

Chapter 2

Acquisition and Processing of Water Resources Data

The objectives of this chapter are:

- to explain various categories of water resources data;
- to discuss techniques of acquisition, validation, and processing of precipitation and discharge data;
- to discuss meteorological, water quality, and other data used in water resources planning and management; and
- to explain important features of a water resources information system.

Data are the foundations on which any analysis rests. The practice of hydrological measurements is very old. Kautilya initiated systematic precipitation measurements in India in the fourth century BC. Streamflow was probably first monitored by Hero of Alexandria in the first century AD. With development in water sciences, there have been simultaneous developments in equipment and techniques of data collection. A number of international / national standards have been prepared to ensure systematic measurements of water resources and it is necessary that the observatories should conform to these standards. The Committee on Opportunities in the Hydrological Sciences (1991) has appropriately summarized the necessity of good water resources data: "Modeling and data collection are not independent processes. Ideally, each drives and directs the other. Better models illuminate the type and quantity of data that are required to test the hypotheses. Better data, in turn, permit the development of better and more complete models and new hypotheses."

The data needed for water resources are: hydrometeorologic, geomorphologic, agricultural, pedologic, geologic, and hydrologic. Hydrometeorologic data include rainfall, snowfall, temperature, radiation, humidity, vapor pressure, sunshine hours, wind velocity, and pan evaporation. Agricultural data include vegetative cover, land use, treatment, and fertilizer application. Pedologic data include soil type, texture and structure; soil condition;

soil particle size; porosity; moisture content and capillary pressure; steady-state infiltration, saturated hydraulic conductivity, and antecedent moisture content. Geologic data include data on stratigraphy, lithology, and structural controls. More specifically, data on the type, depth and areal extent of aquifers are needed. Depending on the nature of aquifers, these data requirements vary. For confined aquifers, hydraulic conductivity, transmissivity, storativity, compressibility, and porosity are needed. For unconfined aquifers, data on specific yield, specific storage, hydraulic conductivity, porosity, water table, and recharge are needed. Each data set is examined with respect to homogeneity, completeness, and accuracy. Geomorphologic data include topographic maps showing elevation contours, river networks, drainage areas, slopes and slope lengths, and watershed area. Hydrologic data include flow depth, streamflow discharge, base flow, interflow, stream-aquifer interaction, potential, water table, and drawdowns. Thus, for a water resources study, one needs data of a number of variables in the vertical as well as horizontal planes.

The activities of a hydrological service are shown in Fig. 2.1. The term *hydrological data processing* is a widely used but loosely defined term that includes a range of activities varying from simple analysis to complete modeling. The processing of hydrological data is a multi-step process that begins with a preliminary checking of raw data in the field and successively higher levels of validation before it is accepted as fully validated data for further use. The passage of data from field to data storage is also not a one-way process and includes several feedbacks. Sometimes, channels for feedback from data users are also maintained. Actually, processing and validation of hydrological data are not a purely statistical exercise – these require an understanding of field practices, the principles of observation, and the physics of the hydrological variable being measured.

Data processing also includes aggregation of data observed at a certain time interval to a different interval, e.g., hourly to daily and daily to monthly. Occasionally disaggregation, i.e., conversion from a long (say daily) to short (say, hourly) time step is also carried out. The computation of areal averages, for example, catchment rainfall, is also required for validation. This also provides a convenient means for summarizing large volumes of data.

Typical stages in water resources data processing are:

- Scrutiny of raw data;
- data entry to computer, validation, and correction; and
- data archival and dissemination.

In view of the central role of water resources data in planning, design, and management of water resources projects, this chapter is devoted to basic concepts of data acquisition, processing, storage, and dissemination. Some of the latest techniques of data acquisition are also discussed.

2.1 TYPES OF WATER RESOURCES DATA

There are several ways to classify water resources data. The most common way is to

classify the data into three categories: time-oriented data, space-oriented data, and relation-oriented data.

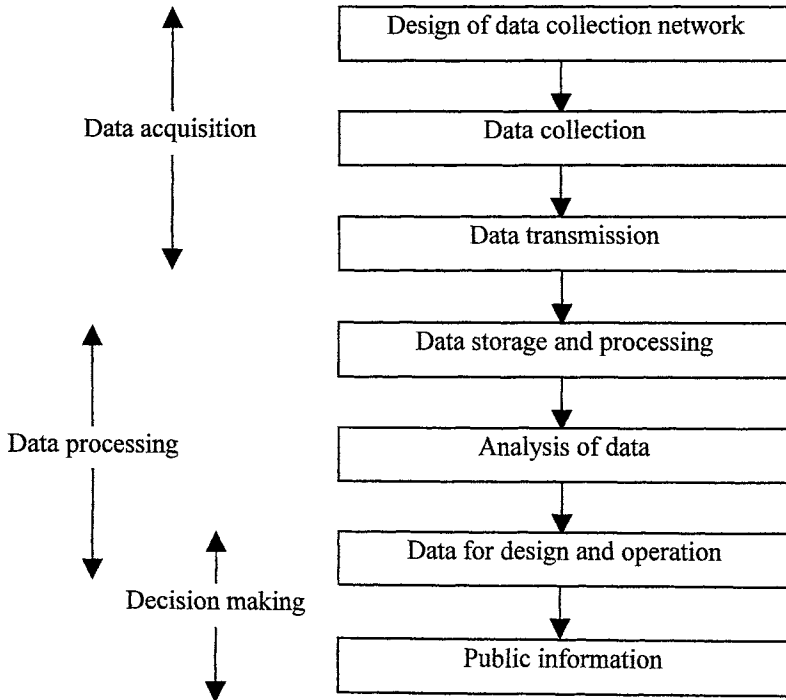


Fig. 2.1 Activities of a hydrological service [adapted from WMO (1994)].

The time-oriented or time-series data consist of hydrometeorological, water quantity, and water quality data that are periodically measured at a station. The time interval between observations can be constant or varying. The examples of such types of data are rainfall, river stage, and sediment concentration. Some surface water data are equally spaced in time. The space oriented data comprise topographic maps of catchments, river networks, soil maps, etc. Traditionally, such data are stored in the form of paper maps and manually analyzed. The recent trend is to use a Geographical Information System (GIS) to input, store and analyze such data. As described in detail in Section 3.3 in Chapter 3, different types of information, such as topographical and land use of an area, are stored in a GIS in different layers of a map which can be overlaid and analyzed. The relation-oriented data consist of mathematical relationships between two or more variables. Typical examples are river rating curves or a spillway rating table.

The water resources data can also be classified as time varying or time non-varying data. The time non-varying or static data includes most space-oriented data which do not change with time, for example catchment topographic map, soil map, etc. Some features, such as river network and land use in a catchment, might gradually change with time and

can be considered as semi-static. A brief description of each type of data is presented in what follows.

2.1.1 Time-Oriented Data

The values of most hydrometeorological and water quality variables change in time and such variables are classified as time-oriented data. These data can be further classified as meteorological data, hydrological data, and water quality data.

The time-series data include all the measurements which have an observation time associated with them and most water resources data have this property. The variable could be an instantaneous value, e.g., water level in a river; an accumulated value, e.g., daily rainfall; an averaged value, e.g., mean daily discharge; or a statistic over a specified time period, e.g., annual maximum flow. The distinction between instantaneous and accumulative values is important when the data are further processed.

Depending on the frequency of observations, the time-series data can also be classified as:

- Equidistant time-series are measurements which are made at regular intervals of time (hourly, daily); the values may be instantaneous, accumulated or averaged.
- Cyclic time-series are the measurements which are made at irregular intervals of time but the irregular time sequence is repeated regularly, for example, the observation of river stage daily at 08:30 and 17:30 hrs.
- Non-equidistant time-series are the measurements which are made when some specified event takes place. For example, in a tipping bucket raingage, each tip of the bucket is recorded after a certain depth of rain has fallen.

The two most important data for hydrological analysis are precipitation and streamflow. The measurement and processing of these two will be discussed in greater detail. The time-series of evaporation data forms another important input in hydrological studies. The temperature of air, soil and water bodies is important as many processes depend on it. Other important meteorological variables include humidity, wind speed and direction, and sunshine duration.

2.1.2 Space-Oriented Data

The space-oriented data comprise of catchment data (physical and morphological characteristics), river data (cross-sections, profile, bed characteristics), and lake or reservoir data (elevation-area-storage capacity). These have been further discussed in Section 2.8.

2.1.3 Relation-Oriented Data

This data contains relationship between two or more variables. The variables themselves may form a time-series but their relationship is of interest here. The relationship may be expressed in mathematical, tabular, or graphical form and is derived using the data. The

stage-discharge rating at a site is a typical example of relation-oriented data. Note that this relation may change with time.

A mathematical relationship between two or more variables is established for a variety of purposes, such as data validation, filling-in of data gaps, etc. The relationships between stages at two adjacent gauging stations and between the average rainfall in a catchment and the resulting outflow are some typical examples. In some instances, relationships may be established between water quality parameters and discharge to determine pollutant loads. The parameters of the relationship along with the ranges of independent variables, error statistics and the period of applicability are required while establishing a relationship.

The stage-discharge data are the most common example of this type of data. Stage-discharge observations are the primary data to establish the relationship called the rating curve at a river-gauging station. Normally, such relationships may be expressed in parabolic or power form. More than one equation may be required to characterize the relationship which may change with time.

2.1.4 Techniques for Observation of Water Resources Data

There are many ways in which the data that are used for water resources studies can be collected. The major techniques are described below.

Gaging Equipment

This is the most common way to observe hydrometeorological variables, such as precipitation, streamflow, etc. A gaging site is established and is equipped with the devices that can measure the variable(s) of interest. An observer visits the site to manually note the value of the variable and record or transmit it to the place of use. Using a modern means of communication, it is possible to get the desired data from the stations geographically spread over an area at a central place. An automated hydrologic station can measure a number of hydrometeorological variables and store/transmit the data. The equipment may be programmed to transmit the data after selected time interval or it can be interrogated at any time to get the data. The design of networks, equipment, and methods of observation of some important variables are described in detail in later sections.

Remote Sensing

In this technique, the data about an object are obtained without coming in physical contact with the object. This technique repetitively provides spatial data of terrain features and is discussed in detail in Chapter 3. Weather radars are being increasingly used for measurement of precipitation and are described in Section 2.4.1.

Chemical Tracers

In this approach, some chemicals, known as tracers, are added to the process whose data are

to be obtained. The procedure to measure river discharge using tracers has been described in Section 2.6.3. Tracers can also be used to determine the flow path of water or a pollutant. The nuclear or isotope techniques are employed to trace the movement of water molecule in any part of the hydrological cycle and derive information about hydrological processes. Nuclear techniques are helpful to assess the rate of sediment deposition in a water body, identify the rainfall recharge and recharge areas of aquifers, study of seawater intrusion in coastal regions, measure seepage and leakage from surface water bodies, analyse surface water and ground water interaction, etc. The stable isotopes, such as Oxygen-18, Deuterium, Carbon-13 (for C-14 dating), and N-15, are commonly used.

2.1.5 Sources of Data

The sources of water resources data can be obvious or usual as well as unusual. The usual data sources include water resources/irrigation departments, river basin / regional water authorities, experimental and research organizations, universities (for research and experimental basins, farms, etc.), public health authorities, and the like. The unusual sources include non-governmental organizations, airport authorities (mainly meteorological data), municipal bodies, etc. In any detailed study, it is advisable to search and contact unusual data sources too. This could be a painful effort but may turn out to be worth the trouble. A field visit is always helpful in getting supplementary information. For example, high-water marks along rivers are useful in delineating flood-prone areas and can also be used to crosscheck peak discharges.

The collection of hydrologic data involves locating the data sources, followed by inspection and evaluation of these data to establish their suitability and sufficiency for the study. In view of wide differences in the practice of data storage and dissemination, the efforts required for data collection tremendously vary from country to country. In some cases, it may just mean browsing the Internet and downloading the requisite data. In others, it may mean physically visiting the concerned offices and manually copying the data from the available records.

Many times, one data-observing organization is unaware of the data collection efforts of others; even governmental agencies often know little about the data collected by other governmental and non-governmental institutions. This poses additional problems during data collection and processing. Some of the data that are used in water resources analysis may fall under the category of secret data and special procedures and precautions are to be followed to obtain, handle, analyze the data and disseminate the results.

2.2 DESIGN OF HYDROMETEOROLOGICAL NETWORKS

The information on temporal and spatial characteristics of water resources is obtained by a network of observational stations. The main purpose in planning a hydrometeorological network is to find out the hydrological characteristics of an area and gather data for planning, design and management. Setting up a station requires investment for equipment, logistics, and for operation and maintenance. Scientific planning is, therefore, necessary for network design so that the desired results could be achieved with minimum cost.

The requirement of water resources data depends on their end use. Therefore, it is difficult to formulate general rules on network design. Based on spatial features, there are two types of networks: a) areal networks, such as those for precipitation, and ground water levels, and b) linear networks such as those for streamflow and river sediment. Areal networks are established to get spatial characteristic of the variables over an area while the linear networks are set-up for rivers, canals, etc. On the basis of purpose, the networks can be classified in three categories: basic (to get the fundamental characteristics of the variables of interest), specific (to gather data for some specific purpose, e.g., a reservoir project), and temporary (which are in operation for a short period of time). While designing hydrologic networks, the items to be decided are:

- i. the variables to be measured and the frequencies and duration of observations;
- ii. the location of gauging stations;
- iii. the instruments to be installed and methods of observation; and
- iv. data observation and transmission system.

The basic network is designed to provide a level of hydrological information at any location within its region of applicability that would preclude any gross mistake in water resources decision making (WMO, 1994). In the early stages of development of a network, the first step should be to set up a minimum network. Such a network should consist of the minimum number of stations which are required to initiate planning for exploitation of water resources in the region. The number may be based on experience or judgment.

Since the hydrometeorological data networks are operated by a number of independent agencies, it is important that there is a good coordination and exchange of data among them. This will reduce the overall expenditure and improve data quality. Of particular importance is the coordination between water quantity and quality data networks.

In view of their central importance, the precipitation and streamflow networks are discussed separately. The *Guide to Hydrological Practices* (WMO, 1994) published by World Meteorological Organization (www.wmo.ch) contains useful guidelines to set up networks for various types of data, and observe and analyze the data. Some sections in this chapter are significantly influenced by this publication. A number of other relevant WMO publications are listed in references. The handbook by ASCE (1996) also contains a lot of relevant information.

2.2.1 Precipitation Networks

The optimum density of a precipitation gauge network depends on the purpose for which the observed data are to be used. For example, accurate measurements of precipitation for flood forecasting require denser networks as compared to rainfall-runoff modeling. WMO (1994) has recommended the following (Table 2.1) as minimum network densities for precipitation stations.

Table 2.1 Recommended minimum densities for precipitation stations [Source: WMO (1994)].

| Physiographic Unit | Minimum densities per station (area in km ² per station) | |
|--------------------|---|-----------|
| | Non-recording | Recording |
| Coastal | 900 | 9000 |
| Mountainous | 250 | 2500 |
| Interior plains | 575 | 5750 |
| Hilly/undulating | 575 | 5750 |
| Small islands | 25 | 250 |
| Urban areas | | 10-20 |
| Polar/arid | 10 000 | 100 000 |

The optimum network should be such that it should be possible to determine required characteristics of the variable with sufficient accuracy by interpolation between values of different stations. The optimum number of raingage stations (N) in a network is given by (Singh, 1992):

$$N = [C_v / p]^2 \quad (2.1)$$

where C_v = the coefficient of variation of the rainfall values of the existing raingage stations, and p = the desired percentage error in the estimate of basin mean rainfall. Here, C_v is computed by

$$C_v = 100 * S / P_m \quad (2.2)$$

In which S is the standard deviation and P_m is the mean rainfall of the existing stations. A typical value of p is 10 percent. Obviously, a decrease in the percentage error would mean an increase in the number of gauges required. Mukherjee and Kaur (1987) have proposed a small change in eq. (2.1) by including the mean correlation (r) of precipitation over the area

$$N = [C_v / p]^2 (1 - r) \quad (2.3)$$

2.2.2 Streamflow Networks

Every major stream should be gaged at or near its mouth. Likewise, a number of its tributaries should also be gaged. Naturally, gaging depends on the existing and likely development in the basin. According to WMO, the first gaging station is selected at the most upstream location where the drainage area is about 1300 km². The second station is located at a point in the downstream direction where the drainage area is approximately doubled. The WMO recommendations for a minimum density of hydrometric stations are given in Table 2.2.

Table 2.2 Recommended minimum density of streamflow stations [Source: WMO (1994)].

| Physiographic Unit | Minimum densities per station (area in km ² per station) |
|--------------------|---|
| Coastal | 2750 |
| Mountainous | 1000 |
| Interior plains | 1875 |
| Hilly/undulating | 1875 |
| Small islands | 300 |
| Polar/arid | 20000 |

2.3 DATA VALIDATION

The need for data validation or quality control arises because field measurements are subject to errors. Errors may also arise in data entry, during computations and (hopefully rarely), from the mistaken ‘correction’ of ‘right’ data (DHV, 1999). Data validation is the means by which data are checked to ensure that the corrected values are the best possible representation of the true values of the variable. Basically, data validation is carried out:

- to correct errors in the observed values where possible,
- to assess the reliability of data even though it may not be possible to correct errors, and
- to identify the source of errors to ensure that these are not repeated in future.

Measurement errors may be classified as random, systematic, or spurious in nature (Fig. 2.2). Hydrometric measurements are often subject to a combination of random and systematic errors. *Random errors*, sometimes referred to as experimental errors, are equally distributed about the mean or ‘true’ value. The errors of individual readings may be large or small, e.g., the error in a staff gauge reading where the water surface is subject to wave action. Usually, they tend to compensate with time or are minimized by taking a sufficient number of measurements. A *systematic error* or bias is a systematic difference, either positive or negative, between the measured value and the true value. Systematic errors are generally more serious and the validation process must be able to detect and correct them. Spurious errors arise due to some abnormal external cause. For example, an animal may drink water from the evaporation pan and introduce errors in the data. Sometimes, such errors may be readily detected but it may not be easy to correct them. Often, the measured data may have to be discarded.

