of :

- land acquisition
- civil works
- equipment
- data processing, and
- staffing and training

The above aspects are discussed in the Sections 4.2 to 4.7. Finally, practicalities, necessary for a proper execution of the site survey, are dealt with in Section 4.8,

4.2 TECHNICAL ASPECTS

Prior to the site visit the preferred location from a technical point of view has to be determined. This requires two steps:

- First, approximate positioning of the station on the map to obtain maximum reduction of estimation errors, in relation with the variable of concern and observation interval to be used, and subsequently
- Integration of the site in, or tuning of it to, the hydrometric and/or groundwater network.

Network review

Since everywhere networks are in operation, first the existing network should be reviewed for its suitability. To assess the suitability in view of the required accuracy as derived from the user requirements, a contour plot is made of the estimation errors produced by the present network using point kriging and block kriging. Errors in interpolation between stations and/or estimation of areal averages have been discussed in the previous chapter. If the estimation errors are too large, the network has to be adjusted by repositioning existing stations and/or creating new stations.

Siting of new stations

New sites are located where maximum reduction of the standard error, visualised by kriging, is accomplished. To check the effectiveness of the new location, point kriging is redone with the new site(s) included, and the interpolation or areal average estimation error, whichever is relevant, is evaluated anew. This process is repeated a few times till the estimation error is maximally reduced.

Network integration

These new locations are subsequently compared with the hydrometric and/or groundwater network. Efficiency requires that where possible hydro-meteorological sites are to be combined with hydrometric sites in view of staffing costs, security and logistics. Similar benefits apply for groundwater by integrating hydro-meteorological sites in recharge study areas.

Agencies outside the HIS are also operating hydro-meteorological stations. If their stations fit into the HIS network and their equipment and operational performance meet the HIS standards then discussions should be initiated with those agencies to get access to their data on a regular basis. A prerequisite is, that these stations have been inspected by IMD and are brought up to the mark. The use of data of other agencies applies particularly to the hilly areas, where hydro-meteorological networks are in operation with the Electricity Boards.

4.3 ENVIRONMENTAL ASPECTS

Rainfall stations

The main purpose of establishing a rainfall station is to obtain representative samples of the rainfall over a basin. Particularly wind affects the rainfall measurements, while further losses due to evaporation and splashing play a role. To eliminate or reduce wind effects the site should be chosen such that:

- the wind speed at the level of the rain gauge is as low as possible, but in such a way that the surrounding does not affect the rain catch, and/or
- a horizontal air flow over the gauge orifice is occurring.

Ideally, the protection against the force of wind should come from all directions by objects of uniform height. Trees, shrub, etc. of nearly uniform height are ideal to protect the gauging site from wind, provided that the angle from the top of the gauge to the top of the encircling objects and the horizontal is between 30^o and 45^o. This implies, that if the height of the surrounding objects above the gauge orifice is H then the distance L between the surrounding objects and the gauge should be within the limits: $H \leq L \leq 2H$.

Windbreaks of a single row of trees should be avoided as they tend to increase the turbulence, (WMO, 1994). Similarly, uneven protections create a disturbed wind field over the gauge orifice. If single obstacles affect the wind field around the gauge, the distance between obstacle and gauge should be: $L \geq 4H$. One should make sure that there are no plans in the near future to build any structure in close proximity.

Slopes also affect the wind field. Sites on a slope or with the ground sloping sharply away in one direction (particularly in the direction of the wind) are to be avoided.

The gauge should be on level ground above flood level and free from water logging. Further, the site should have the same ground cover as the natural cover obtained in the surroundings. Surroundings covered with short grass are ideal. A hard ground such as concrete gives rise to excessive splashing and should be avoided. The plot required for an SRG is 5m x 5m, whereas an ARG station needs 10m x 5m.

Full climatic stations

Since an FCS also accommodates rain gauges, the environmental conditions discussed above for rainfall stations apply here as well. The sunshine recorder should at no instant be sheltered from solar radiation. Very essential in case of a full climatic stations is that the area, on which the station is to be built, is representative for a surrounding area of about 5,000 km^2. Sites were abrupt climatic differences are noticed due to swamps, mountains, river gorges and lakes should be avoided, unless the data should be representative for such an area. Some general indications of climatic changes are indicated below (Doorenbos, 1976).

vegetation: transition from dry to irrigated areas results in lower temperature, higher humidity and decreased evaporation; very distinct in dry windy climates (advection)

topography: elevation differences not only largely affects precipitation (>800 m) but also minimum temperature, wind speed and wind direction

rivers: relatively small effect, possibly confined to some 100 m, except for large rivers and river deltas

lakes: depends on the size of the lake, but rapid changes are generally confined to 1 to 2 km

sea: will vary greatly, but rapid changes occur normally over the first 2 km, with gradual changes for the next 10 to 15 km. It affects mostly wind, humidity and temperature

altitude: depends strongly on local climatic conditions but normally with increasing altitude temperature and evaporation decrease, while rainfall and wind tend to increase

mountains: downwind effect up to distances 50 times their height; the affected upwind area is much smaller.

For agricultural purposes the station should be within a cultivated area with a crop cover as large as possible upwind. There should be no road in close proximity. Depressions should be avoided as the temperature in depressions is frequently higher during the day and cooler in the night.

A full climatic station require a level plot of land of the size 18m x 15 m, preferably with green grass cover. To get a proper assessment of the potential evapotranspiration the site should be in the centre of an open space of at least 50 x 50 m, which is covered by grass or a short crop. If needed and feasible, the grass cover of the station should be irrigated and clipped frequently to fulfil the environmental conditions of the definition of potential evapotranspiration.

4.4 LOGISTICAL ASPECTS

Accessibility

The measurement site should be easily accessible even under adverse weather conditions. Hence, while inspecting a location, the surrounding of the site should also be evaluated. Either the existing road or path gives access at all time, or civil works are required to make the site accessible. In the latter case the costs of such works have to be considered in the final selection.

Communication

Proper communication means should be available in the vicinity of the station to ensure that the data from the station can be transferred without difficulty at regular intervals to the nearest sub-divisional office for entry into the computer.

Staffing

Availability of qualified persons near the site to operate the station throughout the year is another aspect to be considered. Schoolteachers prove often to be reliable observers and their attendance is also guaranteed, apart from the holiday season. Availability of qualified staff makes the combination of a hydro-meteorological station with a hydrometric site very attractive, because at the latter site staff will always be present. Hence, at no additional cost but extra training, the staff of the hydrometric station can look after the rainfall or climatic station.

4.5 SECURITY ASPECTS

Stations should be located at safe places to avoid damage or theft of instruments. The locations should therefore be chosen away from residential areas and playgrounds. Though, proper fencing is a prerequisite around a station, it will not prevent unauthorised persons and animals to enter the site. Hence in addition, particularly an FCS site also requires a watchman to guard over the instruments. Furthermore, (wild) animal tracks must be avoided as they may ravage the site entirely.

4.6 LEGAL ASPECTS

The land on which a station is to be established should be state property. If the otherwise ideal site in on private land, it should be realised that the land acquisition process may require about one year. This is therefore a major aspect in the final judgement on the suitability of the location for establishing a station.

Beside acquisition of land also free passage to the plot of land under all weather conditions has to be taken into consideration.

4.7 FINANCIAL ASPECTS

Last, but not least, the financial aspects have to be considered when comparing suitability of sites and for selecting a site. For each location the following cost factors have to be considered:

- land acquisition inclusive of cost of the acquisition process
- civil works, like access to the site, clearance of obstacles, levelling of the site, foundation for equipment fencing, staff quarters and station maintenance
- equipment procurement, calibration and maintenance,
- data collection, transfer and processing, and
- staff fees, travel expenses and training cost.

A proper distinction should be made between investment costs and running costs to make a fair comparison between alternatives possible.

4.8 SITE VISIT PRACTICALITIES

The site selection has to be carried out in collaboration with an IMD Inspector, to ensure full professional input in the selection process. During the site visit the aspects dealt with in the previous sections have to be discussed with the IMD Inspector. While visiting the field for site selection the following items should be available:

- a map of the area,
- a copy of the Master Plan if constructions are likely in the near future,
- a 50 or 100 metre measuring tape,
- a compass, and
- marking white powder.

Before marking the plot the Inspector should measure the distances to the nearest obstacles like trees and assess the height of the obstacles and ensure that the distance between the observatory boundary and the obstructions should fits with the requirement spelled out in Section 4.3. For marking the plot, the dimensions are preferably 5 x 5, 5 x10 for an SRG and ARG station respectively and 18 x 15 metres for a FCS-site.

The Inspector should prepare a sketch of the site indicating close-by buildings, trees and other obstructions and their distances from the boundary of the proposed enclosure. The geographical North should be marked. He/she should also make recommendations like trimming of the trees, clearance of bushes if exposure conditions need improvement or if levelling of plot is needed.

5 MEASURING FREQUENCY

5.1 GENERAL

Hydro-meteorological processes are generally continuous with time. Three procedures are applied for sampling if hydro-meteorological variables:

- Continuous sampling , i.e. the time variation of the variable is recorded on a chart
- Discrete point sampling, i.e. the continuous process is observed as instantaneous values at discrete points in time
- Average sampling, i.e. the sampling is performed over a time and the result is the integral of the process over that interval.

Chart recorders are still in use in hydro-meteorology. For use in HIS the chart record has to be digitised, either as instantaneous values or integrals over an interval. Hence in all cases a suitable sampling interval has to be chosen so as to preserve the relevant features of the sampled process.

The frequency with which hydro-meteorological measurements are taken depends upon several factors:

1. **The function which the data will serve.** Most measurements are made to serve multiple functions. The measurement frequency must meet the requirements of the most critical function for that station and variable.

2. **The target accuracy of derived data.** Few such targets are set either in India or elsewhere, but it must be recognised that a policy of ‘as good as possible’ may lead on occasions to unnecessary expenditure on improving accuracy beyond what is needed for the purpose. There must at least be a notional lower limit to the required accuracy. The frequency of measurement as well as the accuracy of observation will have an impact on the accuracy of the determination of the derived quantity, like evapo(transpi)ration estimated by Penman Method.

3. **The accuracy of observation.** Where observation is subject to random measurement error, a larger number of observations is needed to meet a required target where the measurement error is large.

4. **The time variability of the variable.** Clearly fewer measurements are needed to determine the relevant characteristics of a variable over given time, if the variable is uniform or changing very slowly than for a rapidly fluctuating variable.

5. **The time periodicity of the variable.** Many climatic variables show a regular diurnal variation. This is natural, such as temperature, pressure, evapotranspiration arising from the periodicity of the solar input. The frequency of measurements must be sufficient to define the mean over both the highs and lows of these periodicities.

6. **The marginal cost of improved definition**. Marginal costs tend to be higher where observations are manual than when they are automatically or digitally recorded

7. **The benefits of standardisation.** It is simpler to process and analyse records which are arriving at the Data Processing Centre, all in the same format and with the same frequency of observation. This is true both for manual data and for digital data, where batch processing of records by computer is simplified. It may be preferable for digital observations to standardise on a time interval close to the minimum requirement, than to adjust the frequency at each station to its functions, accuracies and time variability of the variable, many of which are imprecisely known.

The basic principles of optimisation of the sampling frequency have been presented in Chapter 5 of Volume 2, Design Manual, Sampling Principles, to which reference is made. It is shown that proper knowledge of measuring objectives and the time variation of the process is a prerequisite for determination of the measuring frequency.

5.2 RAINFALL MEASUREMENT FREQUENCY

In HIS data on precipitation are being collected for water resources planning, design, management, and research. Whereas planning and management requires data with intervals of days, decades, months or seasons, for design particularly short duration rainfall data is required, with intervals of typically as from 15 minutes onward for extreme events. Generally, stations in urban areas require smallest measuring interval. For design purposes, storm duration’s equal to the concentration time of the system are required. Then a sampling interval of less than 1/5 of the critical storm duration has to be applied to be able to provide a design storm pattern with sufficient detail. The concentration time can be derived from physically based or locally calibrated empirical formulae for flow overland and through drains/sewers and rivers. Finally for research purposes time intervals of very short duration may be required to study the temporal variation of rainfall intensities within a storm.

For HIS therefore the following sampling intervals are applied:

Stations equipped with an SRG only, a sampling interval of 1 day is applied and the rainfall is observed at 0830 hrs. Frequent observations are required in case of heavy rainfall to avoid overflow due to limited capacity of the rain-gauge container. SRG’s located at Full Climatic Stations are read twice daily at 0830 and 1730 hrs.

Stations equipped with an autographic siphon type rain-gauge, the recorder chart will be digitised to hourly values at the clock hours. If the storm total exceeds 100 mm and the intensity at least in one hour exceeds 12 mm then 15 minutes rainfall will be extracted at the clock quarters.

The use of a digital recorder based on the tipping bucket principle provides an opportunity for more flexible recording of short duration rainfall. Such rain-gauges may be programmed to operate in one of two modes (and occasionally in both simultaneously):

1. Time mode
2. Event mode

In **time mode**, rainfall may be observed and stored for any selected time interval, e.g. 5, 15, 30 minutes, 1 hour etc., as the accumulation of tips of given volume within the selected interval. The standard interval will be 1 hour, unless local circumstances require a shorter or larger interval.