Errors during observations typically arise due to:

- faulty equipment, e.g., a current meter with worn-out parts;
- malfunction of instrument, e.g., slippage of float tape in water level recorder;
- improper exposure conditions, e.g., inlet of stilling well blocked so that the water level in well differs from the river;
- personal observation errors, e.g., gauge misread;
- wrong entry of data; and

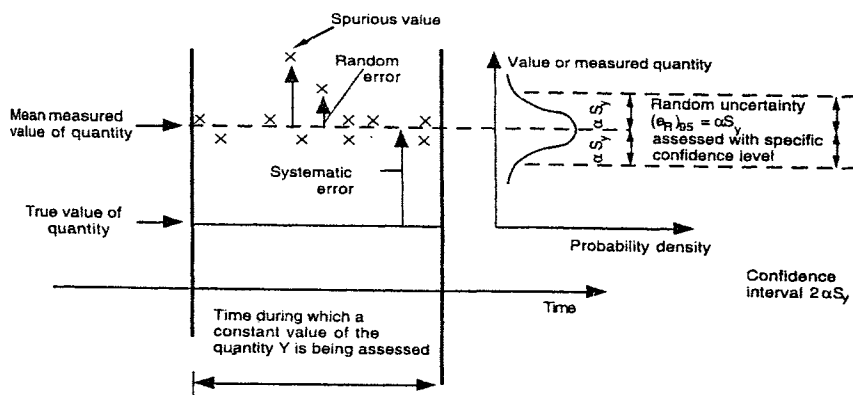


Fig. 2.2 Classification of measurement errors [Source: WMO, 1994].

- error in field computation, e.g., mistake while converting current meter rotations to velocity.

The input variables in an analysis may be directly measured (e.g., rainfall) or they may be derived using a relationship with one or more variables (e.g., discharge that has been obtained from a rating curve). In the latter case the error in the variable (discharge) depends both on field measurements and the error in the relationship. An error may also be introduced if the relationship is no longer valid or the values are extrapolated outside the applicable range. Validation involves different types of comparisons of data and includes the following:

Single series comparison:

- between individual observations and pre-set physical limits;
- between sequential observations to detect unacceptable rates of change and deviations from acceptable behaviour (most readily identified graphically); and
- between two measurements of a variable at a single station, e.g., daily rainfall from a daily gauge and an accumulated total from a recording gauge.

Multiple stations/data:

- between two or more measurements at nearby stations, e.g. flow at two sites along a river; and
- between measurements of different but related variables, e.g., rainfall and river flow.

Levels of Validation

Ideally, data are validated soon after observation and as close to the observation station as possible. This ensures that secondary information to support validation is readily available. However, data validation at or near observation sites is not always possible due to logistics and the lack of the availability of trained personnel. Often a compromise must be reached -- the activities that require interaction with the observers are carried out at or near the station,

whereas more complex analysis is carried out in offices.

The recommended accuracy for selected hydrological variables is given in Table 2.3.

Table 2.3 Recommended accuracy (uncertainty levels) expressed at the 95 percent confidence interval [Source: WMO (1994)].

| Variable | Uncertainty levels |
|---|---|
| Precipitation (amount and form) | 3.7% |
| Rainfall intensity | 1 mm/h |
| Snow depth (point) | 1 cm below 20 cm or 10% above 20 cm |
| Water content of snow | 2.5-10% |
| Evaporation (point) | 2-5%, 0.5 mm |
| Wind speed | 0.5 m/s |
| Water level | 10-20 mm |
| Wave height | 10% |
| Water depth | 0.1 m, 2% |
| Width of water surface | 0.5% |
| Velocity of flow | 2-5% |
| Discharge | 5% |
| Suspended sediment concentration | 10% |
| Suspended sediment transport | 10% |
| Bed-load transport | 25% |
| Water temperature | 0.1-0.5° C |
| Dissolved oxygen (water temperature is more than 10° C) | 3% |
| Turbidity | 5-10% |
| Colour | 5% |
| pH | 0.05-0.1 pH unit |
| Electrical conductivity | 5% |
| Ice thickness | 1-2 cm, 5% |
| Ice coverage | 5% for $\geq 20 \text{ kg/m}^3$ |
| Soil moisture | $1 \text{ kg/m}^3 \geq 20 \text{ kg/m}^3$ |

Note: When a range of accuracy levels is recommended, the lower value is applicable to measurements under relatively good conditions and the higher value is applicable to measurements under difficult situation.

An important aspect in data validation is that none of the procedures are absolutely objective. They are basically tools to screen out suspect data which are to be further examined by other tests and corroborative facts. When it is ascertained that a particular value is incorrect, an alternative value that is likely to be closer to the true value of the variable is substituted; this value is flagged as corrected. Since each hydrological variable has distinct characteristics, it is necessary that specific validation techniques be designed for each variable. It is to be emphasized that validation should never be treated as a pure

statistical exercise; the properties and behavior of the variable under consideration should always be kept in mind.

Based on the information and techniques employed, validation can be grouped in three major categories: a) Primary validation, b) secondary validation, and c) hydrological validation.

2.3.1 Primary Validation

The aim of primary data validation is to highlight and, if possible, correct those data which are not within the expected range or are inconsistent. Primary validation involves comparisons within a single data series or between observations and pre-set limits and/or statistical range of a variable or with the expected behavior of the generating process. Sometimes, information from a few nearby stations may also be pooled. If it is not possible to definitely conclude that the suspected value is erroneous, such value is not changed but is flagged indicating that it is doubtful. All data which have been flagged as suspicious during primary validation are again screened later on the basis of additional information.

2.3.2 Secondary Validation

Secondary validation of data follows primary validation and essentially tests the data for the expected spatial behavior of the variable as inferred from a number of neighboring observation stations. It consists of comparisons between the same variable at two or more stations. The underlying assumption is that the variable in question has adequate spatial correlation within the considered distances. This assumption must be verified on the basis of historical records and the behavior of the variable elsewhere. Some of the checks that are applied at this stage are oriented to trap specific errors known to be made by observers, while others are general and lead to identification of spatial inconsistencies.

The spatial validation is best carried out using the data of key stations which are known to be of good quality. A word of caution: the key stations can also sometimes report incorrect data and will not always be perfect. If all the observation stations are equally reliable then data validation becomes difficult.

When hydrological variables have a high auto-correlation, such as ground water levels, or correlation among neighboring stations, the relationship can be established with a higher level of confidence. However, some processes show a great temporal and spatial variability (e.g., convective rainfall). It is rather difficult to ascertain the behavior of such processes with the desired degree of confidence. If it is not possible to conclude whether the suspected value is erroneous, such value is not changed but is flagged as doubtful. All suspicious data are validated again on the basis of additional information.

2.3.3 Hydrological Validation

Hydrological validation consists of comparing data of (correlated) variables at nearby stations so as to show inconsistencies between the time series or their derived statistics.

Hydrological validation may be applied to a measured variable (water level) or to derived variables (flow, runoff). This is usually done through regression analysis or simulation modeling.

Ideally all the data should be subjected to hydrological validation. For historical data to which no (or few) checks have been applied, hydrological validation provides an effective check on the quality and reliability of records. However, thorough hydrological validation requires a high level of professional expertise and can be time consuming. Therefore, this validation may be applied selectively both in terms of stations and tests. Finally, the validation may be able to identify a particular section of record/ data item that is unreliable, but it may not always be possible to provide a correction.

2.3.4 Data Fill-in

An observed data series may contain gaps due to a fault in equipment, observer absence, etc. and these need to be filled to make the series complete for analysis. Depending on the length of the gap, the type and nature of the variable, and the information available from adjacent stations, a variety of techniques are available to fill-in gaps in a data series. For single value or short gaps in a series with high serial correlation, simple linear interpolation between known values may be adequate. Alternatively, a graph is drawn and the gap is filled by drawing a smooth line through it. Gaps in series with a high random component and little serial correlation, such as rainfall, cannot be filled in this way and must be completed with reference to neighboring stations through spatial interpolation. Longer gaps can be filled through regression analysis and statistical procedures. Large gaps in a discharge series can be filled through rainfall-runoff modeling. Note that the filled-in values will affect the statistics of the series and care is to be taken to preserve historical statistics.

2.4 ACQUISITION AND PROCESSING OF PRECIPITATION DATA

Precipitation is a primary source of fresh water. The amount, intensity and spatial distribution of precipitation are important inputs in many hydrological studies. The total amount of precipitation which reaches the ground in a stated period is expressed as the depth to which it would cover a horizontal projection of the earth's surface. If any part of the precipitation is snow or ice, its depth when melted is included (WMO, 1994). The unit of precipitation is length and daily amounts should be read to the nearest 0.1 mm. Weekly, fortnightly, and monthly amounts should, however, be read to the nearest 1 mm at least. National standards specify the time at which daily observations of precipitation along with other meteorological variables should be made.

2.4.1 Precipitation Gages

Precipitation is measured using a gauge which consists of a collector to delineate the area of the sample and a funnel leading to a storage device. The precipitation, thus collected, is measured by transferring the contents to a graduated measuring jar. The area of the collector and the size of the gauges vary depending on the amount of precipitation normally received in the region where the station is located. Different types of gauges are used to

measure liquid and solid precipitation.

Since the size, shape and exposure affect the precipitation caught by a gauge, a standard gauge should be used so that observations from different gauges can be compared. Most countries have selected one particular type of precipitation gauge as the National Standard gauge which is used in the country wide precipitation gauge network. In India, for example, the Symon's raingage has been adopted as the standard raingage.

The rain gauge is usually fixed on a masonry concrete foundation sunk into the ground and the gauge is cemented into the platform such that the rim of the gauge is approximately 30 cm above the ground level. This height is necessary to prevent the splashing of water into the gauge. The rim of the gauge should be perfectly level. In a non-recording instrument, the rainfall measured at fixed time on any particular date is entered against that date and it is understood that the rainfall so registered has been received in 24 hours preceding that time of the day of observation.

Basically, there are three types of raingages:

- Standard or ordinary raingages (ORG) are manually read, commonly once a day at fixed hours. The readings represent the accumulated depth of rainfall.
- Self-recording raingages (SRRG) record the rainfall depth in the form of a continuous plot. The data are read manually and commonly tabulated at hourly intervals.
- Automatic raingages with data logger. Data are available in digital form either as rainfall at fixed interval or at timings for each event of rainfall of fixed depth (usually 1 mm).

An ordinary raingage (Fig. 2.3) consists of a collector and a funnel; the specifications vary with country. The precipitation caught in the gauge is poured in a graduated measuring cylinder and the depth is noted. Three types of recording gauges are in general use: weighing type, float type, and tipping bucket type. In weighing type instruments, all the precipitation falling is continuously recorded and it can measure all types of precipitation. The float and siphon recording raingage consists of a collector and rainfall recording mechanism mounted on a base. The recording mechanism consists of a float chamber and a siphon chamber. The recording pen is mounted on the stem of the float. A tipping bucket raingage (Fig. 2.4) consists of a circular collector that directs the rain into a bucket that empties when a small amount (say, 0.025cm) of rain fills it. An electrical pulse is generated on each tilt and is recorded to provide a record of the rainfall depth and intensity.

A recording raingage is generally used in conjunction with a non-recording raingage by means of which the readings of the recording raingage could be checked and, if necessary, adjusted. If the equipment has a data logger then the data can be downloaded to a computer directly.

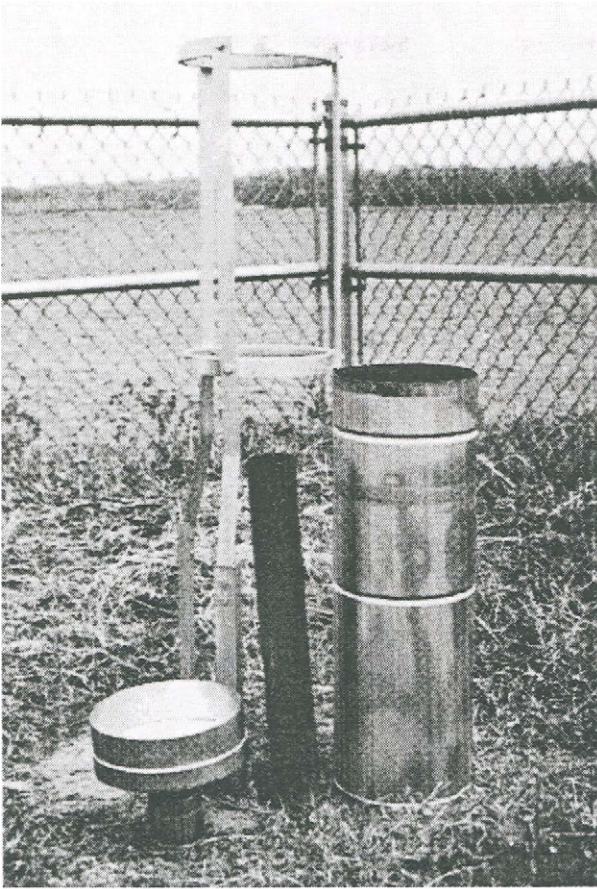


Fig. 2.3 Standard non-recording rain gage.

Precipitation Measurement by Weather Radar

The word *radar* is acronym of radio detection and ranging. Weather radars were developed to overcome the drawbacks of the conventional measurement of rainfall using a raingage. Like an ordinary radar, a weather radar sends electromagnetic waves in all directions from a rotating antenna. These waves collide with raindrops and the echo of returning waves is caught by radar. The time taken by the signal depends upon the distance or range of the object and the strength of returning signal depends on the intensity of rainfall. The main advantage of the weather radar is that it can give the rainfall estimates over wide areas along with location and movement of storms. The system allows measurement of localized storms also which may be missed by raingages. Typically, a grid size of 2km*2km is used. The data are updated frequently, say, every fifteen minutes. The range of radar depends on the hardware; radars with range up to 200 km are common. The factors that control the measurement of precipitation are its type, size of raindrops, width of the radar beam, refraction of beam and atmospheric attenuation. A combined use of raingages and radars provides much more improved rainfall estimates than what any single of them could provide. Cluckie and Collier (1991) discuss the subject in greater detail.

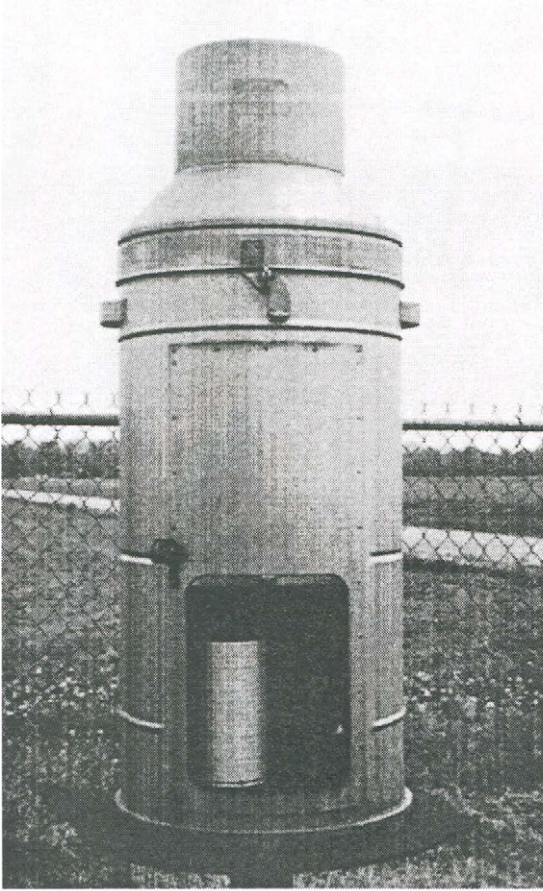


Fig. 2.4 Stevens tipping bucket recording rain gage.

The effective frequency bands that are used in radar depend on climatic conditions and the purpose. The attenuation of radar beam by precipitation is greatest for short wavelengths. The long wavelength radar does not detect light rain and snow as readily as a short wavelength equipment. The three wave lengths in use are (WMO, 1994): Band X – 0.193 to 0.0577m, Band C – 0.0769 to 0.0484m, and Band X – 0.0577 to 0.0275m.

A radar is calibrated using the data of raingages and relationship between the radar reflectivity Z (mm^6/m^3 or the sixth power of the diameter of raindrops in mm per cubic meter of the atmosphere) and rainfall intensity R (mm/h), known as Z-R relationship is established. A commonly used empirical equation is:

$$Z = 200 R^{1.6} \quad (2.2)$$

To estimate rainfall, the most appropriate relation according to the season and event is selected. The estimates are corrected to remove bias in the ratio of radar to gage measurement.

The main advantages of radar are that it can measure precipitation over areas that are difficult to access, it gives areal coverage of rainfall distribution, it is possible to detect the movement of rainfall and it is capable of automatic processing. Due to these reasons, the use of weather radars in precipitation measurement and warning is increasing. The spatial distribution of rainfall is simultaneously displayed on a monitor. The weather radars have been found to be very useful in flood forecasting and warning. On the negative side, the measurements from weather radar are affected by echoes from the ground or ground clutter. In some cases, these radars have been found to underestimate light rainfall and overestimate heavy rainfall.

The measurement of the absolute velocity of a raindrop and its instant direction of movement requires a radar which has a very precise transmitter frequency and a receiver system that is sensitive to changes of frequency induced by a moving target. Such a radar is based on the Doppler effect and is therefore known as *Doppler radar*. Although these radars are more complex and expensive, these are being installed at many places due to obvious advantages. The NEXRAD (next generation radar) system employs doppler radars known as WSR-88D (Vieux, 2002).

Satellites are also being used to estimate precipitation over large areas and in near real-time. Some of the concepts and techniques of analysis of satellite data have been described in Chapter 3. Images from geostationary and polar orbiting satellites along with cloud top temperature, shape, texture, and cloud history are used for estimation of precipitation. Another possibility is to combine satellite images with radar data to obtain improved estimates.

Measurement of Snow

Many catchments receive a large amount of precipitation input in the form of snow. The accumulated snow is a natural storage of water and many major rivers of the world are snowfed. Three variables related to snow are important for water resources: snow depth, area of snow cover, and snow water equivalent.

A common method for observation of snow depth is by stakes that are installed at an accessible location and read to assess the depth of snow. Care is necessary so as to measure only fresh snow. The *water equivalent of snow* is the vertical depth of water that would be obtained by the melting of snow. A snow pillow is a flat circular container that is filled with non-freezing liquid and is used to measure the water equivalent of snow (Singh and Singh, 2001). The weight of the snow on the pillow can be measured by hydrostatic techniques or pressure transducer. The snow water equivalent can also be determined by melting the snow collected in a gauge and measuring the melt water in the same way as rainfall is measured. Isotope techniques are also used to estimate snow water equivalent.

In important catchments, snow surveys are made on permanent snow courses. A snow course is a permanently marked line where snow surveys are made. The snow courses should be carefully selected and should be representative of the area. These should be located in accessible areas where snow falls to the ground without being intercepted by

vegetation, and the site should be protected from strong winds. During surveys, snow samples and depths are also measured at various places at a number of points along the course.

The extent of snowcover can be assessed by areal photography or by satellite imagery. The application of remote sensing for snow-cover mapping has been discussed in Chapter 3.

Sources and Types of Data Errors

Errors in precipitation measurement can occur due to errors in the instrument, errors while reading instrument and transmitting or recording data, errors due to improper instrument exposure or lack of representativeness of the site, and errors that occur during the processing of the data. Most of these errors could be further sub-classified as systematic errors and random errors. Systematic errors are essentially due to malfunctioning of instrument, wrong exposure conditions and/or lack of knowledge of the observer. WMO (1983a) listed the following errors for which adjustments need to be made to get a near accurate estimate of precipitation from a measured report:

- i. error due to the systematic wind field deformation above the gauge orifice,
- ii. error due to the wetting loss on the internal walls of the collector,
- iii. error due to evaporation from the container (generally in hot climates),
- iv. error due to the wetting loss in the container when it is emptied,
- v. error due to blowing and drifting snow,
- vi. error due to splashing in and out of water, and
- vii. random observational and instrumental errors.

The first six errors listed above are systematic and are in order of general importance. The net error due to blowing and drifting snow and due to splashing in and out of water can be either negative or positive while net systematic errors due to the wind field and other factors are negative.

The random errors could arise due to spilling of the water when transferring it to the measuring jar, leakage into or out of the receiver, observational error, etc. The others could be due to the observer, such as misreading and transposing digits, recording the data at a wrong place on the recording sheet, etc.

2.4.2 Processing of Precipitation Data

It is common to find gaps and inconsistent values in raw precipitation data. Hence, validation and preliminary processing of the precipitation data is essential before it is put to further use. Processing of data has two major objectives: to evaluate the data for its accuracy, and to prepare the data in a form appropriate for subsequent analysis.

Before the precipitation data is stored for further use, it is necessary to carry out validation checks. Improper registering of data includes entering data against wrong time and date,

alteration of figures, etc. Some of the statistics that are used for checking are the values of normal rainfall, observed maximum rainfall or value of rainfall corresponding to 25-, 50- or 100-year return period.

Adjustment of Data

The adjustment of data has two principal objectives. The first is to make the record homogeneous with a given environment and the second is to eliminate or reduce extraneous influences by correcting for change in gauge location or exposure. An adjustment for these errors is made by *Double Mass Analysis*.

The double mass analysis is a graphical method to identify and adjust inconsistencies in a station's data by comparing with the trend of reference stations' data. As the name implies, in a double mass curve, both axes are accumulated precipitation values (see Fig. 2.5). Usually, the accumulated seasonal or annual precipitation values of reference station(s) are taken as abscissa and those of the station under test as ordinate. A change in the regime of the raingage, such as change in exposure and the change in location is revealed by the change in the slope of the straight line. The older records are adjusted by

$$\text{Adjusted precipitation} = \text{Raw precipitation} * \frac{\text{slope of later period}}{\text{slope of earlier period}} \tag{2.3}$$

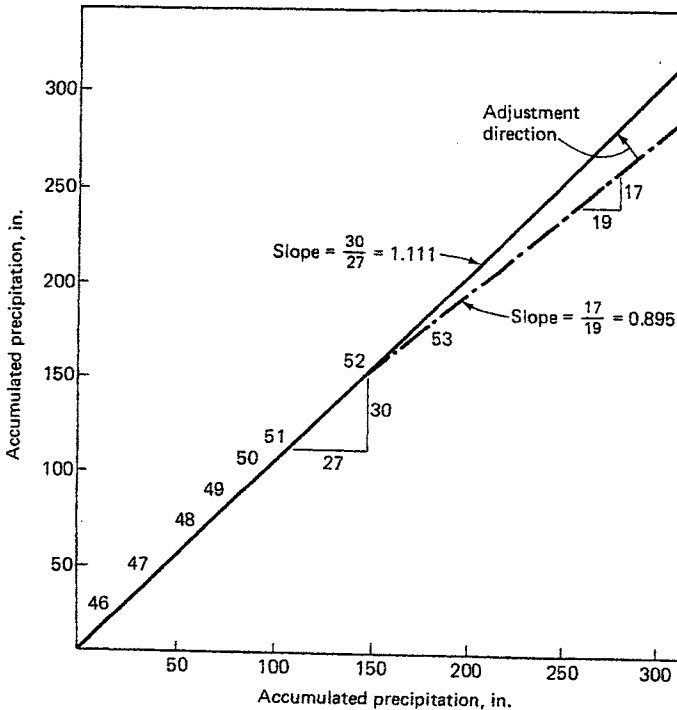


Fig. 2.5 Double-mass analysis to check consistency of rainfall data at Blair, Nebraska. On the x-axis is the eight-station accumulated mean precipitation and on the y-axis is the accumulated precipitation at Blair.

Spatial Consistency Check

Rainfall data exhibit some degree of spatial consistency and this forms the basis of investigating the observed rainfall values. An estimate of the interpolated rainfall value at a station is obtained on the basis of the weighted average of rainfall observed at the surrounding stations. Whenever the difference between the observed and the estimated values exceed the expected limiting value, such values are considered as suspect and are flagged for further investigation and ascertaining the possible causes of departures.

Rainfall poses special problems for spatial comparisons because of the limited correlation between stations. When rainfall is of convective type, it may rain heavily at one location while another only a few km away may remain dry. Over a month or season, such spatial unevenness tends to be smoothed out and aggregated totals are much more closely correlated. The spatial correlation in rainfall depends on: duration (smaller at shorter durations), distance (decreasing with distance), type of storm that has precipitation, and physiographic characteristics of the region.

Spatial consistency checks for rainfall data are carried out by relating the observations from surrounding stations for the same duration with the rainfall observed at the station. This is achieved by interpolating the rainfall at the station under question with rainfall data of neighboring stations. The station being considered is called the test station. The interpolated value is estimated by computing the weighted average of the rainfall observed at neighboring stations. Ideally, the stations selected as neighbors should be physically representative of the area in which the station under scrutiny is situated. The following criteria are used to select the neighboring stations:

- (a) The distance between the test and the neighboring station must be less than a specified maximum correlation distance;
- (b) too many neighboring stations should not be considered for interpolation; and
- (c) to reduce the spatial bias in selection, it is advisable to consider an equal number of stations in each quadrant.

Example 2.1: Rainfall reported at a group of five stations (see Fig. 2.6) is as follows.

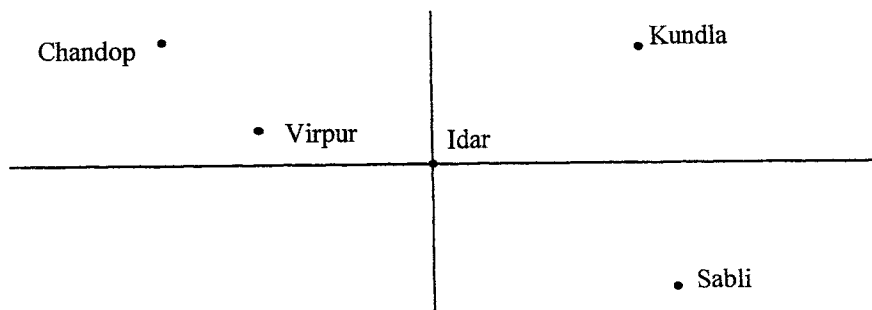


Fig. 2.6 Location of stations for spatial consistency check.

| Station | Kundla | Idar | Virpur | Chandop | Sabli |
|---------------|--------|------|--------|---------|-------|
| Rainfall (mm) | 132.1 | 12.1 | 103.3 | 125.7 | 149.8 |

During a quality control process, the data at Idar is identified as doubtful and is required to be checked for spatial consistency.

Solution: The rainfall at Idar is estimated using the distance power method and compared with the observed value. From the four quadrants around Idar (Fig. 2.6), the station nearest from each quadrant is selected for estimation of rainfall at Idar. Using the reference coordinate system, the distance of each of the estimator stations from Idar is determined and the rainfall at Idar is estimated.

| S. N. | Station | Distance from Idar D_i (km) | $1/D_i^2$ | R_i/D_i^2 |
|-------|---------|-------------------------------|------------------------|-------------|
| 1. | Kundla | 42 | 5.67×10^{-4} | 0.075 |
| 2. | Virpur | 39 | 6.57×10^{-4} | 0.068 |
| 3. | Sabli | 75 | 1.78×10^{-4} | 0.027 |
| | Total | | 14.02×10^{-4} | 0.170 |

$$\text{Rainfall at Idar} = [\sum(R_i/D_i^2)] / [\sum(1/D_i^2)] = 0.17/14.02 \times 10^{-4} = 121.25 \text{ mm.}$$

Since the observed value is very much different from the estimated value, it is rejected and replaced by the estimated value. Note that there is a possibility that the decimal point was wrongly placed while recording the data.

2.4.3 Spatial Interpolation of Precipitation Data

An accurate assessment of the mean areal precipitation is needed in many hydrological analyses. Precipitation observations from gauges are point measurements. However, the precipitation process exhibits an appreciable spatial variation over relatively short distances. Numerous methods of computing areal rainfall from point measurements have been proposed. While using precipitation data, one often comes across missing data situations. Data for the period of missing rainfall could be filled using various techniques. The length of the period up to which the data could be filled is dependent on the individual judgment. Due to the spatial nature of precipitation data, some type of interpolation technique is commonly adopted, making use of the data of nearby stations. The methods that are commonly used for this purpose are discussed in what follows.

Most of these methods can be used for any variable that follows a spatial behavior. The choice of any method is dependent on the quality and nature of data, required precision, and availability of time and resources, and the preferences of the analyst.

Let the precipitation data be available at n stations, spread over an area and P_i be the observed depth of precipitation at the i^{th} station. Using a linear interpolation technique, an estimate of precipitation over the area can be expressed by

$$P^* = \sum_{i=1}^n P_i W_i \quad (2.4)$$

where W_i is the weight of the i^{th} station. The spatial averaging techniques differ in the method of evaluation of these weights. Weights of an optimal interpolation technique are decided such that the variance of error in estimation is the minimum.

Arithmetic Average

The simplest technique to compute the average precipitation depth over a catchment area is to take an arithmetic average of the observed depths at gauges within the area for the time period of concern. If the gauges are relatively uniformly distributed over the catchment and the values do not have a wide variation, this technique yields good results. The weighted average precipitation is:

$$P = \frac{\sum_{i=1}^n P_i W_i}{n} \quad (2.5)$$

where P is the average catchment precipitation from the data of n stations, P_i is the precipitation at station i , and W_i is the weight of i^{th} station.

Normal Ratio Method

In the normal ratio method, the rainfall P_A at station A is estimated as a function of the normal monthly or annual rainfall of the station under question and those of the neighboring stations for the period of missing data at the station under question.

$$P_A = \frac{\sum_{i=1}^n \frac{NR_A}{NR_i} * P_i}{n} \quad (2.6)$$

where P_i is the rainfall at surrounding stations, NR_A is the normal monthly or seasonal rainfall at station A, NR_i is the normal monthly or seasonal rainfall at station i , and n is the number of surrounding stations whose data are used for estimation.

Example 2.2: The normal monthly rainfall at the estimator and estimated stations A, B, C, and D is known. The observed rainfall at the estimator stations B, C & D is also known and is given in the following table. Find rainfall at station A.

Solution: The ratio NR_A/NR_i has been calculated and is given in table below.

| Station → | A | B | C | D |
|----------------------|-------|-------|-------|-------|
| Normal Rainfall (mm) | 331.3 | 290.8 | 325.9 | 360.5 |
| Event Rainfall (mm) | ? | 98.9 | 120.5 | 110.0 |
| NR_A/NR_i | 1 | 1.14 | 1.02 | 0.92 |

The estimated rainfall at station A is:

$$P_A = \frac{1.14 * 98.9 + 1.02 * 120.5 + 0.92 * 110.0}{3} = 112.3 \text{ mm}$$

Distance power method

The rainfall at a station is estimated as a weighted average of the observed rainfall at the neighboring stations. The weights are equal to the reciprocal of the distance or some power of the reciprocal of the distance of the estimator stations from the estimated stations. Let D_i be the distance of the estimator station from the estimated station. If the weights are an inverse square of distance, the equation is:

$$P_A = \frac{\sum_{i=1}^n P_i / D_i^2}{\sum_{i=1}^n 1 / D_i^2} \quad (2.7)$$

Note that the weights go on reducing with distance and approach zero at large distances. A major shortcoming of this method is that the orographic features and spatial distribution of the variables are not considered. The extra information, if stations are close to each other, is not properly used. The procedure for estimating the rainfall data by this technique is illustrated through an example. If A, B, C, D are the location of stations discussed in the example of the normal ratio method, the distance of each estimator station (B, C, and D) from station (A) whose data is to be estimated is computed with the help of the coordinates using the formula:

$$D_i^2 = [(x - x_i)^2 + (y - y_i)^2] \quad (2.8)$$

where x and y are the coordinates of the station whose data is estimated and x_i and y_i are the co-ordinates of stations whose data are used in estimation.

Example 2.3: Using the data of Example 2.2, estimate rainfall at station A using the distance power method.

Solution: Since the coordinates of the stations are known, their distances from station A can be calculated. The weights $1/D_i^2$ are then computed for each station and the rainfall at station A is estimated as follows:

| Station | Distance from station A | $1/D_i^2$ | Rainfall P_i (mm) | Weighted rainfall $P_i * (1/D_i^2)$ (mm) |
|---------|-------------------------|------------------|---------------------|--|
| B | 28.0 | $1.29 * 10^{-3}$ | 98.9 | $125.6 * 10^{-3}$ |
| C | 17.7 | $3.19 * 10^{-3}$ | 120.5 | $384.6 * 10^{-3}$ |
| D | 42.5 | $0.55 * 10^{-3}$ | 110.0 | $60.5 * 10^{-3}$ |
| Total | | $5.01 * 10^{-3}$ | | $570.7 * 10^{-3}$ |

Therefore, rainfall at station A = $570.7 * 10^{-3} / 5.01 * 10^{-3} = 113.9$ mm.

Thiessen Polygon

The Thiessen Polygon method is based on the concept of proximal mapping and weights are assigned to each station according to the area which is closer to that station than to any other station. This area is found by drawing perpendicular bisectors of the lines joining the nearby stations so that the polygons are formed around each station (Fig. 2.7). It is assumed that these polygons are the boundaries of the effective area that is represented by the station. The area governed by each station is planimeted and expressed as a percentage of the total area. The weighted average precipitation for the basin is computed by multiplying the precipitation received at each station by its weight and summing. The weighted average precipitation is given by:

$$P = \sum_{i=1}^n P_i W_i \quad (2.9)$$

in which $W_i = A_i/A$, where A_i is the area represented by the station i and A is the total catchment area. Clearly, the weights will sum to unity. An advantage of this method is that the data of stations outside the catchment may also be used. A major drawback of this method is the assumption that precipitation between two stations varies linearly and the method does not make allowance for variation due to orography. In this method, the precipitation depth changes abruptly at the boundary of polygons. Also, whenever a set of stations are added to or removed from the network, a new set of polygons have to be drawn.

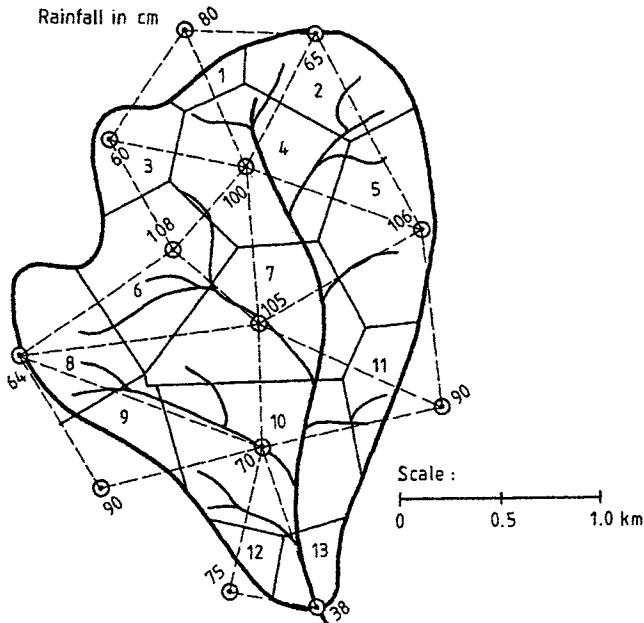


Fig. 2.7 The Thiessen polygon method for computing the mean areal rainfall.

The method fails to give any idea as to the accuracy of the results. If a few observations are missing, it may be more convenient to estimate the missing data than to construct the new set of polygons.

Example 2.4: For a catchment, the rainfall data at six stations for July month along with their weights are as given in Table 2.4. Find the weighted average rainfall for the catchment using Thiessen polygon method.

Solution: Using the observed rainfall and station weight, weighted rainfall at each station is computed. Summation gives the weighted average rainfall for the catchment. The computations are shown in Table 2.4.

Table 2.4 Estimation of the mean areal rainfall by the Thiessen polygon method.

| S. N. | Station Name | Station weight | Rainfall (mm) | Weighted rainfall (mm) |
|-----------------------------|--------------|----------------|---------------|------------------------|
| 1. | Sohela | 0.06 | 262.0 | 15.7 |
| 2. | Bijepur | 0.12 | 521.0 | 62.5 |
| 3. | Padampur | 0.42 | 177.0 | 74.3 |
| 4. | Paikmal | 0.28 | 338.0 | 94.6 |
| 5. | Binka | 0.04 | 158.0 | 16.1 |
| 6. | Bolangir | 0.08 | 401.6 | 12.6 |
| Weighted catchment rainfall | | | | 275.8 |

Isohyetal Method

The isohyetal method employs the area encompassed between isohyetal lines. Rainfall values are plotted at their respective stations on a suitable base map and contours of equal rainfall, called isohyets, are drawn. In regions of little or no physiographic influence, the isohyetal contours may drawn take into account the spacing of stations, the quality, and variability of the data. In regions of pronounced orography where precipitation is influenced by topography, the analyst should take into consideration the orographic effects, storm orientation etc. to adjust or interpolate between station values.

These days, computers are widely used to draw isohyetal maps. The isohyetal map for an area is shown in Fig. 2.8. The total depth of precipitation is computed by measuring the area between successive isohyets, multiplying this by the average of the two isohyets, and totaling. The average depth of precipitation is obtained by dividing this sum by the total area. The average depth of precipitation (P) over this area is obtained by:

$$P = \frac{\sum_{i=1}^n P_i A_i}{\sum_{i=1}^n A_i} \quad (2.10)$$

where A_i is the area between successive isohyets.