In **event mode**, each individual tip of, say, 0.5 mm or 1.0 mm, can be stored with the associated time of its occurrence, creating in effect a non-equidistant time series. From this record a record of rainfall for any selected interval may be automatically created. Similarly, maximums during a given time period, say one month, can be automatically extracted for 15, 30 minutes, 1 hour or other time intervals. Where tipping bucket rain gauges are used, the event mode is recommended.

Note

For processing purposes rainfall measuring intervals used in HIS are related to clock hours/quarters. This may not lead to the most critical rainfall intensities for the same interval. In design therefore, for clock related intervals a multiplier (generally 1.10 to 1.15) is applied to correct for this shortfall. It is assumed that such correction factors are determined from sampling in representative basins, which do not form part of the regular network.

IMD measuring frequencies

IMD applies following measuring frequencies:

- At stations in the world-wide routine collection of hydro-meteorological data collection programme observations are taken simultaneously at the standard hours of 0000, 0300, 0600, 0900, 1200, 1500, 1800, and 2100 hours GMT corresponding to 0530, 0830, 1130, 1430, 1730, 2030, 2330 and 0230 hours IST.
- At stations were **principal observations** are made, i.e. ‘morning observation’ and ‘afternoon observation’, observations are taken at 0830 and 1730 hours IST.
- At stations equipped with a standard rain-gauge (SRG) observations are made once daily at the time of the morning observation at 0830 IST.
- At stations with a siphon type rainfall recorder the record is traced on a chart, which is changed daily at 08.30. Clock hourly rainfall amounts are being extracted from this chart for entry to the database. If at any moment in time the rainfall intensity exceeds 12 mm/hr the rainfall is extracted for sampling intervals of 15 minutes until the rainfall intensity drops below that threshold value. Maximum amounts in 15 mins, are also extracted. Due to chart calibration limitations the least time interval for extracting rainfall data from autographic charts is 15 minutes.

5.3 CLIMATE MEASUREMENT FREQUENCY

Climate measurements are made for estimation of evapo(transpi)ration, used for water resources planning, agricultural and irrigation management, and research. For planning and management interest is in daily and larger time intervals. Van Bavel (1966) showed that with the Penman equation using measured daily radiation and daily average values of temperature, humidity and wind speed acceptably accurate evaporation estimates are obtained. Hence, the sampling interval of the climate variables should be chosen such that reliable daily averages can be determined. The required sampling interval and recording hours are listed in Table 5.1.

Climate variable	Recorder	Type of sampling	Sampling interval	Observation times
Rainfall	SRG	Cumulative	9 to 15 hours	0830, 1730 hrs
	ARG	Cumulative	1 hour	0830 hrs
Evaporation	Evaporation pan	Cumulative	1 day (9 to 15 hrs)	0830 hrs (1730 hrs)
Radiation	Sun-shine recorder	Cumulative	1 day	After sunset
Temperature	Min, max thermometers	Instantaneous	1 day	0830 hrs
	Thermograph	Continuous by chart	1 hour	0830 hrs
Humidity	Dry, wet bulb thermometers	Instantaneous	9 to 15 hours	0830, 1730 hrs
	Hygrograph	Continuous by chart	1 hour	0830 hrs
Wind	Anemometer	Cumulative	9 to 15 hours	0830, 1730 hrs
	Wind-vane	Instantaneous	9 to 15 hours	0830, 1730 hrs

Table 5.1: Observation frequency and observation times of climate variables

For research purposes the variation of evapo(transpi)ration through the day may be of interest. In such cases an hourly sampling interval is required to cover all requirements.

In Table 5.1 it is indicated that the dry and wet bulb thermometers are to be read twice daily; it is noted that a higher frequency is required to obtain useful information on relative humidity and dew point for storm maximisation analysis for PMP/PMF investigations. Such high frequency is not realistic in practice for manual readings. Therefore, for design purposes correction factors have to be applied for maximum dew point calculations. These correction factors can be derived from stations where continuous recording of the relevant variables takes place.

6 MEASUREMENT TECHNIQUES

6.1 ACCURACY OF MEASUREMENTS

The techniques applied for the measurement of rainfall and climatological variables refer to point measurements. In the previous chapters the network density and sampling intervals were discussed. In this chapter attention is focussed on the measurement technique and associated accuracy's. Reference is made to Chapter 4 of Volume 2, Design Manual, Sampling Principles, for an extensive treatise on various types of measurement errors and their effect on the overall accuracy of a measurement.

The following accuracy requirements for the relevant parameters are presented by WMO for climatology and hydrology, see Table 6.1.

Element	Climatology	Hydrology
Atmospheric pressure	± 0.3 hPa	-
Dry bulb temperature	± 0.1 °C	± 0.1 °C
Wet bulb temperature	± 0.1 °C (lag time 3 min)	± 0.1 °C
Relative humidity	± 3% (lag time 3 min)	-
Dew point	± 0.5 °C	-
Vapour pressure	± 0.2 hPa	-
Wind direction	± 10°	
Wind speed	± 0.5 m/s	
Rainfall, total amount	≤ 10 mm 0.1 mm > 10 mm 2%	≤ 40 mm: ± 2 mm > 400 mm: ± 5%

Element	Climatology	Hydrology
Rainfall intensity	≤25 mm/hr: ± 0.5 mm/hr > 25 mm/hr: 2%	± 1 mm/hr
Pan evaporation	≤ 10 mm: ± 0.1 mm > 10 mm: 2%	± 0.5 mm per day
Solar radiation	± 1 $MJ/m^2/day$	
Net radiation		≤ 8 $MJ/m^2/day$: ± 0.4 $MJ/m^2/day$ > 8 $MJ/m^2/day$: ± 5%
Sunshine duration	± 0.1 hr in any hour	-

Table 6.1: Accuracy requirements for hydro-meteorological variables (source WMO)

From Table 6.1 it is observed that, generally, climatological applications require higher accuracy's than hydrological. For HIS the conditions set for hydrological applications will be used and where no condition is specified the requirement stated under climatology has to be applied. Above conditions are incorporated in the specifications for the equipment, which can be found in 'Surface Water Equipment Specifications' Manual. This manual is regularly updated to keep pace with the latest developments in the field of hydro-meteorology.

6.2 MEASUREMENT OF RAINFALL

In the HIS rainfall is measured by the following non-recording and recording rain-gauges:

Non-recording rain-gauge:

- Standard Rain Gauge (SRG)

Recording rain-gauges:

- Autographic natural syphon rain-gauge (ARG), and
- Tipping Bucket rain-gauge (TBR).

Other techniques for rainfall measurement are available, like weighing type rain-gauges and radar techniques, but do not find application in the HIS. Radar is used for weather detection.

In the following sub-sections the SRG, ARG and TBR are described.

6.2.1 STANDARD RAINGAUGE (SRG)

The amount of rainfall at a station in a specified period is measured as the depth to which it would cover a flat surface. The measurement of this is made by a standard rain-gauge made of Fibre Glass Reinforced Polyester (FRP).

The essential parts of a rain-gauge as shown in the Figure 6.1 are:

1. a collector (funnel) with a gun metal or aluminium rim of circular shape and of area 100 or 200 cm^2,
2. a base,
3. a polythene bottle, and
4. a measure glass appropriate to the funnel area.

The rain falling into the funnel collects in the bottle kept inside the base, and is measured by a measure glass. An appropriate measure glass should be used for the 100 and 200 cm^2 collector areas. The most important requirements of a gauge are as follows:

1. The rim of the collector should have a sharp edge and should fall away vertically inside and be steeply bevelled outside;
2. The area of the orifice should be known to the nearest 0.5 per cent and the construction should be such that this area remains constant while the gauge is in normal use;
3. The collector should be designed to prevent rain from splashing in and out; this can be done by having the vertical wall sufficiently deep and the slope of the funnel steep (> 45^0);
4. The container should have a narrow entrance and be sufficiently protected from radiation, to minimise the loss of water by evaporation.

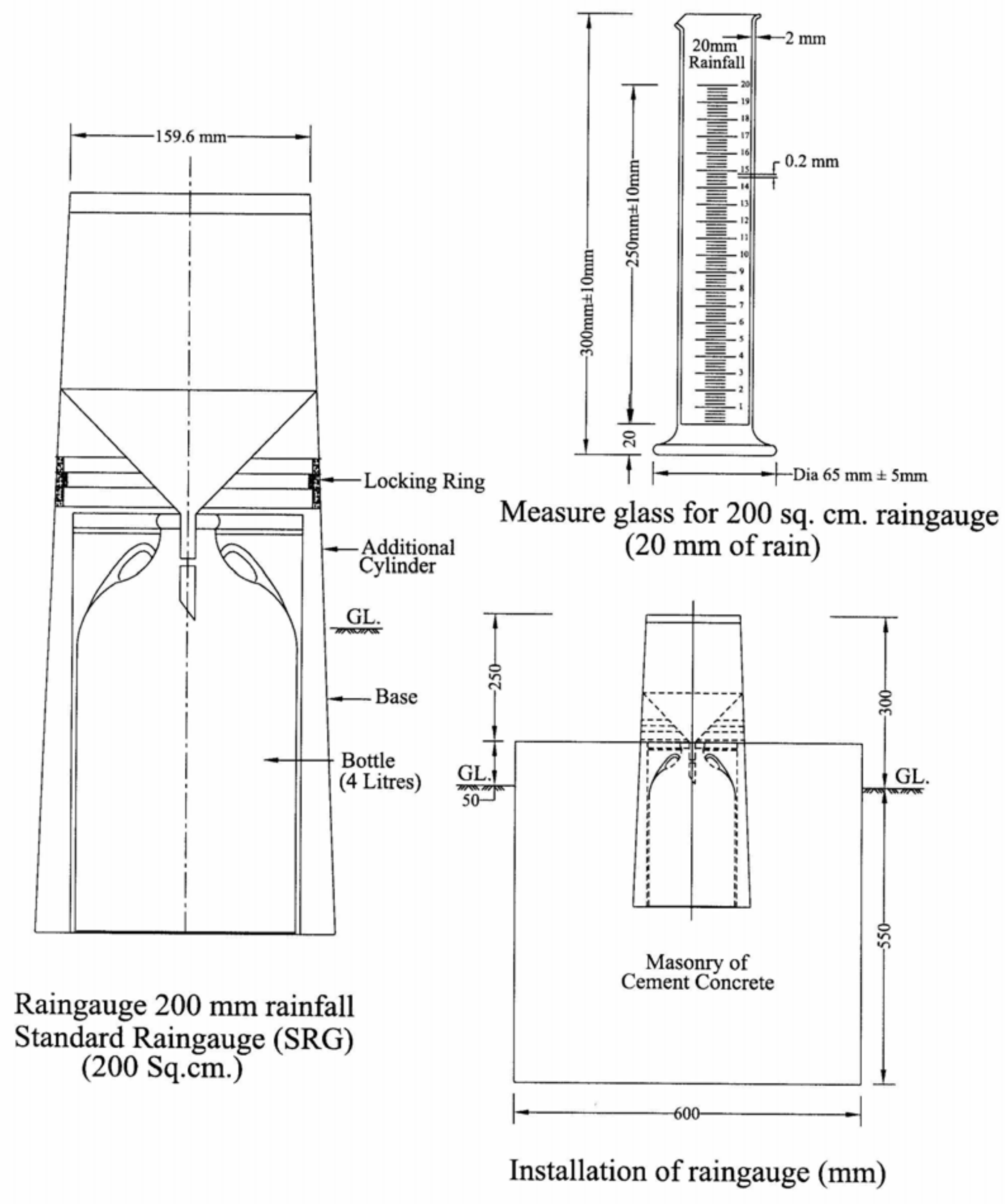


Figure 6.1: Standard rain-gauge SRG (200 cm^2 model)

Two types of apparatus are commonly used for measuring the rainfall caught in the non-recording gauge:

- A graduated measuring cylinder, or
- A graduated dip rod

The measuring cylinder should be made of clear glass having suitable coefficient of thermal expansion and should be clearly marked to show the size or the type of gauge with which it is to be used. Its diameter should be less than 33 percent of that of the rim of the gauge; the smaller the relative diameter, the greater the precision of the instrument. The graduations for the graduated measuring cylinder should be finely engraved, such that the rainfall can be read up to 0.1 mm accurate. To measure small precipitation amounts with adequate precision, the inside diameter of the measuring cylinder should taper off at its base.