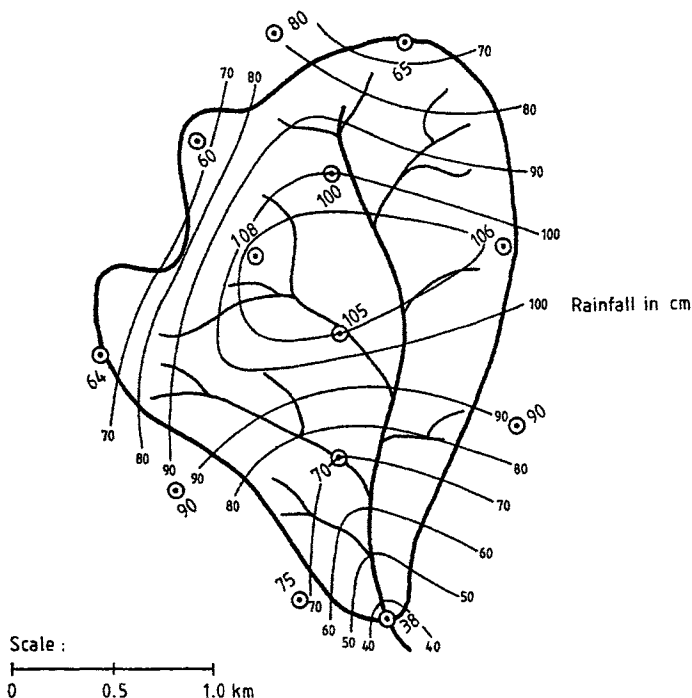


Fig. 2.8 The isohyetal method for computing the mean areal rainfall.

Example 2.5: Using the point rainfall data for a catchment, isohyetal lines were drawn as shown in Fig. 2.8. The area enclosed by each isohyet was calculated as given in Table 2.5. Compute the average catchment rainfall.

Solution: For each isohyet, the average value is worked out (the maximum observed rainfall was 108 cm and the minimum 38 cm). This, multiplied by the area enclosed by that isohyet gives the volume of rainfall for that isohyet. Now the volumes for different isohyets are summed and divided by the area of the catchment to get average catchment rainfall. The computations are shown in Table 2.5.

Kriging

For estimation of the areal averages of the variables which are considered to be realizations of stochastic processes, Matheron (1971) proposed the theory of regionalized variables. A variable, which characterizes a phenomenon varying in space and/or time and shows a certain structure, is called a *regionalized variable*. The variables describing the depth of rainfall, water level in observation wells, and soil transmissivity are a few examples of regionalized variables. The technique of Kriging is named after D.R. Krige who first applied this theory to gold mining in South Africa.

Table 2.5 Estimation of mean areal rainfall by the isohyetal method.

| Isohyet value (cm) | Average value (cm) | Area enclosed (km ²) | Net area (km ²) | Rainfall volume (km ² -cm) |
|--|-----------------------|-------------------------------------|--------------------------------|--|
| 105 | 106.5 | 0.79 | 0.79 | 84.14 |
| 100 | 102.5 | 1.52 | 0.73 | 74.83 |
| 90 | 95 | 2.57 | 1.05 | 99.75 |
| 80 | 85 | 3.47 | 0.90 | 76.50 |
| 70 | 75 | 4.50 | 1.03 | 77.25 |
| 60 | 65 | 5.18 | 0.68 | 44.20 |
| 50 | 55 | 5.39 | 0.21 | 2.20 |
| < 40 | 39 | 5.41 | 0.02 | 0.78 |
| | Total | | 5.41 | 459.65 |
| Average catchment rainfall = 459.65/5.41= 84.96 cm | | | | |

Given the values of the variable at n observation points, p_i , $i = 1, 2, \dots, n$, the problem of Kriging is to estimate a quantity p^* , which is a linear function of variables. Three types of problems may arise:

- To estimate the value of the variable at a point;
- to estimate the value of the variable over a mesh of given area centered at a known point; and
- to estimate the value of the variable over a specified domain.

The first type of problems is called point Kriging, second and third types are called block Kriging. The third type is most generalized and the first two can be considered as special cases of the third type when the domain reduces to a point or a block. According to eq. (2.4), it is required to find the set of weights which give the best possible estimation. For the estimation to be the best, the weights must be: a) unbiased, i.e., there should be no systematic over or under estimation, and b) optimal, i.e., the variance between the observed and computed values must be minimum.

The theory of Kriging assumes the increments of the variables to follow the weak stationarity of second order. Under this assumption, a random function is said to be stationary if the first two moments of its joint probability distribution at k arbitrary points are invariant under simultaneous translation of all the points. The first step in application of Kriging is derivation of semi-variogram which is the graph of variability of the difference of the regionalized variable with respect to the distance between the data points:

$$\begin{aligned} \gamma(d_{ij}) &= \text{Var} [p_i - p_j] \\ &= \sigma^2 - \text{Cov}(d_{ij}), \quad i, j = 1, 2 \dots n \end{aligned} \quad (2.11)$$

where $\gamma(d_{ij})$ is the semi-variogram which is a function of the distance between i and j points. Fig. 2.9 shows a semi-variogram.

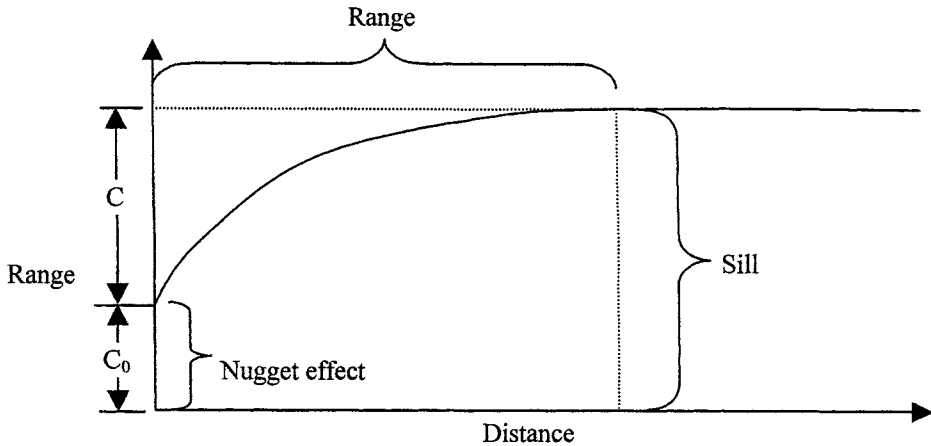


Fig. 2.9 Plot of semi-variogram.

The semi-variogram is first estimated from the observed values and then one of the theoretical semi-variograms is selected. For example, the exponential model of the semi-variogram is

$$\gamma(d) = C_0[1 - \delta(d)] + C[1 - \exp(-d/a)] \quad (2.12)$$

where $\delta(d)$ is the Kronecker delta [= 1 when $d = 0$, = 0 when $d \neq 0$]. The condition of the minimum variance and equation (2.11) yield a set of equations:

$$\begin{aligned} \sum_{i=1}^n w_i \gamma(d_{ij}) + \lambda &= \gamma(d_{0j}), \quad j = 1, 2, \dots, n \\ \sum_{i=1}^n w_i &= 1 \end{aligned} \quad (2.13)$$

The solution of these $(n+1)$ simultaneous equations yields n weights and the Lagrange multiplier λ . As mentioned above, the knowledge of the variogram is required for interpolation using Kriging. A number of models of the variogram have been described by Davis (1986).

Use of Station Characteristics

By the procedures described above, a point estimate can never be greater than the largest amount observed or less than the smallest. However, in some areas particularly in mountainous regions, precipitation patterns have known characteristics which would indicate higher or lower amounts at certain points. The use of 'station characteristics' permits this to be taken into account. The station characteristic is defined as the ratio of the mean monthly precipitation at a given station to the mean monthly precipitation at a base

station. A base station is one which has a long-term reliable climatological record and is representative of a large portion of the basin. The base station serves as a guide for determining the station characteristics at neighbouring stations.

2.4.4 Disaggregation of Rainfall Data

Many applications, such as flood forecasting, require rainfall data of shorter duration, whereas the network of recording raingauges (providing short duration data) is small in comparison to that of daily raingauges. Hence, it is often necessary to disaggregate the daily rainfall data into shorter time intervals. The information of short interval rainfall is used together with the information of daily rainfall from nearby non-recording (daily) gauges. A common method to do this is the mass curve method.

A mass curve is a graphical display of accumulated rainfall versus time. Mass curves of accumulated rainfall at (non-recording) daily stations and recording stations are prepared by plotting the accumulated rainfall values against time for the storm duration under analysis. A comparison of the mass curves of the recording raingauge stations with those of the non-recording stations helps in deciding which recording raingauge or group of gauges is representative of which of the non-recording raingauge for the purpose of distributing daily rainfall into hourly rainfall.

Assume that the daily rainfall is observed at 0800 hours. For converting the daily rainfall into hourly rainfall, the hourly rainfall from 0800 hr to 0800 hr for consecutive days is accumulated and the rainfall during each hour is expressed as a ratio of the total rainfall during 24 hours (0800 to 0800). These ratios are used to distribute the daily rainfall for the corresponding duration at those non-recording raingauge stations.

2.4.5 Rain Storm Analysis

While designing a dam, it is necessary that the outlet capacity is large enough to safely pass a flood of certain magnitude. This critical flood is known as the *design flood* for the structure. The type of the hydraulic structure is the main criterion to decide the design flood hydrograph. For this purpose, the structures are classified as:

- i) large or medium dams;
- ii) medium structures, such as barrages, road and railway bridges; and
- iii) small or minor structures, such as cross drainage works and minor irrigation tanks and minor road bridges.

If long-term runoff data are not available, rainfall data which are generally available for a longer period are used to estimate the *design storm*. This design storm is used with a suitable rainfall-runoff model to obtain a design flood. The rainstorm analysis is the first step in the design storm estimation procedure. The design storm (rainfall) is a magnitude of rainfall and its distribution which is developed for the design of specific types of structures. It has three components, namely, the rainfall amount, the areal distribution of rainfall, and the time distribution of rainfall.

The *Probable Maximum Precipitation* (PMP) is defined (WMO, 1986) as “theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year”. The Standard Project Storm is defined as that rain storm which is reasonably capable of occurring in the region of problem basin. It is generally the most severe rain storm which has occurred in the region of the basin during the period of available records.

The data on volumes of precipitation during severe storms is important for examining and studying storms suitable for design purposes. Such information is generally presented in the form of tables of the maximum average depth of storm precipitation over various standard area sizes, such as 100 km², 500 km² etc. These data are known as the Depth-Area-Duration data and they could be presented in tabular as well graphical form. WMO (1994) has described procedures to estimate the probable maximum flood and standard project flood.

2.5 ACQUISITION AND PROCESSING OF OTHER METEOROLOGICAL DATA

Besides precipitation, the other meteorological variables, such as evaporation, temperature, humidity, wind speed and direction, and sunshine hours, are also important in studies relating to water resources development and management. The acquisition and processing of these data is discussed next.

2.5.1 Pan Evaporation Data

Evaporation is an important component of the hydrologic cycle. The rate of evaporation is a function of climatic variables, such as incoming solar radiation, air and water temperature, wind speed, and saturation vapor pressure deficit. Pan evaporation provides an estimate of open water evaporation. Evaporation data from pans are frequently used to estimate evaporation from water bodies, such as lakes and reservoirs and evapotranspiration from an area. Evaporation pan readings are taken once or twice a day at fixed times.

The evapotranspiration (ET) from crop areas can be directly measured through a lysimeter (see Aboukhaleel et al., 1982). Three types of lysimeters are used. A weighing type lysimeter uses mechanical balance to determine the change in water content of the control volume. The hydraulics-based equipment employs hydrostatic principles of weighing, and in the volumetric based ones, ET is measured by the amount of water added or removed from the control volume to keep constant water content. Note that lysimeters are difficult and costly to install and maintain. In view of the difficulties in direct measurement of ET, indirect methods are generally used to estimate it. This requires measurements of meteorological variables which influence evaporation. Commonly, pan evaporation is multiplied by a coefficient to get the crop ET.

Three types of evaporation pans are in common use: the U. S. Weather Bureau Class A pan, the GGI-3000 pan, and the 20-m² tank. The U.S. pan is widely used throughout the world; the last two are widely used in Russia and some other countries. The

U. S. Weather Bureau Class A pan evaporimeter (a circular pan of 1.22 m diameter and 0.255 m deep), that rests on a white painted wooden stand, is the equipment that is used almost universally (Fig. 2.10). It is a good practice to install additional instruments along with a pan, such as an anemometer to measure wind movement over the pan, a precipitation gauge, and thermometers to measure temperature of pan water and surrounding air. To prevent drinking of water by birds and animals, either some chemical repellants may be added to water (these should not pollute water), or the pan may be covered by a wire mesh. The inner side of the pan is painted white. The water level in the pan changes due to evaporation and rainfall. A stilling well with a pointer gauge is installed in the pan. The change in the water level in the pan and the depth of rainfall at a nearby raingauge yields evaporation losses. The amount of evaporation between two observations of water level in the pan is obtained by:

$$E = P \pm \Delta d \quad (2.14)$$

where P is the depth of precipitation during the intervening period and Δd is the depth of water added (+) to or removed (-) from the pan.

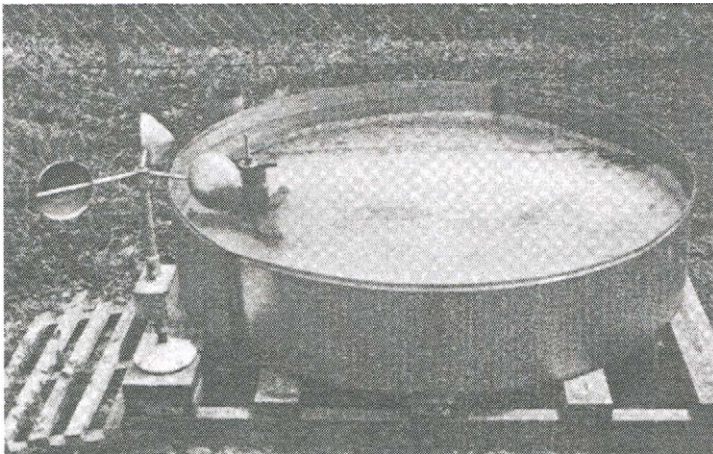


Fig. 2.10 U.S. Weather Bureau class A land pan.

Errors in the data may crop up due to observer's mistakes and instrument errors where leakage from sides or bottom is most common. Birds or animals may drink water from the pan, particularly if the covering wire mesh is damaged. The maximum value of evaporation in the region is used as the first check to screen doubtful measurements.

Since a pan is a small water body whose material is different from a natural body, its heat storage characteristics and air dynamics are different from a large water body. Therefore, evaporation from a pan is higher than a large open water body. An estimate of lake or reservoir evaporation is obtained by multiplying the pan evaporation by a coefficient called pan coefficient:

$$E_R = K_p E_{\text{pan}} \quad (2.15)$$

where K_p is the pan coefficient, E_R is the depth of evaporation from a reservoir, and E_{pan} is the pan evaporation, both in mm/day. The value of pan coefficient depends on climate, location, season, size, and depth of the water body. This coefficient generally varies from 0.6 to 0.8. The lower values are typical of dry seasons and arid climates while higher values are observed in humid climates. In the absence of better estimates, an average value of 0.7 is generally used.

2.5.2 Temperature and Humidity Data

Since temperature affects evaporation and snowmelt, it is needed in many water resources studies. The temperature of air, snow pack, soil, and water bodies is of interest. It is a measure of the ability of the atmosphere and water to receive and transfer heat from other bodies. The temperature of a water body is also an indicator of its quality, since it influences the amount of dissolved gases and the rate of chemical and biological activities. An accuracy of 0.1°C is enough in temperature measurements.

Temperature varies primarily with the magnitude of solar radiation and follows diurnal and seasonal cycles. It is influenced at particular times by the exchange of air masses and by cloudiness which limits incoming radiation. Temperature varies with latitude (which controls solar radiation), altitude, and proximity to oceans. Normally, temperature decreases with altitude at a rate of approximately 0.6°C per 100 meters for moist air and 0.9°C for dry air. The temperature of places near a large water body, such as sea, are moderated by its influence so that the annual and diurnal range is smaller. Generally, temperatures at nearby stations are strongly correlated.

Manual observations of air temperature are made using thermometers. Four types of thermometers: dry bulb, wet bulb, maximum, and minimum thermometers are used. The dry-bulb thermometer gives air temperature. The wet-bulb thermometer is used to measure the temperature of the saturated air to determine the relative humidity and dew point of the surrounding air. The maximum and minimum thermometers indicate these temperatures over a span of time. Observations of temperatures are made once or twice a day at standard times. A continuous record of temperature is obtained using a thermograph in which changes in the temperature are recorded on a clock-driven revolving chart.

The atmospheric humidity has a significant influence on evapotranspiration. The commonly used term *relative humidity* (RH) is the ratio (in %) of mixing ratio to the saturation mixing ratio:

$$\text{RH} = 100 r/r_s \quad (2.16)$$

where the mixing ratio $r = m_v/m_d$. Here, m_v is the mass of water vapor and m_d is the mass of dry air. The saturation mixing ratio r_s is the ratio of the mass of water vapor in a volume of the saturated air to the mass of dry air. The relative humidity (%) can be defined as the ratio of the actual vapor pressure of the air to the saturation vapor pressure at the same pressure and temperature.

The relative humidity does not vary drastically over a short time. Places close to sea have higher RH and a smaller daily variation than inland locations. The most common way of assessing the RH is the joint measurement of dry bulb and wet bulb temperatures. The dry bulb refers to an ordinary thermometer. The wet bulb is so called because it is covered with a clean muslin sleeve, tied around the bulb by a cotton wick which is dipped in a water container so that the wick and muslin are kept constantly moist. From these two measurements, the dew point temperature, and actual and saturated vapor pressures may also be calculated. While the actual vapor pressure may vary little during the day (except with the incursion of a new air mass), RH has a regular diurnal pattern with a minimum normally coinciding with the highest temperature (when the saturation vapor pressure is at its highest). It also shows a regular seasonal variation. RH is calculated from the wet bulb depression (difference between dry and wet bulb readings) using a set of tables.

RH may also be measured continuously by means of a hygrograph in which the sensor is human hair whose length varies with relative humidity. The humidity is registered on a chart on a clock-driven revolving drum and the measurement (chart) period may be either one day or one week.

Errors in the temperature data may arise due to:

- Observer error in reading the thermometer – usually it could be an error of 1°C which is difficult to detect. Reading errors are more common in thermometers with faint graduation etchings.
- Error in registering the thermometer reading.
- Thermometer fault which results in systematic errors in temperature.