The rain-gauge used in the HIS should comply with IS 5225-1992. The dimensions of the 100 and 200 cm models are presented in table 6.2

Equipment part	**100 cm model**	**200 cm model**
Collecting area (cm^2)	100	200
Inner diameter of rim (mm)	112.9	159.6
Collecting Bottle (litres)	4	2
Nominal capacity (mm)	400	100

Table 6.2: Dimensions of 100 and 200 cm rain-gauge models

From Table 6.2 it can be deduced that for areas with high intensity rainfall the 100-cm model is more appropriate than the 200-cm model. A guideline on selection of rain gauges for different rainfall regimes in the states is presented in Table 6.3

No	**State**	**Annual rainfall range (cm)**	**24 hr. max. rain range (mm)**	**Suggested rain gauge (Model (100/200) & bottle capacity in litre)**
1.	Madhya Pradesh	100-200	300-500	100 or 200 4 litre, 10 litre. 4 in plain , 10 in hill (4 litre bottle spare in hills)
2.	Chhattisgarh	100-200	300-500	100 or 200 4 litre, 10 litre. 4 in plain , 10 in hill (4 litre bottle spare in hills)
3.	Gujarat	30-50 West, 50-100 East	400-600	200 2 litre (4 litre spare) 200 or 100 4 litre
4.	Orissa	100-150 plains 150-250 hills	400-600	100 or 200 4 litre 10 litre (4 litre spare)
5.	Maharashtra	>250 W.Ghats, 50-100 Central 150-250 East	600 W. Ghats 200-400	100 I 0 litre 200 4 litre
6	Andhra Pradesh	50-100 Int. 100-150 Coast	200-400 Int. 500 Coast	200 4 litre 100 or 200 4 litre
7.	Tamil Nadu	50-100 West 100-150 East	300-400 Int. 500 Coast	200 4 litre 100 or 200 4 litre

No	State	Annual rainfall range (cm)	24 hr. max. rain range (mm)	Suggested rain gauge (Model (100/200) & bottle capacity in litre)
8	Karnataka	> 250 West 50-150 rest	200-400 Int. 600 Coast & Ghats	100 10 litre for South Interior: 100 or 200 4 litre for North Interior: 200 4 litre
9.	Kerala	>250	300-500	100 or 200 10 litre (4 litre spare)

Note: where a 4 litre bottle is suggested for the main gauge, a 2 litre bottle may also be kept as spare

Table 6.3: Suggested rain gauge models and collecting bottles for different states

Accuracy

The commonly accepted standard method of rainfall measurement by a rain-gauge exposed above the ground level is subject to appreciate systematic error (3 to 30%). Thus the amount of precipitation caught by the gauge is smaller than the amount of incident precipitation. This error is due to wind field deformation above the gauge rim, to wetting, evaporation, and splashing of raindrops. The components of the systematic error are related to the meteorological and instrumental factors and can be statistically analysed. The general model for corrections is of the form:

$$P_k = kP_c = k\,(P_g + \Delta P_1 + \Delta P_2 + \Delta P_3 \pm \Delta P_4) \qquad (6.1)$$

where P_k = adjusted amount of rainfall
k = correction factor due to wind field deformation
P_c = amount of rainfall caught by the gauge
P_g = amount of rainfall measured in the gauge
ΔP_1 = losses from wetting on internal wall of collector
ΔP_2 = losses form wetting on internal wall of container
ΔP_3 = losses due to evaporation from container
ΔP_4 = error due to splash in and out

The random error in the rainfall amount refer to observational errors.

The conversion factor k as well as the corrections $\Delta P_{1\text{-}4}$ for a particular gauge can be estimated experimentally by field comparisons or by laboratory tests, see Table 6.4 for an overview of the order of magnitude. The needed meteorological factors can be estimated using standard meteorological observations at the rain-gauge site. The corrections thus determined can be introduced in the rainfall data of national networks.

Presently the standard rain gauges are so designed that most of the instrumental errors have been minimised. The wetting loss is reduced by making the internal wall of the collector and container very smooth so that no rainwater adheres to them. Splash in and out is minimised by the proper design of the collector. Lastly the wind effect is minimised by keeping the height of the rim 30 cm above the ground level.

Symbol	Component of error	Magnitude	Meteorological factors	Instrumental factors
k	Loss due to wind field deformation above the gauge orifice	2-20%	Wind speed at the gauge rim during rainfall and the structure of rainfall (effect is larger for small intensities)	The shape, orifice area and depth of both the gauge rim and collector
$\Delta P_1+\Delta P_2$	Losses from wetting on internal walls of the collector and in the container when emptied	2-10%	Frequency, amount of rainfall, the drying time of the gauge and the frequency of emptying the container	As above and, in addition, the material, colour and age of both the gauge collector and container
ΔP_3	Loss due to evaporation from the container	0-4%	Saturation deficit and wind speed at the level of the gauge rim during the interval between the end of precipitation and its measurement	The orifice area and the isolation of the container, the colour and, in some cases the age of the collector, or the type of funnel (rigid or removable)
ΔP_4	Splash-in and splash-out	1-2%	Rainfall intensity and wind speed	The shape and depth of the gauge collector and the kind of gauge installation

Table 6.4: Main components of the systematic error in precipitation measurement (adapted from WMO, 1994)

6.2.2 AUTOGRAPHIC RAINGAUGE (ARG)

Short duration rainfall in India has been measured in the past almost invariably using the natural siphon recording gauge. The record is produced on a chart and is therefore referred to as autographic. Although a number of alternatives are now available both with respect to the sensor and the means of recording or logging, the natural siphon will continue to be the mainstay of the network in the immediate future.

Figure 6.2: Autographic natural siphon raingauge (ARG)

The autographic rain gauge (also referred to as recording rain gauge or self-recording rain gauge) is shown in Figure 6.2 and 6.3. In this type of instrument the rain passes into a float chamber containing a light float. As the level of the water within the chamber rises, the vertical movement of the float is transmitted, by a suitable mechanism, to the movement of the pen on the chart. By suitably adjusting the dimensions of the collector orifice, and of the float and float chamber, any desired chart scale can be used.

In the HIS two types of ARG's are in use, differing in the size of the collector area, viz. 130 cm^2 and 325 cm^2, with respective inner diameters of the rim of 128.5 and 203.2 mm. The base and cover (collector) are made of fibreglass reinforced plastic (FRP). The recording mechanism is mounted on the base with three screws, which keep the receiver levelled. The cover with its gun metal rim and funnel lifts off the base and carries a hasp, which can be engaged with a staple on the base and padlocked. The working mechanism consists of a copper float, capable of linear vertical movement inside a float chamber and having one siphon chamber attached to it. The siphon can be fixed at a desired height on the float chamber so that siphoning action commences corresponding to a particular level of the float chamber. The actual siphoning process should begin precisely on command with no tendency for the water to dribble over at either the beginning or the end of the siphoning period, which should not be longer than 15 seconds. The capacity of the float chamber is so designed that the volume of water required to reach that particular level will be exactly 25 mm (130 cm^2 model) or 10 mm (325 cm^2 model) of rain. The charts in use are replaced daily, though versions with lower drum speeds do exist. The autographic siphon type raingauge in HIS shall comply with IS 5235-1992.

The ARG produces a continuous record of the rainfall in an cumulative form. As a standard the continuous record is discretised to hourly totals. The ARG is always used in combination with a non-recording rain gauge. The daily totals of the recording and non-recording gauge are compared and generally the ARG record is adjusted to the SRG total.

Accuracy

The error sources indicated for standard rain gauges also apply to the recording rain gauges. Evaporation from the float chamber will be shown as a downward trace in the record. Additional errors may be generated by imprecise clock movements and pen-trace coverage.

Advantages and disadvantages

The ARG gives a continuous record of rainfall. The smallest interval that can be extracted from the chart is 15 minutes. There is basically no limitation to the rainfall intensity and rainfall amount.

The instrument is rather delicate; it is sensitive to dust and insects. Typical recording problems are apparent if the rainfall intensity is very high. Then the pen-traces become very close and the number of siphonings may be difficult to identify, particularly when ink is blotting on the paper. The instrument needs very regular checking. The clock drum and float assembly should be periodically checked to ensure that after each siphoning the pen returns from the top graduation to zero on the chart.

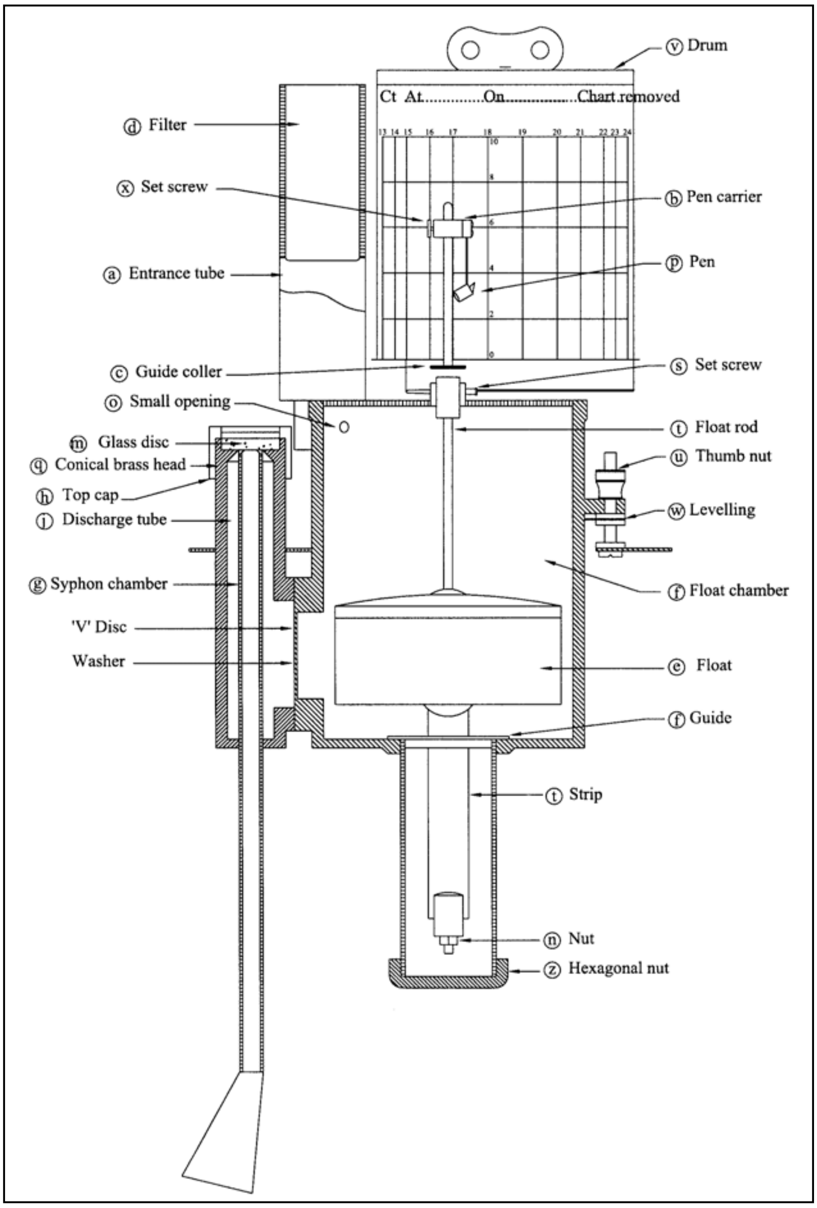


Figure 6.3:
The recording mechanism of an ARG

6.2.3 TIPPING BUCKET RAIN GAUGE (TBR)

Tipping bucket (or tilting bucket) rain gauges linked to data loggers are a widely proven technology for recording rainfall amounts and intensities particularly in remote or unattended places. It consists of a stainless steel bucket divided into two equal compartments mounted on a spindle, see Figure 6.4. The buckets are balanced in unstable equilibrium about the horizontal axis. In normal position the bucket rests against one of two stops, which prevents it from tipping over completely. Rainwater is conducted from a collector into the uppermost compartment, and when a definite amount of water has been added, the bucket tips to the other position. With a collector diameter of 200 mm a volume of rainwater of 31.4 cc will let the bucket over - balance and dips for every 1 mm. Then the other side begins to collect rainfall. This process continues and the bucket tips for every 1 mm. Each time the bucket tips a magnet actuates a read switch fitted on the casting. The magnet is fixed to a vertical rod attached to the spindle. The number of contacts of the switch transmitted by the rain-gauge are recorded and stored in a data logger. The equipment used in the HIS requires a recording interval settable from 1 minute to 24 hours when the instrument is running in time mode. In the event mode the time of occurrence of every tip is recorded. The total number of counts per interval gives the intensity of the rainfall.

Accuracy

Reference is made to Sub-section 6.1.1 for a summary of the error sources of standard rain gauges, which apply also for recording gauges. Additional inaccuracies due to the characteristics of the instrument are listed below as disadvantages. The TBR introduces a systematic error when rainfall amounts of rainstorms have to be determined, since the bucket may be anywhere between empty and full at storm's end. This however can be cancelled out if a similar error is made at the beginning of the storm. In the specifications for the TBR in the HIS it is required that the accuracy of the instrument should at least be 2 % of reading for non-monsoon conditions and 5% of reading under monsoon conditions.

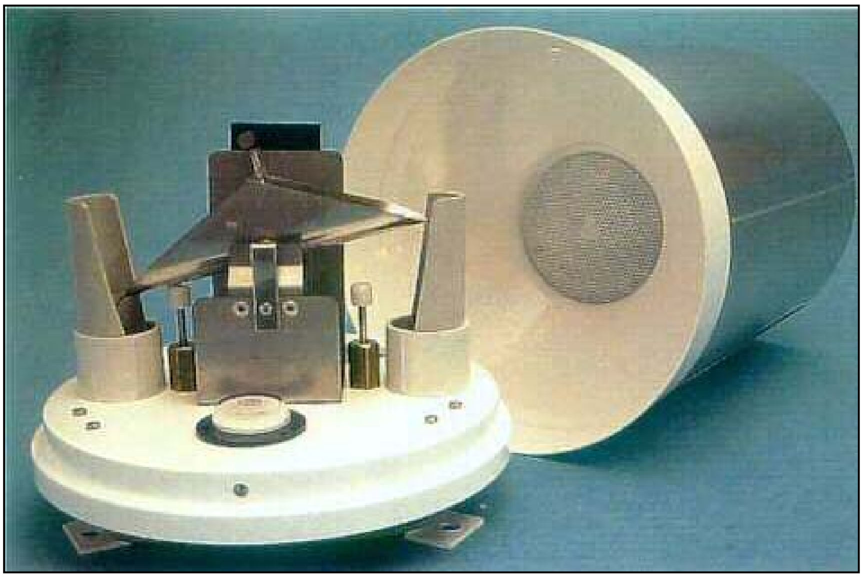


Figure 6.4:
Tipping bucket rain-gauge

Advantages and disadvantages

Advantages:

- It can be used for rainfall recording at remote places. Its use in less populated upper reaches of river basins is advocated, as it does not require regular attendance different from an autographic type rain gauge.
- The rainfall pattern is automatically digitised and immediately ready for transfer to the database. Hence, error sources related to the manual transfer of a continuous record to a digital one is omitted.
- Any intensity variation can be recorded; the data are stored as equidistant time series (number of tippings per unit of time) or as a non-equidistant series (time labelling every tip).
- The recorder is comparatively robust.

Disadvantages:

- The bucket takes a small but finite time to tip over and during the first half of its motion additional rain may enter the compartment, which already contains the calculated rainfall. This error can be appreciable during heavy rainfall.
- Its performance is not satisfactory during light drizzle or very light rain, as the time of onset and cessation of rainfall cannot be accurately determined.
- The exposed water surface of the bucket is large in relation to its volume so that appreciable evaporation can occur. This error will be most significant in light rain.

IMD TBR Mk3

The IMD Tipping Bucket rain gauge Mk 3 consists of a 750 cm^2 collector, a tipping bucket switch and mounting and a support tube. The closures of a reed-switch by a magnet are used to provide an indication of rainfall amounts, one tip of the bucket is equivalent to 0.2 mm of rainfall. Normally an indicator in the form of an electromagnetic counter is used, but for special purposes an incremental recorder or a magnetic tape event recorder may be used.

The 750 cm^2 collector is in the form of a funnel, with an internal rim diameter of 309 mm. The lower end of the funnel is fitted with a skirt, which has locking lugs moulded onto it. The TBR switch mounting is comprised of a small funnel and tube with a spoiler fitted inside the tubing to prevent swirling of the rain inside the tube. The TBR switch Mk 3 assembly consists of a stainless steel bucket divided into two equal compartments mounted on a spindle. Measured quantity of rainwater is led into the compartments as they tip alternately.

6.3 MEASUREMENT OF CLIMATIC VARIABLES

6.3.1 SOLAR RADIATION/SUNSHINE RECORDER

Although a wide range of instrumentation is available for the measurement of short-wave long-wave and net global radiation (e.g. (net)-pyranometer, sunphotometer, pyrradiometer, pyrgeometer), the only instrument which is in common use in the India meteorological network with which to estimate solar radiation is the Campbell-Stokes sunshine recorder (Figures 6.5 and 6.6)

The Campbell-Stokes sunshine recorder complying with IS 7243-1974 consists of a glass sphere about 16 cm in diameter, mounted on a section of a spherical bowl. The diameter of the bowl is such that when exposed to the sun’s rays, the sphere focuses the rays sharply on a card held in grooves in the bowl. Three overlapping pairs of grooves are provided in the bowl to take cards suitable for different seasons of the year. Long curved cards are used in summer, short curved cards in winter and straight cards at equinoxes.

Figure 6.5:
Campbell-Stokes sunshine recorder (Latitude 5°S to 45°N)

The principle of the recorder is based upon the burning of the card by the heat of the sun's rays, which are focused on the card through the glass sphere. The cards are changed daily after sunset. The total length of the burn (or burns) is compared with the time scale on the card to obtain the sunshine duration. Here the sunshine recorder uses the movement of the sun, instead of a clock, to form the time base for its record. Burn duration measurements are made up to 0.1 hr accurate.

6.3.2 TEMPERATURE

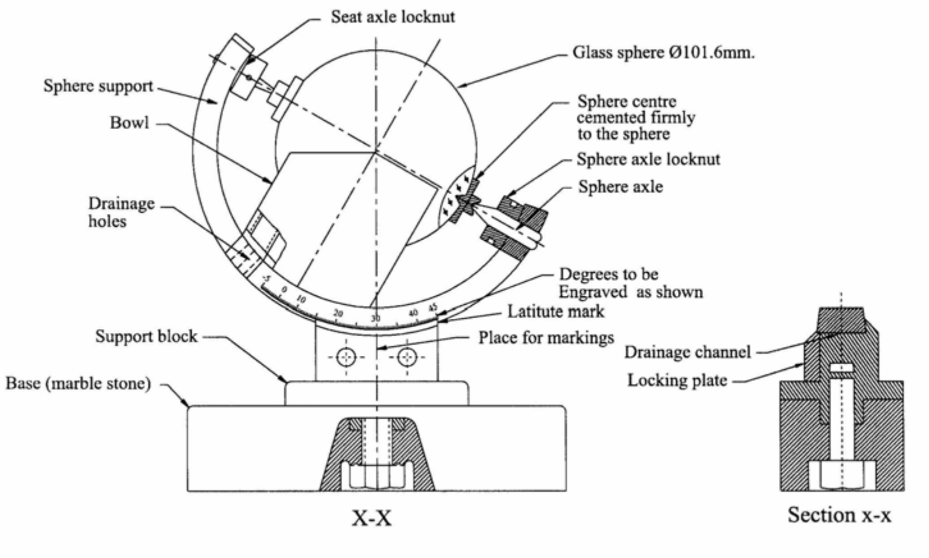
Temperature is primarily of interest to hydrology as a controlling variable in the evaporative process. The temperature of the air, of the soil and of water bodies is all of interest. Whilst a number of physical principles have been used to develop sensors for measurement of temperature, standard measurements are primarily made by periodic observations of a thermometer, whilst continuous but less accurate measurement is made using a thermograph.

Thermometers

The thermometer consists of a glass bulb containing mercury or spirit connected with a glass tube of very small bore closed at the top. The rise or fall of the liquid column in the tube due to expansion/contraction of the liquid is measured from the scale marked on the stem. The scale is in degrees Celsius (^{o}C).

The types of thermometers in standard use at Indian meteorological stations are:

1. Dry-bulb thermometer (mercury in glass) is used for measuring the temperature of the surrounding air.
2. Wet-bulb thermometer (mercury in glass) is used to determine the relative humidity and dew point of the surrounding air.
3. Maximum thermometer (mercury in glass), which indicates the highest temperature reached since previous the setting.
4. Minimum thermometer (alcohol in glass), which indicates the lowest temperature reached since the previous setting.



Campbell-Stokes sunshine recorder
(Latitude 5°S to 45°N)

Figure 6.6: Details of Campbell-Stokes sunshine recorder

Both the dry bulb and wet bulb mercury thermometers are mounted vertically inside the Stevenson screen, which is well ventilated. The maximum and minimum thermometers are fixed horizontally on two wooden mounts inside the Stevenson Screen. In the case of the maximum thermometer, the bulb end of the thermometer is kept about 5 mm lower than the other end.

The thermometers should comply with IS 5681-1983. The range of the mercury in glass thermometers is –35 to 55 °C, the graduation interval is 0.5 °C and an accuracy of 0.2 °C. The alcohol in glass minimum thermometer should have a measuring range of –40 to 50 °C, a graduation interval of 0.5 °C and an accuracy of 0.3 °C.

Thermograph

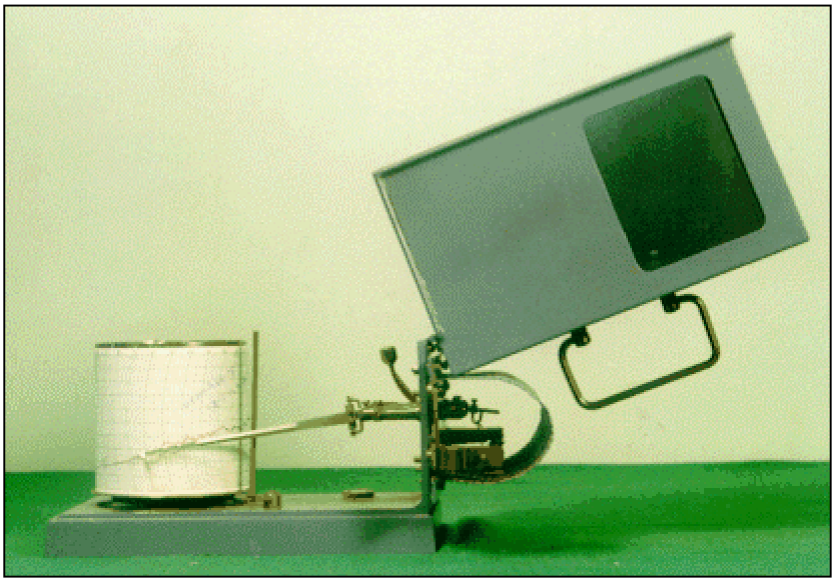


Figure 6.7: General arrangement of bimetallic thermograph

A thermograph is an instrument for recording the temperature of the surrounding air continuously and automatically. It consists of a temperature sensitive element - a bimetallic strip, connected by a system of linkages to a pen, recording on a chart, fixed on a drum driven by clockwork (Figure 6.7 and 6.8). The bimetallic strip consists of two metals having widely different coefficients of expansion like invar and bronze welded together and rolled in the form of a thin single strip bent to form a helix. One end of the helix is rigidly attached to the frame of the instrument, while the other end is fixed to the horizontal spindle to which the pen arm is screwed. When the temperature changes, the curvature of the bimetallic helix changes as a result of the differential expansion of the metals. This movement is transmitted to the pen point and is recorded on a chart fixed on a revolving clock drum.

The thermograph is kept inside a large Stevenson Screen, which is erected by the side of a small Stevenson Screen in the observatory enclosure. The instrument is so placed inside the screen that the sensitive element is at least 15 cm from the louvered sides. Before use, the bimetallic strip should be well annealed or aged by repeated heating and cooling over the entire range of temperature measurement, which is -20 to 60 °C. The thermograph should comply with IS 5901-1970. The recording resolution is 0.2 °C and the accuracy should be 1 °C or better.

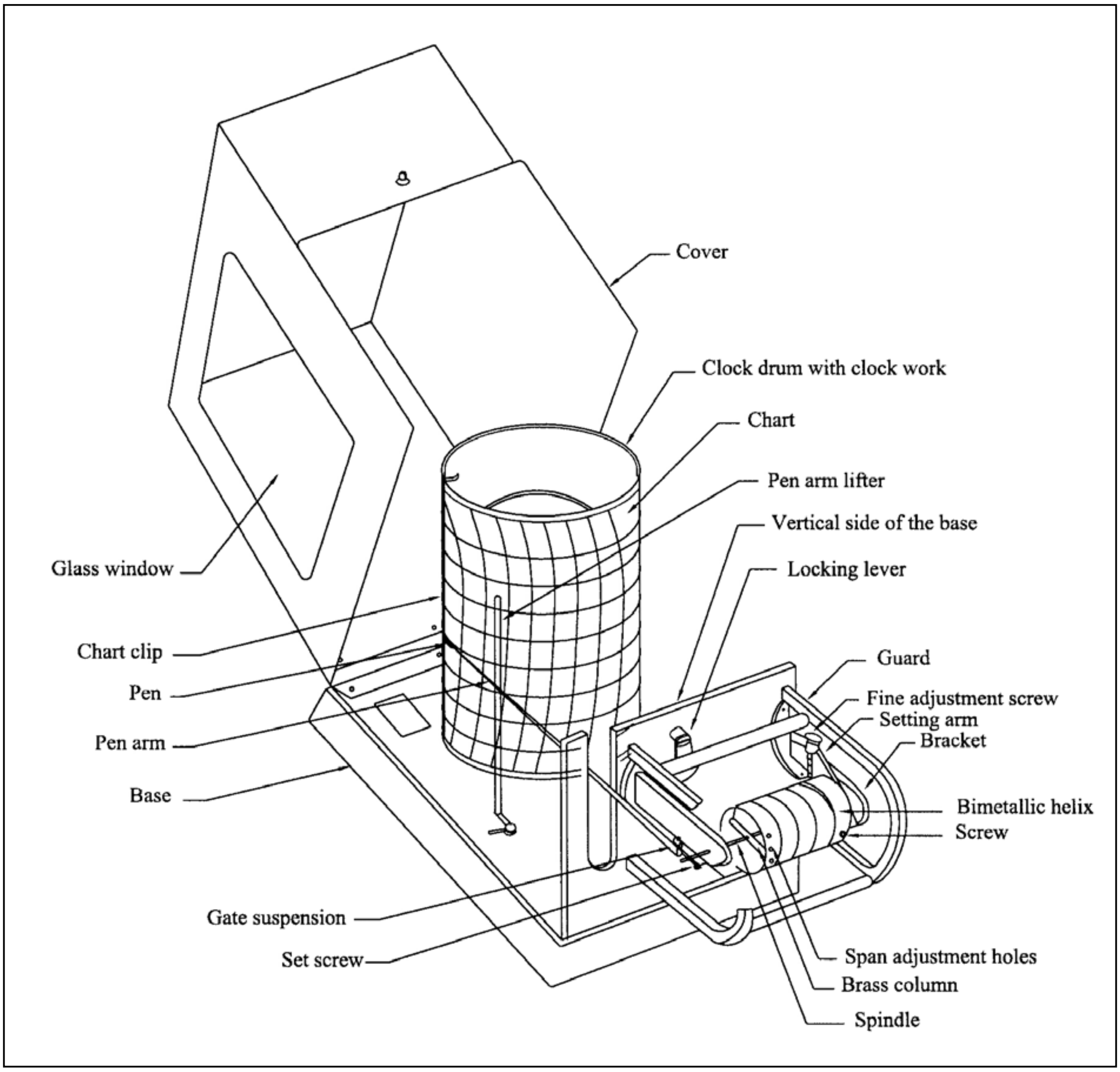


Figure 6.8: Details of thermograph

6.3.3 HUMIDITY

The standard means of assessing the relative humidity or moisture content of the air is by means of the joint measurement of dry bulb and wet bulb temperatures, although continuous but less accurate measurement of humidity is made by means of a hygrograph.