Measurement errors, if dry and wet bulb thermometers are used, are the same as for temperature. Additionally, an error will also occur if the muslin and wick of the wet bulb are not adequately saturated or the muslin becomes dirty or is covered by slime. These defects will tend to give a high reading of the wet bulb temperature and consequently a high value of RH. Errors in the hygrograph may result from poor calibration.

Validation of temperature data is based on location and site conditions and comparison between stations. Common errors can be detected by setting up appropriate maximum, minimum, and warning limits. For example, the summer maximum temperature can be expected not to exceed 50°C and the winter maximum temperature may not exceed 35°C. The maximum value for RH is 100%. The dry bulb temperature should be greater than or (rarely) equal to the wet bulb temperature.

2.5.3 Wind Speed and Direction

Wind speed and direction are inputs in calculation of evapotranspiration. Wind speeds are controlled by local pressure anomalies which in turn are influenced by the temperature and local topographic features. The wind speed exhibits a wide variation not only from place to place but also during the day. The wind direction may influence evaporation if the surrounding environment has different humidity in different directions.

The wind speed is measured using an anemometer (usually a cup type). The number of rotations of the anemometer over a time interval is displayed by a counter or logged using a data logger and indicates the average speed over that interval. Normally, the wind speed over a three- minute period is considered as the instantaneous wind speed at that time. The daily wind run or the average wind speed is calculated from counter readings on successive days at the principal observation times. The wind direction is reported as 16 points of the compass either as a numerical figure or an alphabet character. Observations are made daily in the morning or twice daily in morning and evening. Wind speed measurements may be instantaneous; these are accumulative if the wind run over a time interval is observed.

Errors in wind speed might arise as the result of observer mis-reporting the counter total. Instrumental errors might arise from poor maintenance or damage to the spindle. Because of large variability in wind speed in space and time, it is difficult to set up convincing rules to detect suspect values.

2.5.4 Sunshine Duration

The sunshine duration data is an input variable in estimation of evapotranspiration. It is widely used in computation of evapotranspiration in the absence of radiation measurements. The potential maximum sunshine duration depends on latitude and season; the actual sunshine hours vary due to clouds, fog, etc. The amount of bright sunshine in urban areas may be reduced by atmospheric pollution and in coastal areas it may be reduced by sea mist.

The instrument commonly employed for observation of the sunshine duration is the Campbell Stokes sunshine recorder. It is a glass sphere mounted on a section of a spherical bowl. The sphere focuses sun's rays on a card graduated in hours, held in the grooves of the bowl which burns the card linearly through the day when the sun is shining. The card is changed daily after sunset. Hence, the sunshine recorder uses the movement of the sun instead of a clock to form the time basis of the record. Different grooves in the bowl must be used in winter summer and the equinoxes, taking different card types. The lengths of burnt traces on the sunshine card indicate the sunshine duration. Sunshine duration data at required resolution is tabulated from the card.

The use of the sun as a timing device avoids timing errors. Possible errors may arise from the wrong placement of chart which may result in the burn crossing the edge of the chart and remain unregistered. The errors may also creep in while the observer notes the duration of sunshine from the chart. The values below zero or greater than the maximum possible sunshine for the location are rejected.

2.5.5 Automatic Hydrologic Stations

An automatic hydrologic station (AHS) is a system of micro-processor controlled hardware sensors to measure, store, and transmit data of a number of hydrometeorological variables. Its main advantage is that a number of variables can be measured at one place and the

whole operation of data collection, storage, and transmission is automatic. The frequency of data collection can be as small as the order of a few minutes. The variables that are measured through such a system typically include incoming and outgoing solar radiation, air and soil temperature, wind velocity and direction, etc.

Modern systems are capable of performing some additional actions, such as collecting additional data or initiating a set of instructions like issuance of warnings depending on the value of a particular variable. The systems that have facility for telemetry can be interrogated and controlled from a distant location and commands can be issued from this control center to collect and transmit additional data as per the needs.

The energy to operate these stations is commonly provided from a battery pack which can be recharged from solar power. Thus, these stations may remain unattended for months together. A technician can visit the station after several months to download the data and do maintenance. Of course, data from a telemetry system can be downloaded as and when needed. This property of AHS makes them very useful for data collection from remote or inhospitable locations.

2.6 ACQUISITION AND PROCESSING OF STREAMFLOW DATA

The most important hydrological data for surface water analysis pertains to streamflow. Streamflow has served as the lifeline for mankind and continues to do so. Its importance is also relatively more, since this source is visible in contrast to ground water which is hidden. Streamflow records are primarily continuous records of flow passing through a particular section of the stream. Streamflow data are analysed to determine the magnitude and variability of surface waters. These records are input in planning, design, and operation of surface water projects and are also used in design of bridges and culverts, flood forecasting systems, and flood plain delineation.

The sections where river measurements are carried out are known as stream gauging stations. A network of these stations is established to collect data about surface water resources of a region. The location of gauging sites is dictated by the purpose of data collection. If the site is needed for a specific project, the general location is in the vicinity of the project. However, if the network of gauging stations is to be established to study the general hydrology of a region, careful planning is required to identify locations so that optimum information is obtained for the resources deployed in the data collection.

River gauging stations are of three types: basic data stations, operational stations, and special stations. The basic stations collect data for a variety of uses, including planning and design of projects, and to understand the hydrological characteristics of the area. The operational stations collect data to run projects and issue forecasts. The objective of special stations is to meet specific data needs that may arise in cases, such as research, project investigation, special studies, legal cases, etc. Their operation is terminated when the specific need is fulfilled. Sometimes, auxiliary stations are set up to augment the records of the network. An auxiliary station may, for example, record only the peak discharge which occurs at that site during a certain period.

The number of gauging sites depends on the cost of installation and operation, the value of the data, watershed size, degree of development, objective of data collection, accuracy, hydrologic characteristics, etc. Some of these factors are interrelated. For example, large watersheds involve costlier projects and more data and higher accuracy are, therefore, needed.

The streamflow data that are of immense use in water resources are river water level or gage and discharge. The terms stage and gauge height are interchangeably used to express the elevation of the river water surface with respect to an established datum. A continuous observation of the river water level or stage may be made with comparative ease and economy. At important stations, the stage is measured at short intervals and discharge is measured once or twice each day. At less important stations, only stage measurements are made regularly.

The amount of flow passing through a section per unit time is termed as discharge at that section. A continuous measurement of discharge in a natural channel is comparatively difficult, time consuming, expensive and requires special skills. Therefore, the discharge at a site is measured less often and is estimated by indirect methods. Fortunately, there exists a relation between stage and discharge at a section. This relation is termed as stage-discharge relationship or rating curve which falls under relation-oriented data. This relationship is used to transform the observed stages into discharges. Note that the reliability of such discharge records is dependent on the reliability of stage data and the accuracy of the stage-discharge relation.

At many sites, the discharge is not a unique function of stage; variables other than stage must also be simultaneously measured at such sites to obtain a discharge record. For example, if variable backwater occurs at a site, the information on stream slope is required. The slope can be measured by installing an auxiliary stage gauge downstream. The rate of change of stage can be an important variable where the flow is unsteady and channel slopes are flat. Artificial controls are sometimes built to stabilize the stage-discharge relationship. These are constructed only for low flows owing to a very high construction cost.

The International Standard Organisation (ISO) has brought out a large number of standards dealing with measurement of liquid flow in open channels. The ISO technical committee TC113 deals with this theme. The publication ISO (1983) is a useful collection of standards dealing with various aspects of streamflow measurement. WMO has also brought out many publications related to streamflow measurement. Of course, the individual countries have their own standards. The topic is covered in detail in Herchey (1978, 1986, and 1995).

2.6.1 Selection of Gauging Sites

After the general location of a gauging station has been determined, its precise location is selected to get the best conditions for stage and discharge measurement and to develop a stable discharge rating. For example, consider that the outflow from a reservoir is to be gauged. The general location of the gauging station will be along the stretch of the river

between the dam and the confluence with the first major stream. The gauge site should be so located that it is far enough from the dam for the flow to be established fairly uniformly across the entire cross-section. On the other hand, the site should not be so far downstream that there is an appreciable flow from the intermediate catchment.

The ideal gauge site satisfies the following criteria:

- (a) The general course of the stream is straight for about 100 metres upstream and downstream from the gauge site,
- (b) the river should not be braided at the gauge site and all the flow must be confined to single stream at all stages,
- (c) the stream-bed is not subject to scour and fill and is free of weeds,
- (d) banks are permanent, high enough to contain floods,
- (e) the gauge site is far enough upstream from the confluence or from tidal effect to avoid any variable influence on the stage at the gauge site,
- (f) a satisfactory reach for measuring discharge at all stages is available within reasonable proximity of the gauge site, and
- (g) the site is readily accessible for ease in installation and operation of the gauging station.

An ideal site is rarely found for a gauging station and judgment has to be exercised in choosing between adequate sites, each of which may have some shortcomings. The detailed guidelines for selection of sites are given in the standard ISO-1100. A gauging station may also have hardware for real-time communication of data to a central location.

2.6.2 Measurement of Stage

Stages are measured with reference to a recognized datum, such as the mean sea level or an arbitrary datum that is selected for convenience. To eliminate the possibility of negative values of the gauge height, the datum selected should be below the elevation of zero flow. The gauge height is usually expressed in hundredths or thousandths of a meter. The water level data is measured using a variety of equipment: staff gauges, autographic water level (chart) recorders, and digital type water level recorders. The advantages of the non-recording gauge are low initial cost and ease of installation. The disadvantages are the need for an observer and less accuracy. For a long-term operation, the advantages of a recording gauge outweigh those of a non-recording gauge. Sometimes, an automatic and a non-recording gauge are maintained together because the electro-mechanical recording gauge equipments are liable to breakdowns.

Staff Gauge

Staff gauges are either vertical or inclined. Vertical staff gauges are normally porcelain enamelled iron sections, graduated every 10 mm. The vertical staff gauge is used as an inside reference gauge (if installed in a well), or as an outside gauge if installed in the stream. If river stage varies over a large range during the year, observations using a single staff gauge might be difficult. In such cases, the gauge consists of stepped sections (Fig.

2.11) installed at different locations in a line normal to the flow. Each of these stepped gages refers to the common datum and there should be sufficient overlap among them. An inclined staff gage is usually a graduated surface attached securely to a permanent foundation. The rock outcrops on the river bank also make good base for inclined staff gage. Inclined gages built flush with the stream bank are less likely to be damaged by floods, floating ice, or drift than are projecting vertical staff gages. The gages should be located as close as possible to the measuring section, without affecting the flow conditions. Staff gauges are manually read, generally each day in the morning in lean season and at (multi) hourly intervals during high flows.

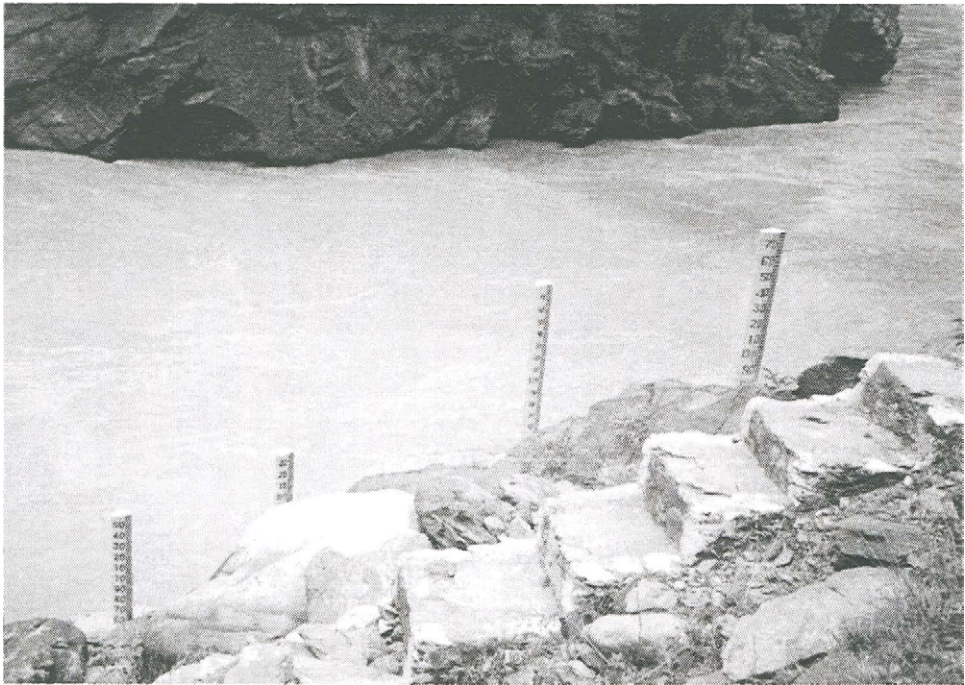


Fig. 2.11 Sectional staff gage.

Water Level Recorder

A water level recorder is an instrument to sense and record water level. It consists of a time element and a gauge height element which together produce a time-series of water levels. The time element is controlled by a clock while the gauge height element is actuated by a float or a pressure actuated system. These recorders can be classified as either analogue type or digital type, depending on the way the data are recorded. The analogue type recorders produce a graphic record of fluctuations of the water level with respect to time.

The water level recorders are generally of shaft-angular-input type, and the angular rotation of the shaft is recorded. The depth of water surface is sensed for automatic

recording by a float in a stilling well (Fig. 2.12) which follows the rise and fall of the water level. A gas-purge system that transmits the pressure head of water in a stream to a manometer is known as a bubble gauge.

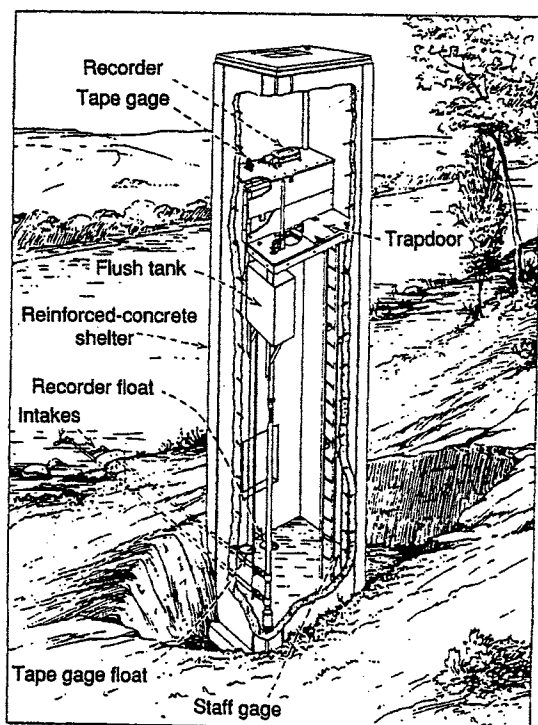


Fig. 2.12 Stilling well for the float-type recorder.

A water level recorder gives a continuous record of the water level on a chart from which values are manually extracted at desired intervals. The data from a digital water level recorder can either be at equal intervals of time, usually at (fraction of) an hour interval, or at only those instants when there is a change in water level by more than a pre-set amount. The digital recorders store data in an electronic memory unit and these data are downloaded to a computer.

2.6.3 Measurement of Discharge

Discharge is the volume of water passing through a certain section in a unit time period. It is commonly expressed in cubic metres per second (m^3/s or cumec). The discharge at a site is a function of the cross-section area and flow velocity. The cross-section area is a function of the river stage. At most stations, discharge is measured once a day; at important stations, it might be measured more frequently. Discharge measurement techniques can be broadly classified into two categories as (i) direct determination and (ii) indirect determination. There are scores of methods under each category. The important ones are discussed below.

Direct Determination of Discharge

These are the methods in which either discharge is directly measured or some variable on which discharge depends is measured. The commonly used methods are: velocity-area methods, dilution techniques, electromagnetic method, and ultrasonic method. The first two are described here.

Velocity-Area Methods

The basic procedure in velocity-area methods involves measuring the flow area and velocity and these are multiplied to get discharge. Since the velocity of flow at a cross-section varies laterally and with depth, it is not enough to measure the velocity at a single point. Depending on the accuracy required, the width of the stream is divided into a number of vertical portions (Fig. 2.13). In each of these portions, the velocity is measured at one or more points along the depth to get a representative velocity in that portion. The area of the individual portion can be easily calculated if the bed profile and stage are known. The velocity may be measured by a conventional method (for example, float or current meter) or by an advanced procedure, for example, the moving boat technique.

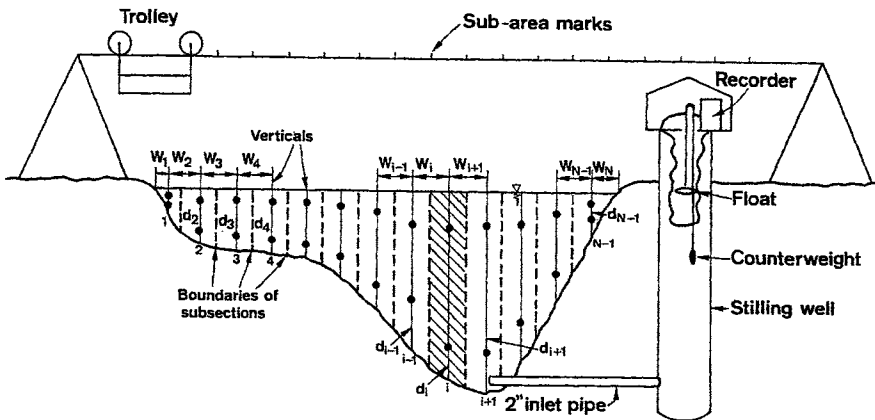


Fig. 2.13 Schematic sketch for a velocity-area station.

A *float* is a distinguishable article that floats on the water surface, such as a wooden log, a bottle partly filled with water, or branch of a tree. For a float measurement, two cross-sections sufficiently far apart on a straight reach of channel are selected. A number of floats are introduced uniformly across the stream width a short distance before the actual upstream cross-section so that they lose inertia and move with the velocity of water when they reach the upstream cross-section. Normally, the floats are tossed from a bridge or cableway but if there is no such opportunity, they can be launched from the stream bank. The position of each float with respect to distance from the bank is noted. A stopwatch is used to measure their travel time between the end cross-sections of the reach.

The velocity of the float is equal to the distance between the two cross-sections divided by the time taken by the float to cover this distance. The mean velocity in the

vertical is equal to the float velocity multiplied by a coefficient whose value depends on the shape of the vertical-velocity profile of the stream and on the depth of immersion of the float with respect to depth. A coefficient of 0.85 to 0.90 is commonly used. The float method is not very reliable and its use is normally restricted to an emergency or to measure high discharges when current meter is not available or can't be used.