Wet bulb thermometer

As noted in 6.2.2, both the dry bulb and wet bulb thermometers are mounted vertically inside the Stevenson Screen. The wet bulb is covered with muslin cloth tied round the bulb by a cotton wick (Figure 6.9). Care should be taken not to fasten the wick too tightly round the neck of the bulb, otherwise the circulation of water along the wick, thence to the muslin, will be stopped at this point. It is essential to keep the water circulation continuous as the thin water film forming over the bulb keeps evaporating. The heat energy for this change of state comes from the surrounding air by which the temperature of the surrounding air decreases and the wet bulb thermometer records the lower temperature. This process continuous till the surrounding air becomes fully saturated and the temperature becomes steady. The difference between the dry bulb and wet bulb temperatures is a measure of the relative humidity. The greater the difference in temperatures the drier is the surrounding air. If the difference is zero i.e. both dry bulb and wet bulb record the same temperature, the relative humidity is 100%. For calculating the relative humidity, hygrometric tables are available at the station.

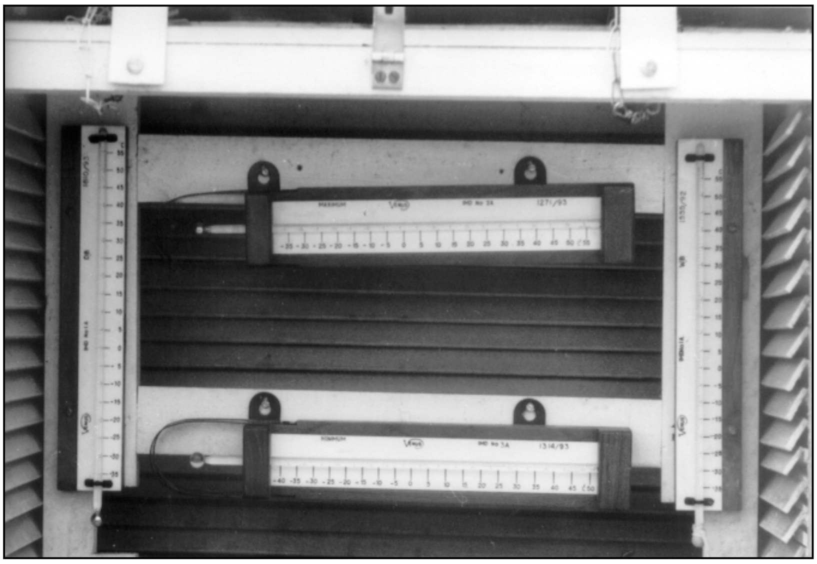


Figure 6.9:
Wet bulb thermometer (right)
And
Dry bulb thermometer (left)

Hygrograph

The hygrograph records the relative humidity of the air continuously. The sensor used is human hair and it works on the principle that the length of the hair increases as the relative humidity increases and vice-versa. The change in length of the hair is, however, not directly proportional to the change of the relative humidity. A suitably designed cam has been introduced in the hygrograph to modify the magnification so that the movement of the pen is proportional to the relative humidity (Figure 6.10 and 6.11). The equipment should comply with IS 5900-1970. The required recording resolution is ± 0.2% RH and the accuracy of the equipment above a humidity of 20% should be 5% RH.

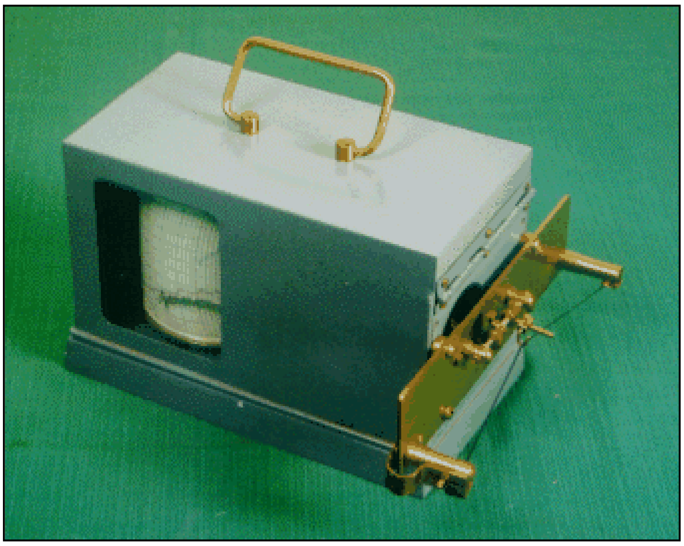


Figure 6.10:
Hair hygrograph

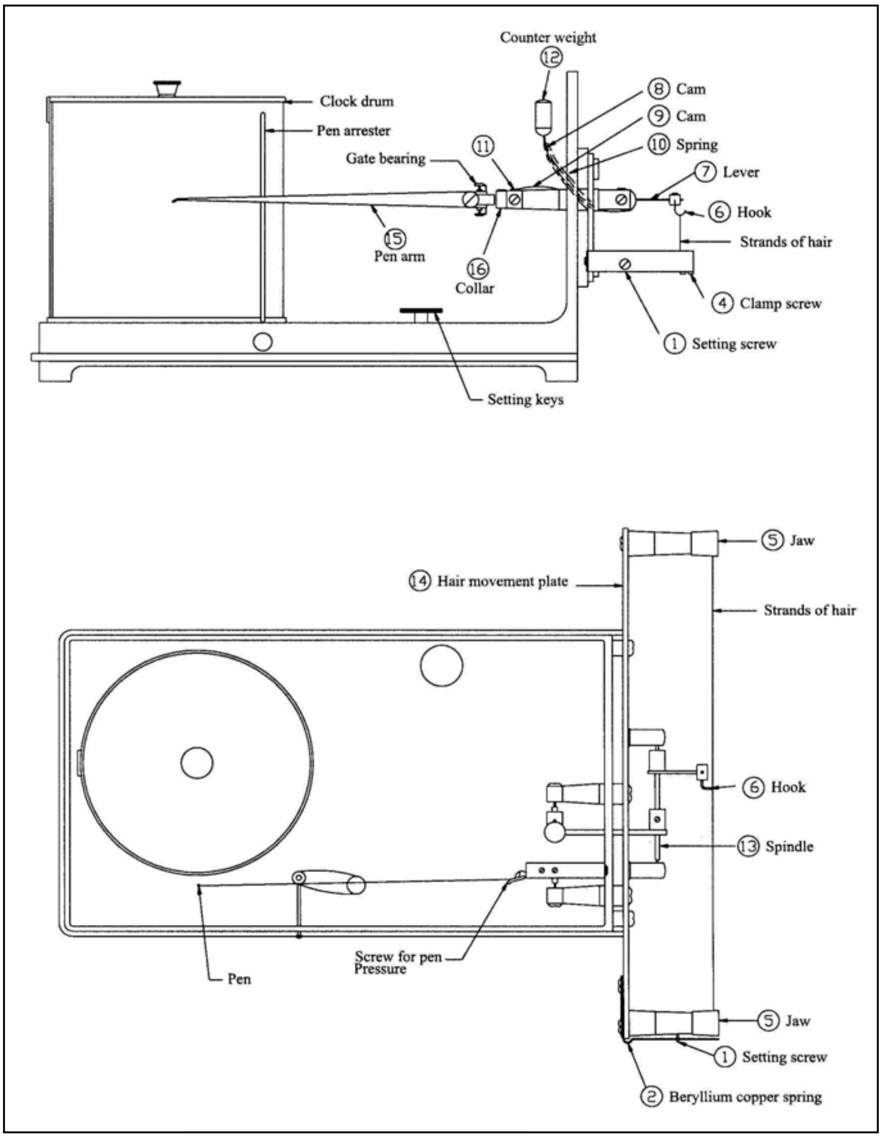


Figure 6.11:
Details of hair hygrograph

For recording the relative humidity of the air, the hygrograph is generally placed by the side of a thermograph in large Stevenson Screen located in the observatory enclosure. The screen should be located at a place where the surrounding air is free from pollution like excessive smoke, dust, oil vapour, ammonia gas etc

6.3.4 WIND

Wind Speed

Wind speed is of particular importance in hydrology as it controls the advective component of evaporation.

An anemometer measures the wind speed. The instrument generally used is a cup anemometer shown in the Figure 6.12. It works on the principle that the force on the concave side of the cup due to wind is greater than that on the convex side. In this position, the cup rotates. The rate of rotation does not depend on the direction of the wind. The cups drive a revolution counter via a gear arrangement. To obtain the wind speed, the counter is read at the beginning and end of a certain period and the difference in two readings in noted. The mean wind speed during this period is obtained by dividing the difference in counter readings by the time interval.

The counter type anemometer should comply with IS 5912-1970, and should have a range of 50 m/s and an accuracy of 0.25 m/s for wind speeds up to 2.5 m/s and 10% full scale for higher wind velocities.

Wind direction

Wind direction is of interest in showing the source of moisture laden air masses, but is not used directly in the calculation of evapotranspiration. Measurements are made at the same time as wind speed.

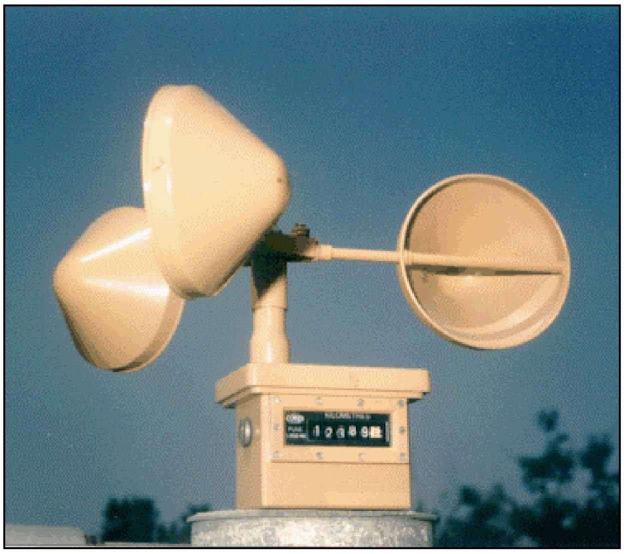


Figure 6.12:
General arrangement of cup counter anemometer

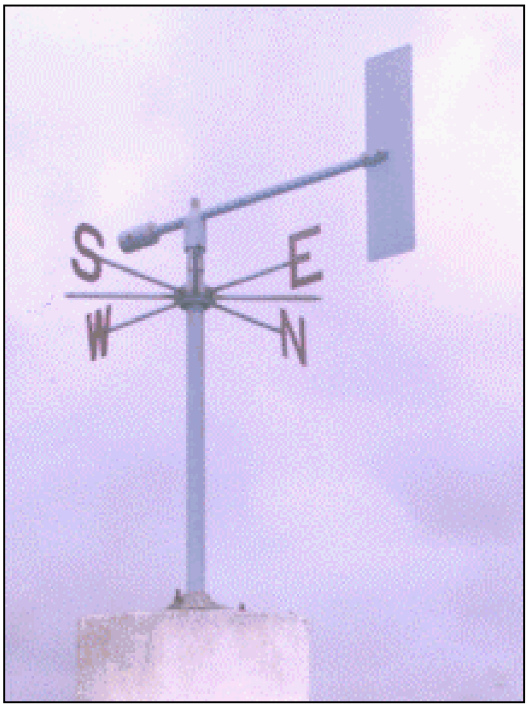


Figure 6.13:
General arrangement of wind vane

Wind direction is defined by the direction from which it blows. It is determined with reference to true north and is expressed to the nearest 10 degrees or to 16 points of the compass i.e. NNE, NE, ENE, E, ESE, SE, SSE, S. SSW, SW, WSW, W, WNW, NW, NNW and N. The wind direction is estimated by a wind vane, see Figure 6.13. It is a balanced lever, which turns freely about a vertical axis. One end of the lever exposes a broad surface to the wind while the other end is narrow and points to the direction from which the wind blows. The wind vane should comply with IS 5799-1970. It should have 8 direction arms, with direction letters for N, E, S and W.

6.3.5 EVAPORATION

Evaporation is a process by which water changes from liquid to vapour state continuously at all temperatures. For practical purposes, over a given area, evaporation is proportional to the depth of liquid water lost in unit time and is generally measured in millimetres. The instrument used for measuring evaporation is called an evaporimeter.

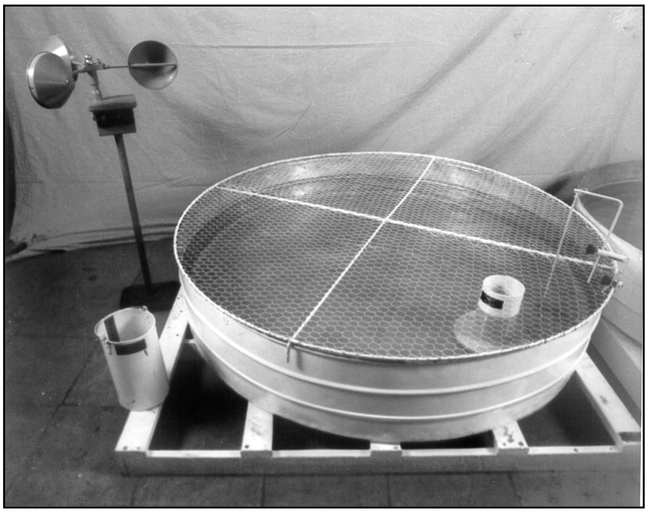


Figure 6.14:
US Class A pan evaporimeter, general set up

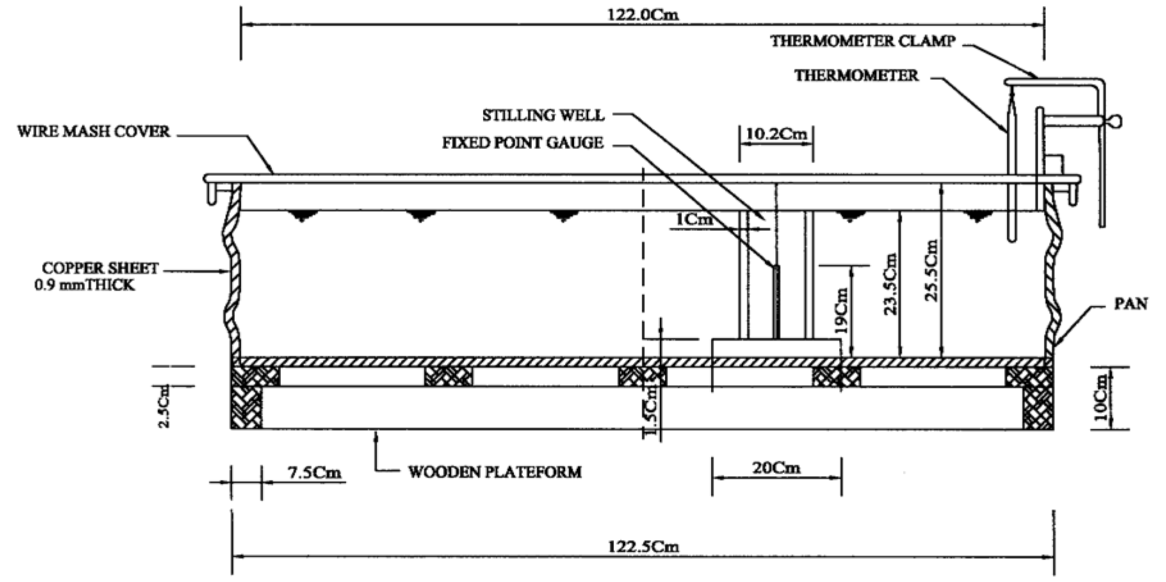


Figure 6.15: US Class A pan evaporimeter, details

The commonly used evaporimeter is the US 'Class A' Pan Evaporimeter (see Figure 6.14). It consists of a large circular pan with a stilling well to provide an undisturbed water surface around the point of a hook gauge as shown in the Figure 6.15. The diameter of the pan is 122 cm and is 25.5 cm deep. The pan is made of a 20 gauge copper sheet or a galvanised iron base. The pan rests over a white painted wooden stand on hard soil, which ensures that the bottom of the pan is not tilted and always remains above the level of rainwater in a rainy period. The rim of the pan should be exactly 36.5 cm above ground level. The pan is covered with a wire-netting of standard mesh to avoid loss of water due to birds or animals' interference. The base of the pan is painted white from inside (chlorinated rubber paint). A thermometer to measure the surface temperature of the water is fixed with a brass clamp to the side of the pan so that the bulb just dips in the water. An anemometer is generally mounted at the level of 2 m above the ground near the instrument to provide wind speed data.

The pan evaporimeter is installed in the observatory enclosure by the side of the rain gauge so that the exposures of the two instruments are identical and the amount of rain caught by the pan is represented by the amount caught by the rain gauge. The stilling well is placed in the pan about 30 cm from the north edge of the pan so that the gauge can be conveniently observed. The graduated measuring cylinder, from which water is poured into the pan, is a brass container with a scale 0 to 20 cm. It has a diameter of exactly one tenth that of the pan, i.e. 122 mm, so that the cross-sectional area of the cylinder is 1/100 of the pan, that is 200 mm water from the cylinder added to the pan raise the level in the pan by 2 mm. Measurements can be made correct to 0.1 mm. The pan should comply with IS 5973-1970.

6.3.6 ATMOSPHERIC PRESSURE

The pressure of the atmosphere at any point is the weight of the air column, which lies vertically above a unit area. It is usually measured by means of a mercury barometer where the weight of the mercury column represents the atmospheric pressure. For continuous recording of air pressure a barograph is used.

The unit for pressure is hectopascal. Under standard conditions, a column of mercury having a true height of 760 mm exerts a pressure of 1013.250 hectopascals (hPa).

In order that barometer readings made at different times and at different places should be comparable, the following corrections should be made:

- correction for index error,
- correction for gravity, and
- correction for temperature.

Barometer

The barometer used at the meteorological stations is the Kew pattern barometer. The essential parts of a Kew pattern barometer are:

- a glass tube about 90 cm long, closed at the top and open below,
- a cistern, and
- a brass scale.

The glass tube is filled with mercury and its open end is dipped in mercury in the cistern, which prevents air from entering the tube. The space above the mercury column in the tube is totally free from the air. The weight of the mercury column in the tube is balanced by the pressure of the atmosphere on the surface of mercury in the cistern. As the mercury in the barometer tube rises or falls due to changes in the atmospheric pressure, the mercury level in the cistern changes in opposite direction. These changes in the cistern level are taken into account in the graduation of the scale itself. There is a milled head screw at the side of the barometer for operation of a small moveable scale known as the vernier. There is a sliding piece along with the vernier at the back of the instrument. Its object is to ensure that the observer's eye is at the same level as the top of the mercury column to avoid errors due to parallax while reading the scale. A thermometer is attached to the barometer to record the temperature before measuring the pressure. The barometer is installed in a room, which is not subject to sudden temperature change or vibration. The top of the instrument is above 1.8 meter above the ground.

Barograph

The barograph (see Figures 6.16 and 6.17) is less reliable than the barometer discussed above, but convenient for use in the field. The essential parts of the barograph are an aneroid element, which is sensitive to changes in atmospheric pressure, a system of levers and a clock mechanism, which drives a drum on which a chart is wrapped. The movement of the aneroid element, which either expands or contracts due to changes in the atmospheric pressure, is amplified by means of the system of levers and recorded by a pen on the chart.

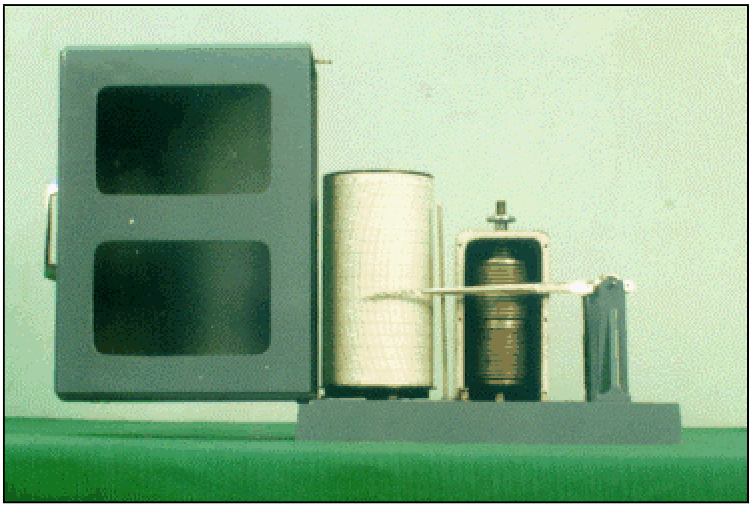


Figure 6.16: Barograph

For a good barograph, the reading should not change more than 0.5 hPa for a change of temperature of 30 ^{o}C. The hysteresis should be small to ensure that the difference in reading before a change of pressure of 50 hPa and after return to the original value does not exceed 0.5 hPa.

The barograph is installed in a place where it is protected from sudden changes of temperature, vibration and dust. It is best to install the barograph in a room on a horizontal shelf or masonry pillar about one meter high and protected from direct sunshine.

The initial setting of the barograph is done with the help of the mercury barometer and it is so set that the mean station pressure is about the centre of the chart.

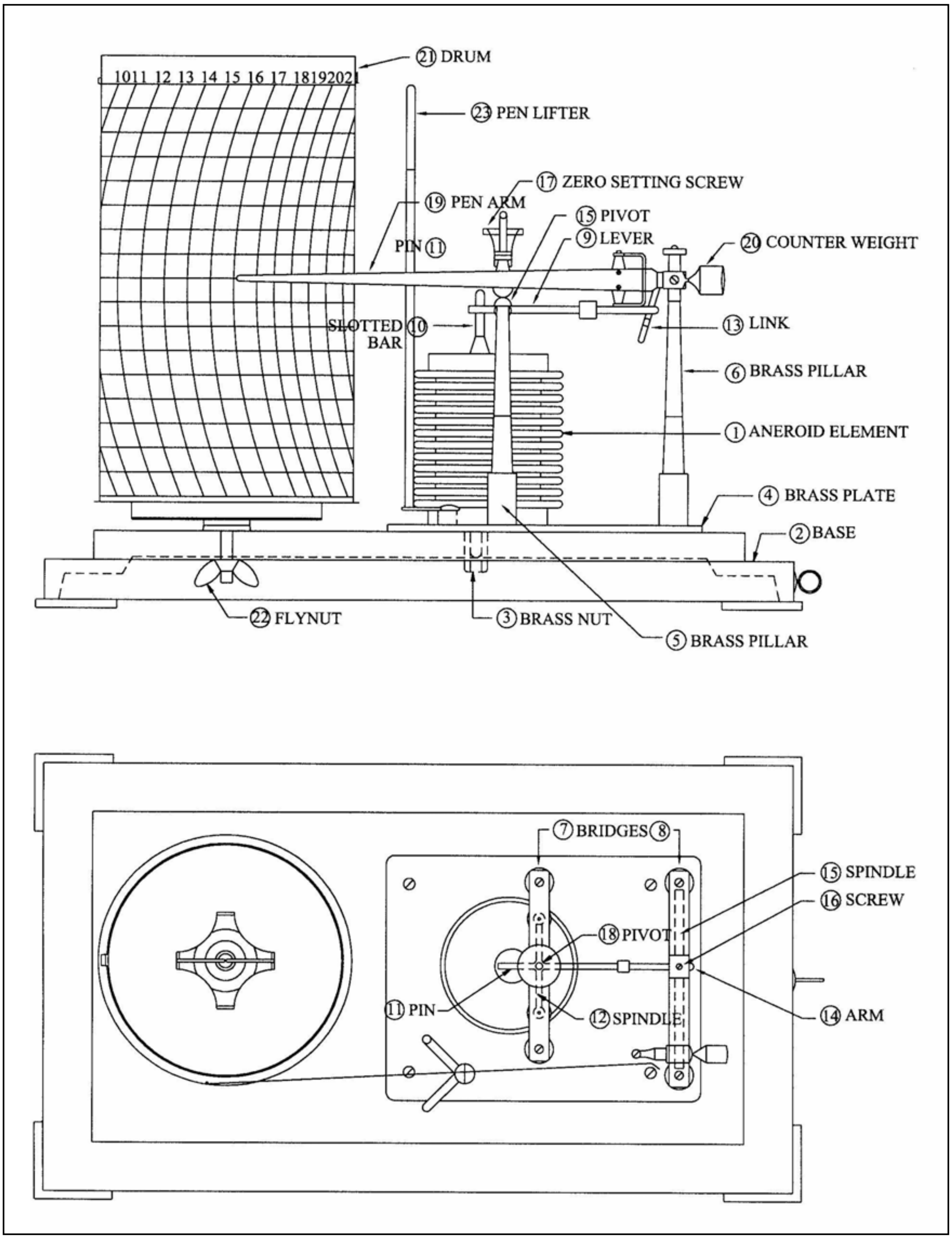


Figure 6.17: Open scale barograph

7 EQUIPMENT SPECIFICATIONS

The specifications for meteorological equipment are presented in the ‘Equipment Specification Surface Water’ as a separate volume, which is regularly updated so as to provide the latest state of the technology.