Measurement of Velocity using Current Meter

Current meter is the most commonly used instrument to measure the velocity of flowing water. It consists of rotating element (rotor) whose movement is due to the reaction of the stream current. The angular velocity acquired by the rotor is proportional to the velocity of water. By placing a current meter at a point in a stream and counting the number of revolutions of the rotor during a time interval, the velocity of water at that point is determined. Current meters are of two types: those having a propeller rotating around a horizontal axis and those having a series of conical cups mounted around a vertical axis. The normal range of velocity which can be measured varies from 0.15 to 4.0 m/s.

Horizontal-axis meters consist of a propeller mounted at the end of a horizontal shaft (Fig. 2.14). These are available in a range of propeller diameters. Recently, propellers made up of plastic have been introduced. These are cheaper and respond more quickly to changes in velocity. Some current meters come with propellers of different pitch and diameter to suit various flow conditions. The horizontal axis rotor with valves cause less disturbance to flow than vertical axis rotors. Furthermore, due to axial symmetry with the flow direction, the rotor is less likely to be entangled by debris than vertical axis rotors and the bearing friction is less compared to the vertical axis rotors. The vertical axis rotor with cups or valves can operate in lower velocities than the horizontal axis meters, the bearings are well protected from silty water, and a single rotor serves for a range of velocities.

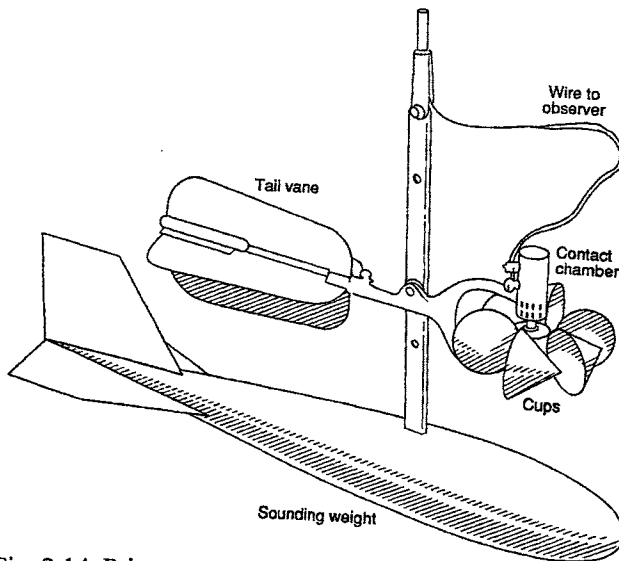


Fig. 2.14 Price current meter.

The current meter measurements are usually classified in terms of the means used to cross the stream during measurements, such as wading, cableway, bridge, or boat. Wading is possible in small streams of shallow depth only; the current meter is held at the requisite depth below the surface by an observer who stands in the water. In narrow well-defined channels, a cableway is stretched from bank to bank well above the flood level. A carriage moving over the cableway serves as the observation platform. Bridges are advantageous from the viewpoint of accessibility and transportation, although these are not the best locations hydraulically. The velocity measurement is performed on the downstream of the bridge to minimize the instrument damage due to drift and knock against bridge piers. Boats are most satisfactory for measurements in wide rivers.

The current meter measures the velocity at a point. However, the mean velocity in each of the selected verticals is required to estimate discharge. The mean velocity in a vertical is determined from velocity observations at one or more points in that vertical. Current meters are held down and positioned in a stable manner at the required location in flowing water by sounding weights. The weights are connected to the current meter by a hanger and pin assembly.

The section line at the gauging site is marked by permanent survey markings. The cross-section along this section line is determined by surveying with the help of sounding rods or sounding weights. When the depth of water is more or if quick and accurate depth measurements are needed, an echo sounder is used.

Moving Boat Method

On very wide streams and estuaries, the conventional methods of measuring discharge by current meter are frequently impractical or involve costly and tedious procedures. In the moving boat technique, data are collected while the observer is aboard a boat traversing the stream along a pre-selected path, generally normal to the direction of flow. During the traverse, an echo sounder records the geometry of the cross-section and a continuously operating current meter senses the combined stream and boat velocities. The angle between the current meter, which aligns itself in a direction parallel to the movement of the water past and the pre-selected path, it is also measured. Normally, data are collected at 30 or 40 observation points in the cross-section for each run. These days instruments automatically and simultaneously record the required parameters.

The velocity observed at each of the observation points in the cross-section (Fig. 2.15), v_v , is the velocity of water past the current meter resulting from both stream flow and boat movement. It is the vector sum of the velocity of water with respect to the stream bed (v) and the velocity of the boat with respect to the stream bed (v_b). The velocity of streamflow can be obtained by measuring the angle α between the selected path of the boat and a vertical vane which aligns itself in a direction parallel to the movement of the water past it.

The flow velocity v , perpendicular to the boat path (true course) at each observation point 1, 2, 3, ..., can be determined from the relationship

$$v = v_v \sin \alpha \quad (2.17)$$

This equation yields that component of the stream velocity which is perpendicular to the true course even though the direction of flow may not be perpendicular.

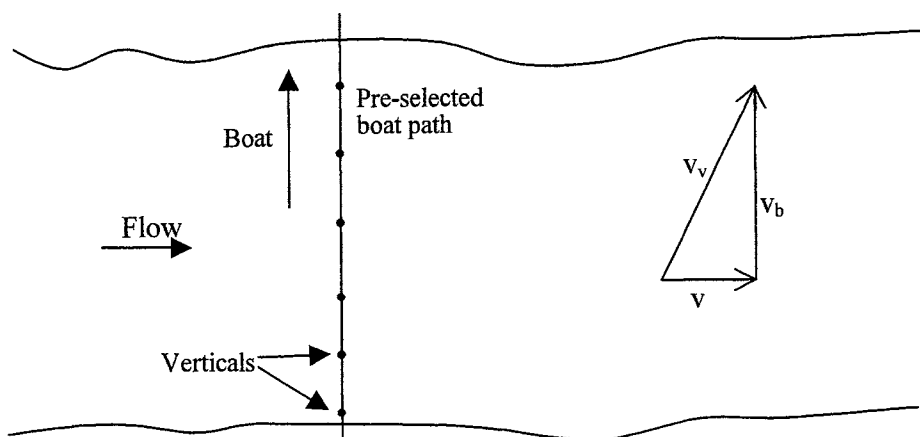


Fig. 2.15 Moving boat method of discharge measurement.

Since the current meter is usually immersed at a depth of 0.5 m from the water surface, the velocity v corresponds to the surface velocity and not the average velocity in the vertical. This surface velocity is multiplied by a coefficient ranging from 0.85 to 0.95 to obtain the average velocity of flow at the section.

Computation of Discharge

After the cross-section has been selected, the width of the stream is divided into an adequate number of partial sections so as to have lesser variation between two adjacent verticals. If previous measurements have shown uniformity of both the cross-section and the velocity distribution then fewer verticals may be taken. It is better if no partial section carries more than 5 to 10 percent of the total discharge. Fig. 2.13 shows the cross section of a river in which $(n-1)$ verticals are drawn. The velocity averaged over the vertical at each section is known. Considering the total area to be divided into $(n-1)$ segments, the total discharge is calculated by the method of mid-section as:

$$Q = \sum_{i=1}^n (v_i a_i) \quad (2.18)$$

where Q is the total discharge, a_i is an individual partial cross-section area, and v_i is the mean velocity in that area. The area extends laterally from half the distance from the preceding observation vertical to half the distance to the next and vertically from the water surface to the sounded depth.

Dilution Technique of Streamflow Measurement

The dilution method of flow measurement, also known as the chemical method, is based on the principle of continuity applied to a tracer which is allowed to completely mix with the flow. A tracer is an ion or compound which is introduced into the flow to follow its behavior. A known quantity of a tracer is introduced in the flow at an upstream section. At a downstream cross-section of the reach, the concentration of the tracer is measured at regular intervals of time.

The reach selected for measurement should be such that there is no loss or gain of water and the reach length should be sufficient to achieve complete mixing. The tracer can be introduced in two ways: (1) constant rate injection, and (2) gulp injection. In the constant rate injection method, the duration of injection should be such that a steady regime of concentration is achieved for an adequate duration (about 10 to 15 minutes) in the sampling section. In the integration method, a quantity of tracer of volume V and concentration C is added to the stream. At the sampling station, the passage of the entire tracer cloud renders a relationship between concentration and time. Common salt (NaCl) is frequently used as a tracer and it can be detected with an error of 1% up to a concentration of 10 ppm (parts per million). A cocktail of tracers may also be used.

If the tracer of concentration C_1 is injected at a constant rate Q_t at section 1, the concentration at section 2 gradually rises from a background value C_0 to a constant value C_2 (see Fig. 2.16).

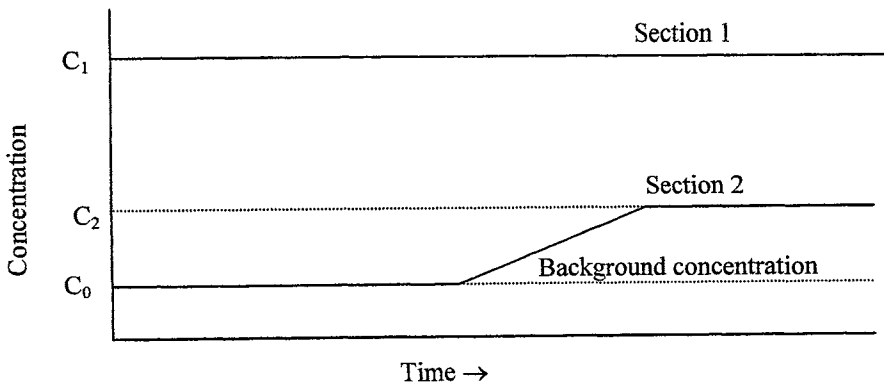


Fig. 2.16 The concept of dilution method of discharge measurement.

At steady state, the stream discharge Q is

$$Q = Q_t (C_1 - C_2) / (C_2 - C_0) \quad (2.19)$$

Indirect Determination of Discharge

These methods make use of the relationship between the flow discharge and the depth at

specified locations. The field measurement is restricted to the measurements of depths only. Two important indirect methods are flow measuring structures and slope-area method.

Flow-Measuring Structures

The structures, such as notches, weirs, flumes, and sluice gates, are commonly used for flow measurement in laboratories. Sometimes, these structures are also used in field conditions, but they are limited by the ranges of head, debris or sediment load of the stream, and the backwater effects produced by the installations. Such structures are usually built only in upper and middle reaches; in wide rivers, the size and cost of the structures are prohibitive. A typical setup consists of a reasonably straight (at least for a distance of five times the width) approach channel, a downstream channel, and the structure itself. The structure having smooth surfaces should be rigid, water-tight, normal to the flow direction, and capable of withstanding peak flows without any damage to its body. The section where the water level is measured should be at a distance of 2 to 4 times the maximum likely head.

The basic principle governing the use of a weir, flume or similar flow-measuring structure is that these structures produce a unique control section in the flow. At these structures, the discharge Q is a function of the water-surface elevation measured at a nearby upstream location:

$$Q = f(H) \quad (2.20)$$

where Q is discharge (m^3/s), and H is the head of water (m) at the structure. The equation for weirs, for example, is

$$Q = K H^n \quad (2.21)$$

where K and n are constants. Eq. (2.21) is applicable as long as the downstream water level is below a certain limiting water level known as the modular limit. The flows unaffected by the downstream water are known as free flows. The flow that is affected by tailwater conditions is known as drowned or submerged flow. Discharge under drowned conditions is obtained by applying a reduction factor to the free flow discharge. For a two-dimensional weir, the discharge is estimated as

$$Q = C_d \sqrt{g} b H^{1.5} \quad (2.22)$$

where C_d is the discharge coefficient, g is the acceleration due to gravity, and b is the crest width (m).

Various flow measuring structures can be broadly considered under three categories:

- (a) Thin-plate structures consist of a vertically set metal plate. The V-notch and rectangular and contracted notches are typical examples of this category.
- (b) Broad-crested weirs are made of concrete or masonry and are used for large

- discharges.
- (c) Flumes are made of concrete, masonry, or metal sheets depending on their use and location. They depend primarily on the width constriction to produce a control section.

Slope-Area Method

In the slope-area method, discharge is estimated by observing the water surface slope and cross-section area. It is an indirect method of discharge estimation which is used when measurement by more accurate methods, such as the velocity-area method, is not possible. Although the accuracy of slope-area method is less compared to the velocity-area methods, it is sometimes necessary to use this method because the magnitude of flows is so high that the other methods of discharge estimation cannot be used.

A measurement reach is chosen for which three things are known: (i) The cross-sectional geometry and properties at its ends, (ii) the value of Manning's n , and (iii) water-surface elevations at the end sections. In the selected reach, a minimum of three cross-sections are generally desirable. As far as possible, the length of the reach should be such that the difference between water levels at the upstream and downstream gauges is not less than ten times the uncertainty in the difference. Slope is computed from the gauge observations at either end of the reach, the intermediate gauge(s) are used to confirm that the slope is uniform throughout the reach.

The mean velocity is established by using known empirical formulae which relate the velocity to the hydraulic mean depth, the surface slope corrected for the kinetic energy of the flowing water and the roughness characteristics. The discharge is computed as the product of the mean velocity and the mean cross-sectional area of the flow. Contracting reaches have been found to yield consistent estimates of discharge and are preferred to expanding reaches.

The resistance equation for uniform flow in an open channel, e.g., Manning's formula, can be used to relate the depths at either ends of a reach to the discharge. Fig. 2.17 shows the longitudinal section of a river between two sections, 1 and 2. The head at a section consists of water surface elevation and the velocity head. The head loss is made up of two parts: (i) frictional loss and (ii) energy loss due to expansion or contraction. The friction slope can be written as

$$S_f = \frac{(h_1 - h_2) + \left[\frac{V_1^2}{2g} - \frac{V_2^2}{2g} \right] (1 - k)}{L} \quad (2.23)$$

where L is the reach length, k is the coefficient for energy loss; its value is 1 for contractions and 0.5 for expansions. According to Manning's formula, the mean velocity in reach 1-2 is calculated as

$$v_{1-2} = (1/n) R^{2/3} S^{1/2} \quad (2.24)$$

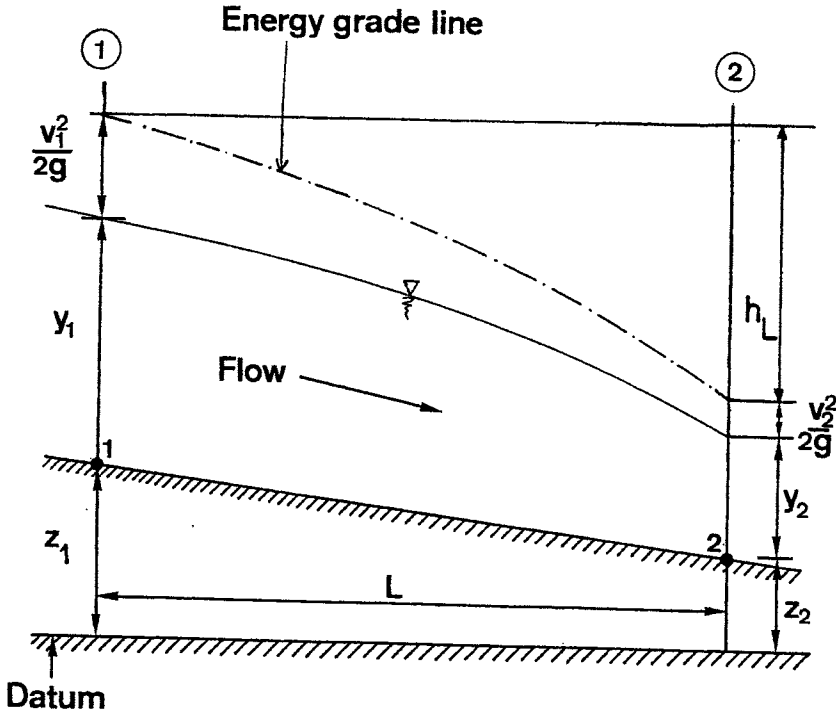


Fig. 2.17 Channel reach for the slope-area method.

where R is the hydraulic mean depth, n is Manning's roughness coefficient, and S is the friction slope. If A is the cross-section area, then the discharge Q is

$$Q = (1/n)AR^{2/3} S^{1/2} = K S^{1/2} \quad (2.25)$$

The term $(1/n)AR^{2/3}$ is known as *conveyance* (K) of the channel and it depends on channel characteristics. As the flow in the reach may not be truly uniform, the average conveyance of the reach is expressed as the geometric mean of the conveyances of the two end sections (K_1 and K_2):

$$K = \sqrt{K_1 K_2} \quad (2.26)$$

The discharge can be calculated by

$$Q = K\sqrt{S} = \sqrt{K_1 K_2 S} \quad (2.27)$$

The slope-area method can be used with some degree of accuracy in open channels with stable boundaries, or in channels with relatively coarse bed material. This method may also be used in other cases, such as alluvial channels including channels with over-bank flow or non-uniform channel cross-sections, subject to the acceptance of large uncertainties involved in the selection of the value of the rugosity coefficient, such as Manning's roughness coefficient n .

Special Problems in Streamflow Measurements in Arid and Semi-arid Regions

Special problems associated with the measurement of streamflow in arid and semi-arid regions arise from the interaction of many climatic and geological factors. The degree of difficulty varies from one region to another, depending on the combination of these factors. The main problems associated with these regions are:

1. These regions mostly have inadequate infrastructure which makes movement and communication difficult, time-consuming, and expensive.
2. The harsh environment, dust, high soil erosion by strong winds, and the sediment carried by floods create problems for the conventional equipment. The end result is frequent malfunctioning of equipment and loss of records.
3. The short duration and rapidity of onset of floods, coupled with (1), imply that the team intending to measure such flows may miss them unless present at the site. The duration of the peak flow may be so short that it is almost impossible to carry out measurements.
4. Soft erodible beds make sounding operations difficult when scouring may occur beneath the sounding weight as it touches the river bed.
5. The channel may shift laterally, isolating gauge and recorder well from the flow.
6. The bed level may vary due to scour and fill, particularly during the passage of a flood. Such bed variations are difficult to measure and lead to errors in the application of cross-sectional area rendering the resultant discharge value erroneous.

A detailed planning of logistics, local knowledge, and experience are the key factors in successfully tackling the problems of such regions. New and appropriate technology in the shape of automation, telemetry, and remote sensing is necessary to overcome such difficulties. Many equipments with minor improvements could work equally well under arid and semi-arid conditions. Data logging systems, with retrieval and telemetry have proved reliable under many harsh environments, and should be adapted in arid and semi-arid regions. Remote sensing data can assist in planning field trips and serve as an indirect method of assessment of water resources.