The meteorological equipment included in the specifications are:

- Digital Weather Station, to monitor:
  - Wind speed
  - Wind direction
  - Air temperature
  - Relative humidity
  - Rainfall
  - Solar radiation
- Counter type anemometer (IS 5912-1970)
- Wind direction indicator (IS 5799-1970)
- Rain-gauge, non-recording (IS 5225-1992)
- Rain-gauge, autographic (siphon type) (IS 5235-1992)
- Rain-gauge, tipping bucket type
- Sunshine recorder (IS 7243-1974)
- Liquid in glass thermometers (IS 5681-1983)
- Thermograph, bimetallic type (IS 5901-1970)
- Hygrograph, hair string type (IS 5900-1970)
- Stevenson screen (IS 5948-1970)
- Evaporimeter, US Class A pan (IS 5973-1970)

8 STATION DESIGN AND CONSTRUCTION

8.1 GENERAL

A hydro-meteorological station is set up to monitor basic hydro-meteorological elements like pressure, temperature, humidity, rainfall, evaporation and sunshine regularly, and as such it represents the climatic features of that region. A complete lay out of the station with detailed specifications is shown in Fig. 8.1. The specifications are to be followed faithfully while undertaking the construction work. A levelled plot of land preferably 18 x 15 metres should be selected in the open for setting up the hydro-meteorological station. It should be ensured that the site has good exposure conditions and no high buildings or trees exist close-by. It should also be free from human interference like close-by residential areas or play grounds. Further, all the installation work is to be carried out in accordance with the standards by skilled masons under the supervision/guidance of an IMD Inspector.

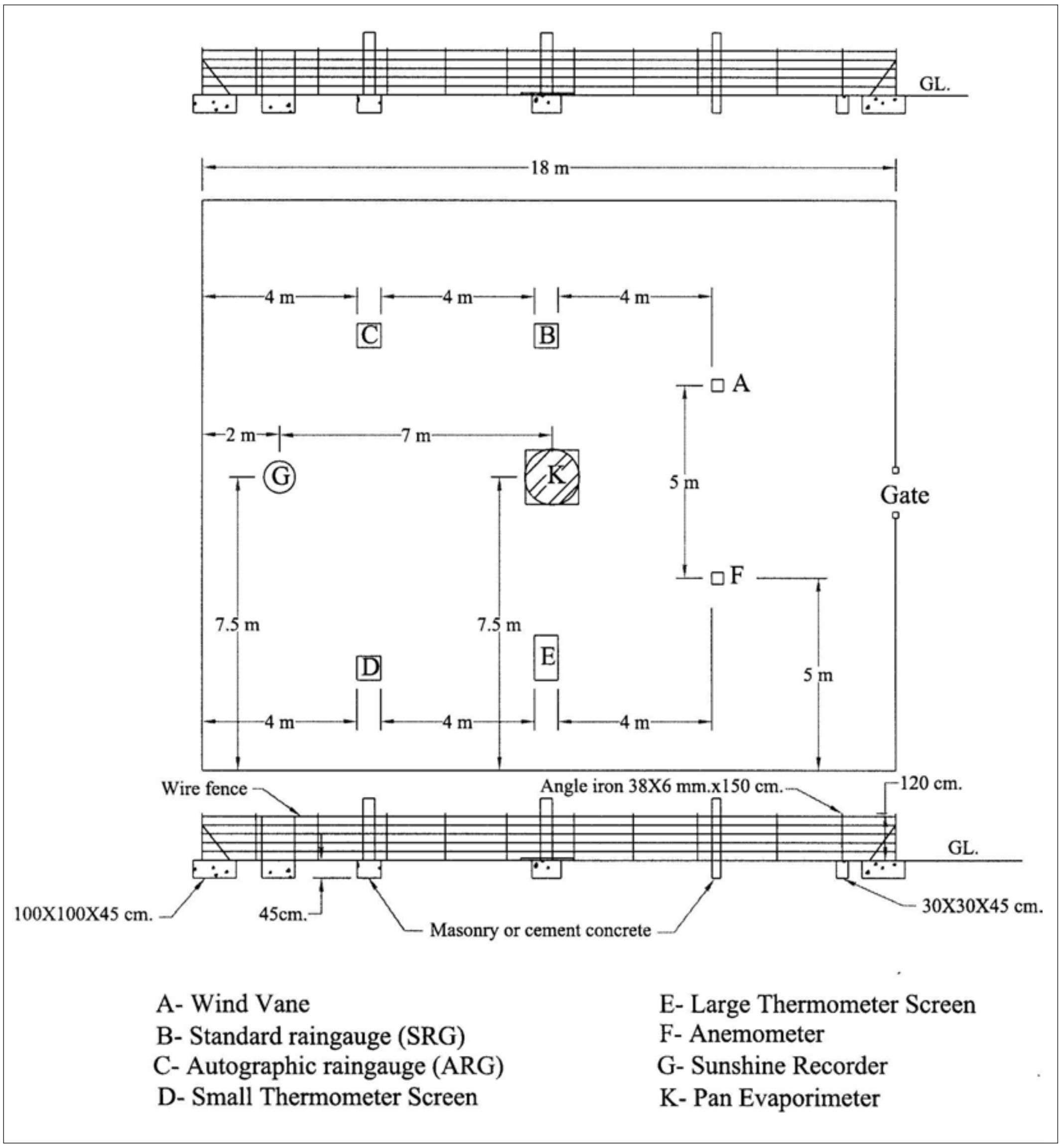


Figure 8.1: Layout of observation station

The working condition of each instrument is checked before actual installation. It is preferable if the observer, earmarked to man the station, is also present at the site when the installation work is carried out. This will provide a better understanding of the mechanism involved in the functioning of different hydro-meteorological instruments.

8.2 RAINFALL STATION

8.2.1 DESIGN (LAYOUT) OF SRG AND ARG STATIONS

There are two types of rainfall stations. The first one is equipped with a standard rain gauge (SRG) and the second one is equipped with a standard rain gauge and an autographic rain gauge (ARG) or a tipping bucket type recording-gauge installed side by side. For the safety of the instruments, the observatory is fenced with barbed wire. It is necessary that the plot of land selected should have the same ground cover as the natural cover common to the surrounding area. Further obstructions like trees, buildings, shrubs, etc. should not be closer than, at least, twice the height of the object.

8.2.2 INSTALLATION OF SRG

For a standard raingauge, a fairly levelled plot of land, free from obstruction, of the size of 5 x 5 m is required and the raingauge is installed at the centre of the enclosure. The standard rain gauge is fixed on a concrete foundation 60 x 60 x 60 cm sunk in the ground. The rim of the SRG is kept exactly 30 cm above the ground level, see Figure 6.1. The purpose of keeping the rims above the ground level is to minimise the wind effect and splashing.

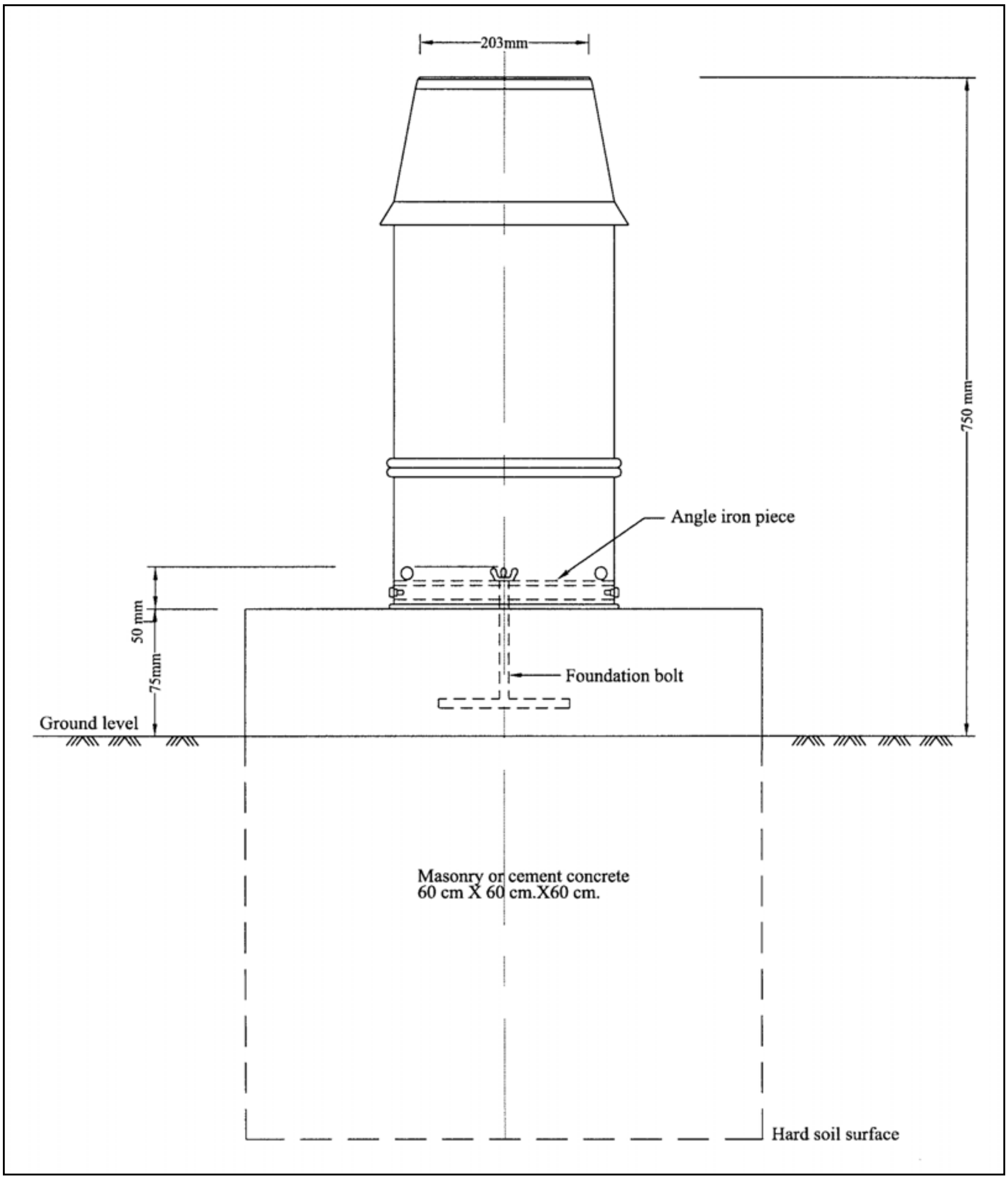


Figure 8.2: Installation of natural siphon type recording rain gauge

8.2.3 INSTALLATION OF ARG

For an ARG and an SRG, a fairly levelled plot of land, free from obstruction, of the size of 10 x 5 m is required and the rain gauges are installed side by side 2 meter apart at the centre of the enclosure.

The ARG is installed inside the enclosure on a concrete or masonry platform of 60 x 60 x 60 cm cube erected from a hard soil surface, see Figure 8.2. If the soil is loose, dug deeper and fill up with rubbles up to the depth of 45 cm below ground level. A 15 cm long foundation bolt is fixed in the centre of the platform so that 5 cm of the bolt projects above the top of the platform. Next, the galvanised iron base of the rain gauge on the platform is fixed as follows:

- Remove the three thumbnuts and raise the recording mechanism straight up from its seat.
- Place the recording base on the platform so that the foundation bolt passes through the holes in the centre of the angle iron piece and fix it with the fly nut. This can be done through the opening in the base.
- Place the cover and see that the instrument is firm and vertical. This is checked with the help of a spirit level.
- Replace the recording mechanism in its place and lock it with three thumbnuts.
- The height of the rim is kept exactly 75 cm above the ground to avoid splashing.

8.2.4 INSTALLATION OF TBR

The space requirements for a TBR station are similar to an ARG station. The TBR will be mounted on a concrete slab with dimensions 60 x 60 x 5 cm. Appropriate surface treated mounting bolts (M 6 x 130) with nuts and washers should be supplied with the delivery of the TBR. The required civil works shall be finalised in collaboration with the supplier.

8.3 CLIMATIC STATION

8.3.1 OBSERVATORY ENCLOSURE

For a full climatic station, the size of the plot should be 18 x 15 m. The height of the fence is kept 1.2 m above ground level and has 6 strands of barbed wire running parallel 20 cm apart as shown in Figure 8.1. The barbed wire strands are tightly secured with the help of iron angles 38 mm x 6mm x 150 cm in dimension. Each iron angle is fixed in a concrete block of the size 30 x 30 x 45 cm and kept 1.5 m apart. The four corner angles are provided with inclined iron supports. The fenced enclosure has one opening fitted with an iron gate. The specifications of the gate are shown in the Figure 8.3. The gate is kept locked to prevent any undesirable intrusion of stray cattle or dogs.

8.3.2 INSTALLATION OF INSTRUMENTS

A full climatic station (FCS) is equipped with eye reading and autographic instruments like rain gauges, wind instruments, thermometers, thermograph, hygrograph, evaporimeter and sunshine recorder.

A complete layout of the installation of the meteorological instruments is shown in Figure 8.1. The wind vane (A) and Anemometer (F) are fixed 5 m apart, each to be 4 m from the fence inside and 2 m above the ground level. Both the instruments are fixed on a 13 mm diameter standard gas pipe the base of which is rigidly embedded in concrete block.

The Standard Rain-gauge (B) is fixed on a concrete foundation 60 x 60 x 60 cm sunk in the ground, 4m from the fence inside and 4 m from the alignment of wind vane (A). The rim of the SRG is kept exactly 30 cm above the ground level. The autographic rain-gauge (C) is fixed on a concrete platform 60 x 60 x 60 cm sunk in the ground, 4 m from the SRG (B) and also 4 m from the fence inside. The rim of the ARG is kept exactly 75 cm above the ground level. The purpose of keeping the rims above the ground level is to minimise the wind effect and splashing.

The Pan Evaporimeter (K) is installed at the centre of the observatory, closer to the SRG (B), so that the exposures of the two instruments are identical and the rainfall amount caught by the pan is represented by the amount caught by the rain-gauge. The instrument is placed on a wooden stand which is kept on hard surface so that the instrument does not get tilted even after heavy rains. The rim of the pan should be exactly 36.5 cm above ground level.

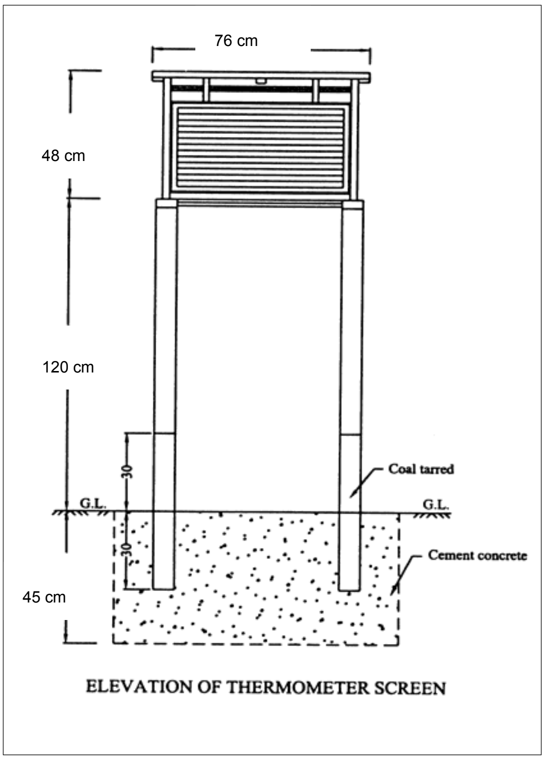


Figure 8.3:
Installation of Stevenson Screen

The Small Thermometer Screen (D) and the Large Thermometer Screen (E) are fixed on the other side of the observatory enclosure, side by side, 4 m apart and also 4 m inside from the fence. The four posts of the thermometer screen are to be erected perpendicular to the ground by embedding the tarred ends underground in concrete such that the tops are exactly 1.2 m above the ground. It is important to ensure that the door of the screens should open northwards. Inside the small screen (D), the Wet bulb, the Dry bulb, and the Maximum and Minimum thermometers are fixed at their proper places. Only the Maximum thermometer is so fixed that the bulb end is 5 mm lower than the other end so that any vibration of the screen will not disturb the mercury column. The Large Thermometer Screen (E) houses the Thermograph and the Hygrograph. Detailed specifications on installation of small and large screens inside the enclosure are shown in Figure 8.3. The purpose of housing the temperature instruments inside the screen is to provide shade from the sun without restricting natural ventilation.

The Sunshine Recorder (G) is installed in-line with Pan the Evaporimeter at a distance of 7m from it and 2 m from the fence as shown in Fig. 8.1. The instrument is set up on a firm and rigid brick or concrete pillar 36 x 36 cm square and 1.2 m in height above the ground. The four sides of the pillar should face the four cardinal directions E, W, N & S.

Each instrument is made approachable, particularly during rainy season, by laying a 1m wide footpath right from the gate of the enclosure.

8.3.3 INSTALLATION OF WIND INSTRUMENTS

The wind velocity near the surface varies rapidly with height and is also affected by obstacles like trees and buildings. For synoptic reports and general climatological records, the IMD standard exposure height is 10 metres above the ground for a levelled and open terrain. Where the exposure is obstructed , the instrument may be erected on a building parapet wall, at least 3 metres higher than the highest obstacle in the immediate vicinity.

For hydrological purposes, the wind instrument at all FCS is required to be fixed at 2 metres height above the ground for estimation of evaporation / evapotranspiration. The instrument is fixed on the top of a gas pipe, the base of the gas pipe is embedded in a masonry structure. The top portion of the gas pipe is 13 mm in diameter, the middle and lower portions are between 38 to 50 mm in diameter. The Anemometer is fixed by the side of the wind vane, separated by a distance of at least 2 metres.

8.3.4 INSTALLATION OF STEVENSON SCREENS

The large and small Stevenson Screens (SS) are erected inside the enclosure, side by side, 4 m apart. The four legs of the SS are embedded 30 cm deep in a concrete or masonry block of the dimension 180 x 78 cm for the large, 100 x 60 cm for the small screen and 45 cm deep. The lower portion of the legs is coated with coal tar. The screen is designed with a double wall louvered arrangement in order to allow free air passage over the instruments housed inside the SS. The height of the screen is kept at 1.5 m above the ground. The screen is made of pinewood and painted white to minimise the absorption of solar radiation. The door of the screen opens towards North in the Northern Hemisphere.

8.3.5 INSTALLATION OF THERMOGRAPH

For recording free air temperature the instrument should be kept inside the large SS in the observatory enclosure. The sensitive element is kept at least 15 cm from the louvered sides.

8.3.6 INSTALLATION OF HYGROGRAPH

For recording the relative humidity of the air, the hygrograph should be exposed in the large SS by the side of the thermograph.

8.3.7 INSTALLATION OF CLASS A PAN EVAPORIMETER

The Pan Evaporimeter is installed in the enclosure about 2 m from the SRG so that the exposure of two instruments is the same and the amount of rain caught by the pan is equal to the amount caught by SRG. For installation, the wooden stand is placed on levelled hard soil. The earth fill should be used around the stand to anchor it but ensure to leave airspace between the bottom of the pan and the ground. The rim of the pan is kept exactly 36.5 cm above ground level. Next, place the stilling well with reference gauge in the pan about 30 cm from the North edge of the pan. Check the level of the top rim of the stilling well with spirit level. Add water to the pan till the water level reaches the tip of the Reference Point. Place the wire mesh cover over the pan rim tightly. Clamp the thermometer with bulb dipping in water. Mount the anemometer at a height of 2 m above the ground by the side of the evaporimeter.

8.3.8 INSTALLATION OF SUNSHINE RECORDER

The Sunshine Recorder should be ideally set up on a firm and rigid support and free from any obstruction to sun’s rays at any time of the day and of the year. An uninterrupted exposure requires a free horizon between east - north - east and east - south - east on the eastern side and between west - north - west and west - south - west on the western side.

Precise information about the exposure requirements for latitudes is obtained from Fig. 8.4. These show the altitude and azimuth of the sun at different times of the year and in various latitudes 0 - 34 degree North, with the hours of the day in local apparent time marked on the curves. A single diagram corresponds to a particular latitude and the five curves of each diagram are for different times of the year, according to the following key:

Date	**Solar Declination**	**Key**
June 22	23 ½ ^{0} N	A: Summer Solstice
April 21, August 23	11 ¾ ^{0} N	B:
March 21, September 23	0	C: Equinox
February 18, October 25	11 ¾ ^{0} S	D:
December 22	23 ½ ^{0} S	E: Winter Solstice

Where a good exposure is available at ground level, a brick or concrete pillar 36 cm square forms a suitable support. The pillar height is kept 1.2 m. The four sides of the pillar should face the four cardinal points. The base of the instrument is fixed to the pillar by means of two angle iron pieces 33 cm long and 2.5 cm square, four 10 mm foundation bolts 15 cm long and four G.I. pipe sleeves 15 mm external diameter and 42 mm high. The foundation bolts are first embedded in the pillar to a depth of about 5 cm. into the masonry about 4 cm from the North or South side of the pillar and 8 cm from the East or West side.

The instrument must confirm to the following conditions:

- the centre of the sphere and the bowl must be coincident,
- the bowl must be level in the east - west direction, and
- when a card is in position , the hour lines printed across it must be in meridian planes of the celestial sphere corresponding to the hour angle 15, 30, 45 degree etc. measured from the geographical meridian. (This condition is ensured during manufacture).

8.3.9 INSTALLATION OF BAROGRAPH

The barograph is installed in a place where it is protected from sudden changes of temperature, vibration and dust. It is best to install the barograph in a room on a horizontal shelf on a masonry pillar of about one meter high and protected from direct sunshine.

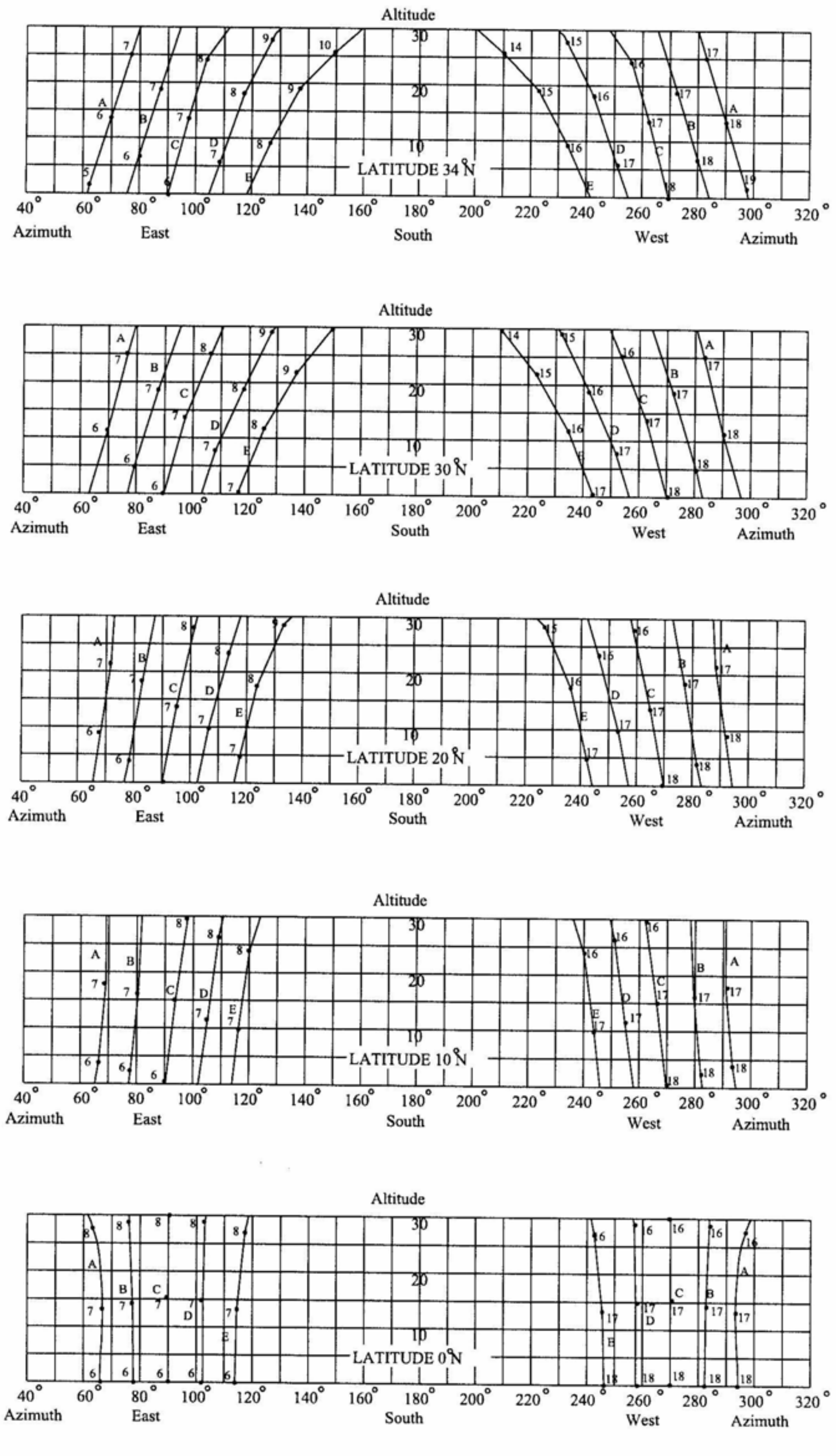


Figure 8.4: Variations of the sun's altitude and azimuth

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