2.6.4 Processing of Streamflow Data

The first check of a stage data is against maximum and minimum limits. The absolute maximum and minimum limits at a particular station are carefully set such that values outside these limits are clearly incorrect. But this check does not highlight those values which are within the limits but still may be incorrect. Less extreme upper and lower warning limits are sometimes set and values outside the warning range are flagged for subsequent scrutiny. The underlying objective, while setting the upper and lower warning levels, is that the limits are violated 1–2 times every year. This would ensure that, on an average, one or two extreme events are scrutinised more closely for their correctness. These limits may also be worked out using suitable statistics but care must be taken of the time interval and the length of data series under consideration.

A comparison of each data value with immediately preceding and following observations is an effective way to screen the variables that exhibit a significant serial correlation such as water level. A limit is set as the maximum acceptable positive or negative change between successive observations. Note that what is an acceptable change in level during a rising flood hydrograph may be unacceptable during the dry season. Violations of the rise and fall limits are more readily identified from graphical plots of the hydrograph.

A visual check of the time-series data is an effective technique to detect data anomalies and must be applied to every hydrograph data. A screen display may also show the maximum and minimum limits and the upper and lower warning levels. Potential problems identified using a numerical technique can be inspected and accepted as correct or flagged as spurious or doubtful. Ideally, attempts may be made to interpret identified anomalies in terms of the performance of the observer, instruments or station and this should be communicated to field staff for remedial actions.

Figure 2.18 shows a record of the recession limb of a hydrograph. The erroneous recording produced by an automatic water level recorder could be due to an obstruction in the mechanical movement that caused the float to remain hung, blockage of the intake pipe or siltation of the stilling well. The later part of the curve showing the correct behavior was measured after removing the fault. The recession limb was corrected by drawing a smooth curve during validation.

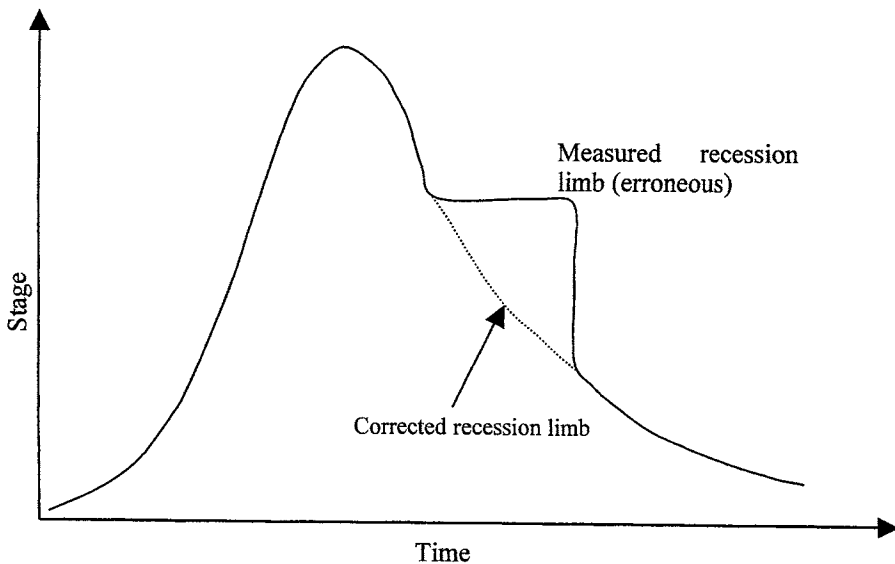


Fig. 2.18 Erroneous recording of recession curve due to faulty equipment.

Some of the methods for quality control of streamflow data are:

- Test the stage or discharge of a given day in a year against the highest and lowest value of the same date in all the previous years.
- Apply the same test on the difference between the value on the day and the day before.
- Compare the observed data with estimates based on data from adjacent stations. The estimates may be based on regression. By transforming the data it is possible to increase the weight on high or low values. By plotting the estimates possible errors are easily identified.
- Compare the observed discharge with estimates based on a precipitation-runoff model.
- Compare runoff at a station with runoff at an upstream station.
- Apply the double mass curve analysis to identify shift in control.
- Apply the time series analysis to detect changes in the homogeneity in time series.

The most common techniques to fill short data gaps are: interpolation from adjoining values by plotting a smooth hydrograph, double mass curve techniques, correlation with adjoining stations and auto-correlation (for short gaps only). If a catchment has undergone significant changes, data may have to be adjusted to virgin conditions.

The processed data are used for a variety of purposes. Some of these are computation of flow duration curves, unit hydrograph analysis, flood or low-flow frequency analysis, computation of the inflow to a reservoir, flow routing, and flood forecasting.

Stage-Discharge Relationship

The measurement of discharge at a gauging station is costly and requires trained manpower, time, and special equipment. Therefore, it is usual not to frequently measured discharge. The measurement of river stage is much easier and is carried out frequently. A relation, known as rating curve or stage-discharge relation, exists between river stage and discharge at a cross section. A rating curve is developed by using the concurrent data of stage and discharge observed over a period of time. It is important that the data covers the range of stages that are likely to occur at the gauging station. Since most hydrologic analyses, such as assessment of water yield and design of projects, are based on discharge data, the rating curve has important bearing in hydrology.

The characteristics of a stable channel do not change with time. The rating relation changes in unstable channels and, therefore, sites without a stable control should be avoided, as far as possible. The factors that influence the rating curve can be broadly classified in two groups: natural and artificial. The natural factors include the geometry of the cross-section, the properties of bed and banks, the alignment of channel upstream of the gaging station, the properties of sediment being transported by the river, etc. The artificial factors include flow regulation structures, such as a weir, channel improvement works, a bridge, land use changes, river training works, etc.

The combination of element(s) that control stage-discharge relation at a station is known as control. Different types of controls are: section and channel controls; natural and

artificial controls; and complete, partial, and compound controls. When the geometry of a cross-section downstream of a gage constricts the flow or there is a break in the bed slope (e.g., a fall), a section control is said to be effective. If the relation is controlled by the geometry and roughness of a reach downstream, a channel control is said to exist. A complete control governs the rating relation over the entire range of stages. This is a rare occurrence. More common is a compound control in which a section control dominates lower discharges and another channel control dominates higher discharges.

When the stage is uniquely related to discharge, this is known as simple rating curve. In a compound rating curve, more than one curve is required. To establish a rating curve, the stage and discharge data are plotted on a graph paper, as shown in Fig. 2.19, wherein stage is plotted on the Y-axis and discharge on the X-axis. Ideally, there should be a sufficient number of points, well distributed over the entire stage and discharge range at the gaging station. If the scatter of the plot is negligible or very small, a smooth curve can be drawn through the points. The scatter in the data can be due to several reasons including backwater effect, unsteady flow at the gauging site, scour of the bed and banks at the gauging site, or errors in observations.

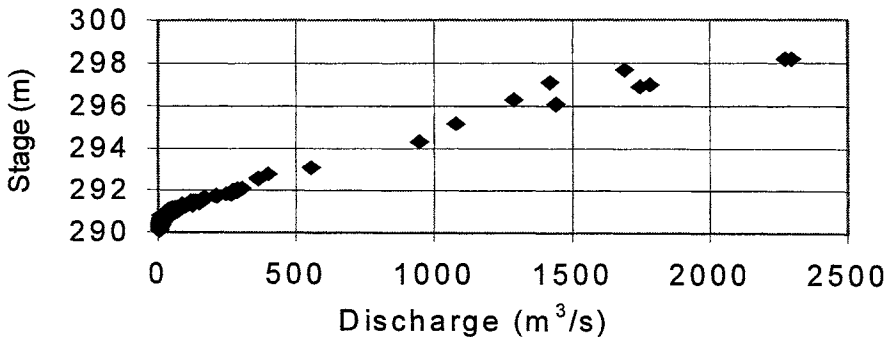


Fig. 2.19 Plot of stage and discharge at a gauging station.

A simple rating curve is commonly represented by a power equation that has the form

$$Q = a (H - c)^b \quad (2.28)$$

where Q is the discharge (m³/s), H is the river stage (m), a and b are constants, and c is the stage (m) at which discharge is nil (known as the datum correction). This equation plots as a straight line in the log domain. The method of least squares is commonly used to estimate the coefficients of rating curves a and b in eq. (2.28). To estimate the datum correction c , iterations are performed by varying c and the value which yields best results is adopted. The selected value of the datum correction should be physically plausible. After establishing a stage-discharge relation, it is necessary to test it for absence from bias and goodness of fit.

In many situations, a single curve may not be representative for the entire range of stages because the influence of roughness and boundary conditions is not the same at all stages. Up to three curves may be required – one for lower range of stages, one for middle range, and another for higher range, leading to a compound rating curve.

In large rivers with flat bed slopes and significant changes in flow rates, the effects of unsteady flow on the rating curve may be significant. The slope of flood wave front during the rising stage is much steeper than during the steady-state condition and the situation is reverse during the falling stage. This phenomenon is known as hysteresis and it gives a loop rating curve, i.e., discharge is not a unique function of stage.

Very few channels are stable over all stages and at all times. If the geometry and properties of the cross-section change with time due to scour or deposition, growth of vegetation, etc., this is known as a shifting control. This requires frequent updating of the rating curve. A shift in the rating curve is said to have occurred if a group of consecutive observations of discharge plots a certain percentage (say, about 5%) either to the left or the right of the established rating curve. The vertical shift of the rating curve is accounted for through a shift adjustment. In the simplest case, for a discharge measurement, the shift adjustment is obtained by subtracting the observed gage value from the gage value which corresponds to that discharge on the rating curve. To obtain discharge from the rating curve under shifting conditions, the shift adjustment is added to the gage height and then the rating curve is used to read discharge.

Extrapolation of Rating Curve

Rating curves are required to be extrapolated when the discharge measurements are not available over the entire range of observed stages. In simple cases, the curve may be smoothly extended. This will not be correct if, in the extended range, channel geometry changes, there is flow over flood plain, or the roughness coefficient changes significantly. For extrapolation in low flow ranges, it is better to plot the curve on a simple graph paper since zero discharge cannot be plotted on a log scale. A rating curve is smoothly extended. The extrapolation in high flow ranges should be attempted with utmost caution and only if indirect methods of discharge estimation such as the slope-area method cannot be used. Rantz (1982) recommended the use of the conveyance-slope method as it is superior to the velocity-area and other methods.

The process of establishing a rating curve is a mapping problem where stage is the input variable and discharge is the output variable. Among the emerging data analysis techniques, the Artificial Neural Networks (ANN) technique is a powerful procedure for non-linear function mapping. Jain and Chalisgaonkar (2000) applied this technique to establish stage-discharge relations. An ANN can also successfully model a looped rating curve.

Standards have been developed by many countries for establishing stage-discharge relation. The standard ISO 1100/2 (see ISO, 1982) deals with determination of stage-discharge relations. Rantz (1982) has given a detailed discussion of the topic.

2.7 WATER QUALITY DATA

A large number of variables are associated with water quality information, the measurement frequency depends on the changes in the variable as well as its use. The major groups of water quality variables are organic matter, major and minor ions, toxic metals, nutrients and sediment data. The biochemical oxygen demand, chemical oxygen demand and dissolved oxygen are indicators of the presence of organic matter in water. The toxic metals include mercury, lead, arsenic and nickel. The nutrients, such as phosphorus and potassium, are important from the point of view of water resources.

Water quality parameters are rarely measured continuously because of logistical reasons and are, therefore, based on sampling which may be at regular intervals or more often at irregular intervals. The recorded values represent the state of the water at a particular time. Important water quality parameters or those which change rapidly with time are measured with greater frequency than those which vary slowly. For a few water quality parameters, the analysis is carried out at the observation station. Most analyses require sophisticated equipment and are, therefore, carried in a laboratory.

The clean water is a clear, colorless, and odorless substance. Most natural waters are often colored by organic materials picked up from decaying plants. The physical parameters of quality include turbidity, solids, electrical conductance, color, odor, and temperature. Temperature measurements are important to understand the problem of density, viscosity, vapor pressure, oxygen saturation value and rates of biochemical degradation. The test for residue is of great importance in the sewage treatment process to indicate the physical state of the principal constituent. The solids present in the dissolved form are related to the electrical conductivity of the water. Common measurements to assess the presence of physical impurities in water are turbidity, solids, electrical conductance, color, odor, and temperature.

There is a wide range of measurement techniques for water quality parameters. Here, the discussion is categorized according to physical, chemical, and biological parameters.

2.7.1 Physical Parameters

The important physical properties of water from the point of view of a water quality study include temperature, density, viscosity, specific weight, and vapor pressure. The variation of these physical properties with temperature is widely available in literature. McCutcheon et al. (1993) have tabulated range and typical concentrations of water quality parameters in streams and rivers.

Turbidity: Clear natural water allows images to be seen distinctly at considerable depths. Turbidity is measured by determining light transmission using standard light sources. The test has little meaning in relatively clear waters but is useful in defining the drinking water quality.

Solids: All contaminants of water, except dissolved gases, contribute to solids load. Solids can be classified by their size and state, by their chemical characteristics, and by their size distribution. Solids are divided into two broad groupings: dissolved (including colloidal and small suspended particles) and suspended (including settleable). The distinction is made using a membrane filter with a pore size of about 1.2 micron. Any particle passing the filter is considered dissolved, and any particle retained on the filter is considered suspended. Solids are also characterized as being non-volatile or volatile.

The sum of dissolved and suspended (filterable and nonfilterable) solids is the total solids content. The amount of the total dissolved solids (TDS) present in water is an important indicator of its quality for drinking, irrigation and industrial use. As water moves on land, it picks up solids and TDS increases. TDS affects dissolved oxygen concentration and also influences the ability of a water body to assimilate wastes. Dissolved solids affect ionic strength of water and thereby impact mobility and transformation of metals. TDS also affects the growth and decay of aquatic life.

To determine TDS, a sample of known volume is dried in an oven and the weight of the residue divided by the volume of the sample gives TDS which is normally expressed in mg/L. Wide variations in the TDS concentration are observed in natural waters. The TDS concentration in rain water is below 10 mg/L, in river water it may be of the order of hundreds of mg/L. Depending on the presence of salts, the water is categorized from saline to briny.

Color: The color of water depends on the dissolved material as well as suspended particles. Many of the colors associated with water are not true colors but the result of colloidal suspension, e.g., tea. True colors result from dissolved materials, most often organisms. Most colors in natural waters result from dissolved tannin extracted from decaying plant materials. The result is slightly brownish tint. Many industrial wastes are colored and, if not properly treated, can impart color to the receiving stream.

Odor: Odor is an indicator of the presence of pollution or toxicity in water. Pure water does not produce odor. Water usually smells due to the presence of decaying organic matter or, in the case of mineral springs, the reduction of sulphates by bacteria to hydrogen sulfide gas. The decaying organic matter may accumulate in bottom deposits large enough to provide suitable conditions for the anaerobic bacteria that produce noxious gases. Sources of the organics include plant debris washed into streams, dead animals, microorganisms, and the wastewater discharge.

Temperature: Temperature affects a number of important water quality parameters. Chemical and biochemical reaction rates increase markedly with temperature. Gas solubility decreases and mineral solubility increases with temperature. The growth and respiration rates of aquatic organisms depend on temperature, and most organisms have distinct temperature ranges within which they reproduce and compete.

Lakes vary in temperature from surface to bottom, and the aquatic life varies accordingly. Cold-water species stay in deep waters while warm-water species are found in

shallow regions near the edges. The water released from the reservoir surface will be warmer and promote warm-water organisms. When the water is used for irrigation, its temperature must be high enough to induce germination of seeds.

Hardness: Water is classified as hard or soft mainly on the basis of carbonates present in it. Normally water is classified as soft when the carbonate concentration is below 50 mg/L and is termed as very hard when it exceeds 180 mg/L. According to the guidelines of the World Health Organization, the hardness should not exceed 500 mg/L. The hardness is usually measured by titration or by measuring magnesium and calcium ions present.

2.7.2 Chemical Parameters

The chemical characteristics of water can be classified into two categories: (a) inorganic matter, and (b) organic matter. The chemical tests of water quality include an analysis for the presence of specific ions. Gross chemical measures, such as alkalinity and hardness, are also used to define water quality. Most of the common water quality parameters reflect combinations of or interactions between ions.

(a) Inorganic Matter

Major Ionic Species: All natural water contains a variety of dissolved salts in solution originating from rain or soil and rock with which they have been in contact. The principal chemical constituents present in most waters are Cations (Calcium, Magnesium, Sodium, and Potassium) and Anions (Bicarbonate, Sulfate, Chloride, and Nitrate). Typically, these ionic species are derived from the contact of the water with various mineral deposits. The most abundant species are bicarbonates, sulphates, and chlorides of calcium, magnesium, and sodium. The distribution of these species varies with geographic location and the residence time history of the water. Potassium, usually present in small amounts, is derived from soil minerals, from decaying organic matter, and from the ashes of burned plants and trees. Nitrate is usually present in small amounts. Aggregate salts are derived as total dissolved solids (TDS) (mg/l). Besides, many minor ionic species, derived from the contact of water with various mineral deposits, are also present. Some of the minor constituents, such as ammonium, carbonate, and sulfide, may be present because of bacterial and algal activity.

Non-ionic Species: The principal non-ionic minerals found in all natural waters and ground waters are silica, usually expressed as SiO_2 . The presence of silica in water is troublesome, especially in industrial applications, where it causes severe scaling problems in boilers and heat exchangers. In addition to the major and minor ionic species, a variety of inorganic species (principally heavy metals) of anthropogenic origin may also be found. The more important of these are arsenic, barium, cadmium, chromium, lead, mercury, selenium, silver, zinc, and cyanide. These constituents are of concern primarily because of their toxicity to micro-organisms, plants, and animals. Typically these constituents come from the discharge of improperly processed industrial wastes, and high concentrations are often found in wastewater sludges.

Nitrogen and phosphorus are essential elements for growth of plants and animals and are, therefore, often identified as nutrients. Note that both organic and inorganic forms of these constituents are of importance. Nitrogen is a complex element that can exist in seven states of oxidation. From a water quality standpoint, the nitrogen-containing compounds that are of most interest are organic nitrogen, ammonia, nitrite and nitrate. Phosphorus is of importance in water supply systems and in the aquatic environments. Phosphorus compounds are used for corrosion control in water supply and industrial cooling water systems and in the production of synthetic detergents.

Nitrogen

Nitrogen accounts for about 80% of the gases present in the atmosphere and this huge volume maintains equilibrium of nitrogen concentration in open water bodies. The nitrogen solubility in water is very less; it is of the order of 15 mg/L. Human activities influence nitrogen in surface water in several ways. Nitrogen is present in wastes that are discharged into surface water bodies. Runoff from agriculture areas contains nutrients that contain nitrogen. It is also present in the exhaust of automobiles and industries. The key parameters for nitrogen are nitrate and ammonia. The usual range of concentration of nitrate in streams is 0.5 to 3 mg N/L and of ammonia in the range of 3mg N/L. The streams that receive runoff from agricultural areas may have considerably higher concentration of nitrates. Domestic sewage contains about 15-100 mg/L of the total nitrogen. Nitrification which is oxidation of ammonia and nitrite to nitrate, consumes dissolved oxygen in water. Excessive presence of nitrogen in water can lead to eutrophication.

Phosphorus

Phosphorous is an important constituent of organic matter that enters into water bodies through fertilizer, industrial waste and rocks. Phosphorous is vital for all organisms and in many cases it is the nutrient that limits productivity. According to McCutcheon et al. (1993), the common venue of its concentration is 0.05 mg P/L.

pH

The pH of a solution is defined as the negative logarithm of the hydrogen ion activity, $\text{pH} = -\log(\text{H}^+)$. The range of pH is from 0 (maximum acidic) to 14 (maximum basic); pH of a neutral solution is 7. All geochemical reactions are affected by pH. Surface waters become acidic when additions of acid exceed the buffering capacity of the carbonate system. Anthropogenic sources of acidity include acid deposition and acid mine drainage. In addition, some sources of acidity arise naturally due to the oxidation of sulfide bearing ores. Acidic waters are of concern as their low pH increases the solubility and mobility of trace metals.

(b) Organic Matter

Organic matter is important for the health of a water body because the decomposition of organic matter draws upon the oxygen resources in the water and may render it unsuitable

for aquatic life. Common parameters to characterize it are: BOD (biochemical oxygen demand) and COD (chemical oxygen demand). The widely used BOD test measures the oxygen equivalence of organic matter and is the most important indicator of pollution by organic matter. Similarly, a direct measurement of dissolved oxygen is an important indication of the health of the water. The absence of DO or a low level indicates pollution by organic matter. It is recorded as a percentage of saturation.

Natural Organic Compounds: Most organic compounds are composed of various combinations of carbon, hydrogen, oxygen, nitrogen, phosphorous, and sulphur. The principal organic compounds, found in wastewater, and to a much lesser degree in natural waters, include proteins, carbohydrates, and lipids.

Synthetic Organic Compounds: The presence of a large number of organic compounds in water is of concern from health, treatment, and ecological standpoints. Of greatest concern are those organic compounds that may be carcinogenic or that may cause mutation in humans and other living forms at extremely low concentrations, e.g. surfactants, pesticides and agricultural chemicals, organic solvents, etc.

Toxic Metals and Organic Compounds: Toxic metals and other elements may exist naturally in waters but their concentration may be seriously increased through human activity. These metals include Copper (Cu), Chromium (Cr), Mercury (Hg), Lead (Pb), Nickel (Ni), Cadmium (Cd), and Arsenic (As). Measurements of toxic organic substances require advanced instrumentation.

2.7.3 Biological Parameters

The surface water polluted by domestic wastewater may contain a variety of pathogenic organisms, including viruses, bacteria, protozoa and helminths. As the testing for all these organisms is costly and time consuming, the most common test is for *Escherichia coli* (*E. Coli*) whose presence is an indicator of the potential for other pathogenic organisms. The results of testing for *E coli* are recorded as the most probable number (MPN)/100 ml. The principal groups of microorganisms found in water may be classified as protists, plants, and animals. The most important microorganisms of concern in water and wastewater include bacteria, fungi, algae, and viruses.

Bacteria: Bacteria are single cell protists. Although there are hundreds of bacteria, most bacteria can be grouped by form into four general categories: spheroid, rod, curved rod or spiral, and filamentous. Spherical bacteria, known as cocci (singular, coccus), are about 1 to 3 μm in diameter. The rod-shaped bacteria, known as bacilli (singular, bacillus) range from 0.3 to 1.5 μm in width (or diameter) and from 1.0 to 10.0 μm in length. *E. coli*, a common organism found in human faeces, is about 0.5 μm in width and 2 μm in length. Curved rod-shaped bacteria, also known as vibrios, typically vary in size from 0.6 to 1.0 μm in width (or diameter) and from 2 to 6 μm in length. Spiral bacteria known as spirilla (singular, spirillum) may be found in lengths up to 50 μm . Filamentous forms can occur in lengths of 100 μm and longer.

Fungi: Fungi are aerobic, multicellular, nonphotosynthetic, heterophic, eucaryotic protists. Most fungi obtain food from the dead organic matter. Along with bacteria, fungi are the principal organisms responsible for decomposition of carbon in the biosphere. They can grow in low-moisture areas and in low-pH environments. Because of these properties, fungi play an important role in the breakdown of organic materials in both terrestrial and aquatic environments. As organic materials are decomposed, fungi release carbon dioxide to the atmosphere and nitrogen to the terrestrial environment.

Algae: The name algae is applied to a diverse group of eucaryotic microorganisms that share some similar characteristics. Typically algae are autotrophic, photosynthetic, and contain chlorophyll. The other pigments encountered in algae include carotenes (orange), phycocyanin (blue), fucoxanthin (brown), and xanthophylls (yellow). Combinations of these pigments result in the various colors of algae in nature. Algae are important microorganisms with respect to water quality. In an aquatic environment, algae form a symbiotic relationship with bacteria. If allowed to predominate, they can affect the dissolved oxygen balance by causing anaerobic conditions to exist at night.

Viruses: Viruses are parasitic particles consisting of a strand of genetic material - deoxyribonucleic acid (DNA) or ribonucleic acid (RNA) - within the protein coat. They invade living cells where the viral genetic material redirects cell activities towards production of new viral cells at the expense of the host cell growth. When the host cell dies, large numbers of viruses are released to infect other cells. They cause several types of infections, e.g., common cold. A number of viral diseases are transferred via water.

2.7.4 Sediment Data

The amount of sediment transported by a river is important for design and management of water resources projects, flood control structures, bridges etc. The data collected includes the particle size distribution for the sediment and the sediment transport as bed and suspended load. The measurement of sediment is an expensive process and sediment rating curves are, therefore, widely used to indirectly assess the sediment concentration as a function of river stage or discharge.

The movement of solids transported in anyway by the flowing water is termed as sediment transport. Sediment originates from various sources, including river basin soil erosion, river bed and bank erosion. The sediment may be temporarily stored and mobilized again, depending on its source and on the flood events. Consequently sediment transport rates will depend on many factors, and may differ from the sediment transport capacity because of sediment availability. The total sediment transport is the sum of the suspended load and bed load. The sediment might originate as the bed material load and the wash load. The classification of sediment as per ISO (ISO 4363: 1993) is shown in Fig. 2.20.

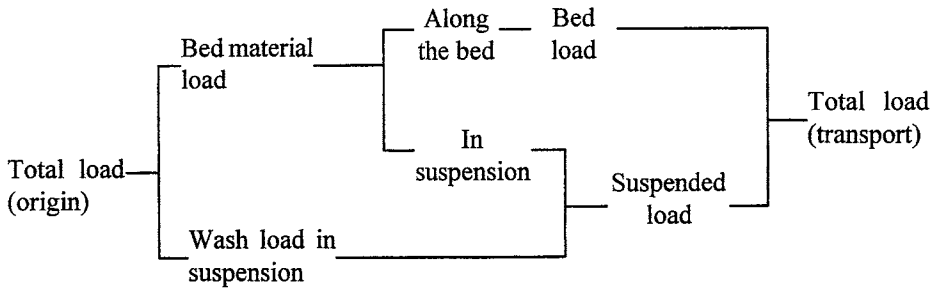


Fig. 2.20 Definition of sediment load and transport (Source ISO 4363: 1993).

To determine the concentration of sediment, sediment samplers are used. The type of sampler depends upon the need and the purpose. The suspended sediment samplers collect samples of water and sediment mixture in a river or lake. The sampler is lowered to the desired depth and is filled with a sample. The size of the sampler should be such that an adequate amount of sample, say at least 0.5 liter, is filled. The depth integrating samplers are filled as they are lowered from surface to bed and then raised up. The rate of lowering or raising should be constant in both directions.

For sampling, the width of the cross-section is divided into sub-areas, depending on the variability of sediment concentration in the lateral direction. Specially designed samplers are used to measure bed load sediments. These are lowered to the bottom and are allowed to be filled up for 5-10 minutes. It is necessary to do sampling at various discharges so that a rating curve relating sediment and water discharge can be prepared. River bed sediment sizes may change during flood events by selective erosion. The concentration of sediments is commonly expressed in g/cm^3 or kg/m^3 . The international standards ISO 3716 and 4363 provide details of sediment sampling. Remote sensing data are also now being used to estimate suspended sediments in water. The reflectance properties of water change depend on the concentration and the properties of suspended sediments and these form the basis to estimate suspended sediments. It is necessary to have adequate ground truth data to obtain reliable results.

The samples are usually analysed in laboratories. After allowing the sediments to settle down, water is carefully removed from the container and the remaining sediments are oven-dried. The particle size analysis is first carried out by sieving and then the finer sediments are analyzed using hydrometer. The sediment transported as suspended load is classified in three categories, depending on the particle size:

- the coarse fraction (particles above 0.2 mm diameter),
- the medium fraction (particles between 0.075 and 0.2 mm diameter), and
- the fine fraction (particles below 0.075 mm diameter).

Acoustic Doppler Current Profilers (ADCPs) are being increasingly used for streamflow and suspended sediment measurements. These instruments measure either the

attenuation of an acoustic pulse due to suspended particles or the backscatter of the pulse by the particles. Reichel (1998) has described the principle and use of ADCP.

2.7.5 Processing of Water Quality Data

The recording and storage of samples and data collected must follow the prescribed set of standards. For each sample, the following information should be recorded: The location of the sampling point, date of collection, purpose, and sample identification number. The location of the sampling point should be recorded in terms of district, tehsil (county or parish) and village, as well as geographical co-ordinates (latitude and longitude). The unique station number identifies a given sampling point in a concise form.

When a sample is collected, the information that should be recorded includes time of sampling (day, month, year, hours, and minutes), the purpose of study, and frequency of sampling. Once the water quality data have been assembled in a data storage system, the next step is to interpret the data with respect to specific questions, environmental problems and water resource management requirements. The most frequently asked questions are:

- What is the water quality at the location of interest?
- What are the water quality trends in a region; is the quality improving or getting worse?
- How do certain parameters relate with one another ?
- What is the total mass loading of materials ?

Flow-sediment Rating Relationship

A sediment rating curve is similar to a discharge rating curve, except that the relationship is established between water discharge and sediment concentration. Usually, the relation is of the form:

$$C = b Q^d \quad (2.29)$$

where C is the suspended sediment concentration (mg/l), Q is the discharge (m^3/s), and b and d are constants. A typical sediment rating curve is shown in Fig. 2.21. Conventionally, discharge and sediment concentration are plotted on a log-log graph paper and a straight line is drawn. A least squares method can be used to obtain the best fit line. Usually, the power equation is log transformed, and linear regression is applied to estimate the parameters. Typically, exponent d in eq. (1) lies in the range $2 < d < 3$.

In most cases, there will be a large scatter in discharge and sediment concentration points. This scatter may span several orders of magnitude. One reason for this scatter is that soil erosion is different during different seasons of the year. If the scatter is large, it might be necessary to develop separate rating curves for different seasons or according to streamflow generation mechanisms, such as rainfall, snowmelt, etc. the data pertaining to rising or falling limbs of the hydrograph may also be separated.

An implicit assumption in deriving a sediment rating curve is that the sediment concentration depends on the transport capacity of flow. This holds good when most of the sediment load consists of suspended channel bed material and is not supply restricted. However, a part of this material originates from the watershed and is transported as washload. Thus, the sediment concentration at a given time depends on the rate of erosion within the catchment and the rate of delivery to the channel, neither of which has to be related to discharge (Pickup, 1988). The extrapolation of sediment rating curves should be carried out carefully. Sometimes, lines joining points of equal concentration, say 10%, 20% are drawn. These are used in the rating curve extrapolation.

The primary use of a sediment rating curve is to obtain the value of sediment concentration for a given discharge. The sediment rating curve along with a flow duration curve can also be used to estimate the amount of sediment being transported over a period of time, say a year. Another important use of sediment rating curve is in estimation of the impact of land use changes and watershed management on sediment yield. After a relationship has been developed and the scatter due to natural changes is accounted for as discussed above, the impact of land use changes, such as logging or watershed management, can be quantified by a shift in the relationship.

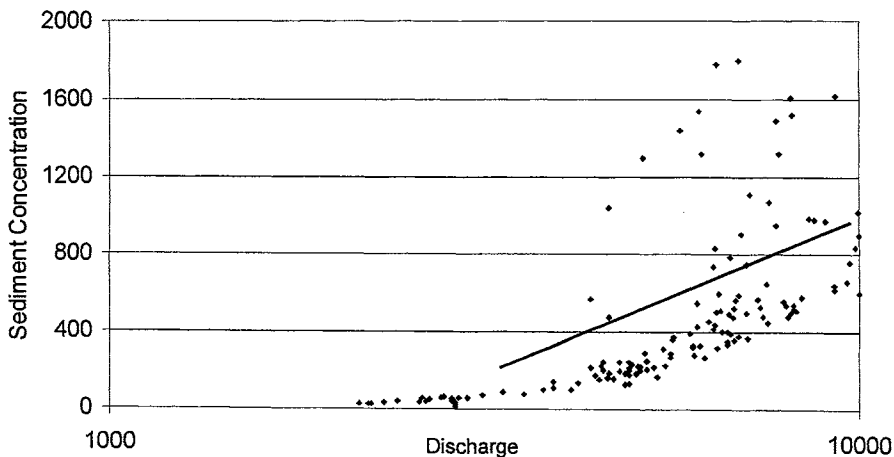


Fig. 2.21 A typical sediment rating relationship.

2.8 OTHER DATA

Besides the major data types discussed, motley of other data are required for planning and management of water resources systems. These are discussed in the following.

2.8.1 Ground Water Data

Groundwater data can be dealt with under three headings: wells, springs, and yields/costs. Well location and hydrogeological logs are single sets of observations which do not change

with time. Piezometer levels, discharge, and water quality are time series data sets which can be validated, processed, and stored using the techniques that have been discussed previously. The well water level is most often obtained by manual dipping techniques and usually at irregular intervals, producing an irregular time series format. The use of automatic level recorders has increased in recent years. Wide variations in frequency of observations are noted in manual systems, ranging from three times a year to monthly/weekly observations. If the wells are pumped, the estimates of water pumped out may come from meters, from duration of pumping, or from the quantity of power consumed. These estimates require knowledge of the pump specification and the pumping head. In addition to defining the surface drainage system of which the spring or well is a part, it is necessary to code the aquifer system(s). In the case of wells, in addition to the basic site description data, the data of well logging are also useful. The discharge of springs can be easily measured by constructing a weir or V-notch as described earlier in this chapter.

2.8.2 Reservoir and Lake Data

The time invariant/slowly-variant data of reservoirs include the elevation-area-storage capacity table, the characteristics of outlet structures, and operating policies. The time-series data include elements of the reservoir working table, viz., inflow, outflow through various outlets, evaporation loss, release to meet the various demands, etc.

Lake bathymetry surveys are carried out to prepare the bed profile and estimate the volume of water in a lake. The water depth can be measured using an echo sounder. A recent development that is of immense use in field surveys is the Global Positioning System (GPS). A GPS enables determination of coordinates of the location of an observer anywhere on the earth, in air, or under water using signals from a constellation of satellites. A range of equipments are available for which an accuracy of the order of cms can be obtained. This system is described in greater detail in Chapter 12. A GPS with echo sounder is extremely helpful in lake surveys.

2.8.3 Spatial Data

Maps are the most effective means of visualizing the spatial data. In water resources, both time-varying and time-invariant data are of use. The spatial data that do not vary with time include the catchment/command boundary, topography, soil map, and stream network, and geological feature. The data that vary with respect to time include land use, cropping pattern, etc. Many times, variation of a hydrological variable is displayed through a map, e.g., isohyetal map.

River channel cross sections, longitudinal profiles and bed characteristics are needed for many hydrological applications. These data slowly vary with time and they can, therefore, be considered as semi-static. It is important that these data are gathered for each observation station with appropriate frequency. Similarly, the longitudinal profile data at each gauging station is to be associated with a time period. River cross sections at gauging stations are of prime importance in interpreting the stage-discharge data. The bed

characteristics in the vicinity of gauging stations, including nature of the river bed and bank material, nature of mobile bed sediments and bed forms, river course stability, river type (meandering or braiding), presence of rapids upstream or downstream from the station, state of vegetation, etc., must also be available. Conventionally, such information is available in the form of paper maps, such as topographic sheets; data such as channel cross-sections are acquired through field surveys and sampling and analyzed using manual means.

The acquisition and management of spatial data using the conventional means is tedious and time consuming. Due to resource constraints, it is not always possible to update these data at a desired frequency. Now-a-days this process has become considerably simpler and faster due to the availability of remotely sensed spatial data at revisit periods of the order of weeks and GIS software for processing of spatial data. The current trend is to use a GIS to store and analyze spatial data. A paper map is an analog depiction of spatial data while the GIS data are in digital form. A digital map can be prepared by digitizing a paper map or from remotely sensed data. Different types of data, such as soil and land cover, are stored in different map layers. GIS permits analysis of single or multiple layers and various layers can be overlaid, one on top of another. Once a map is available in digital form, it is easy to update or modify it.

The concept of data in the form of layers also looks attractive when storing geological data, since the geologists frequently talk in terms of data layers. From a water resources point of view, spatial variation of data is important, e.g., the variation of soil hydraulic properties. After the requisite data are stored in a GIS database, it is easy to answer complex queries like what are the areas in the catchment that have pine forest on shallow clay with 3% slope? The topic of remote sensing and GIS is discussed in Chapter 3.

2.8.4 Socio-economic and Agriculture Data

The data about population and economic activities are mostly needed for planning water resources projects. Census or gathering demographic data is a routine activity in most countries. In India, an elaborate exercise is carried out every 10 years to gather extensive demographic data which forms an important input in national level planning, including the water sector. The census data also form the basis to forecast the population growth for use in planning activities.

Another important input for water resources is the area under different crops, and crop yield. Agricultural departments usually gather such data for individual administrative units. Since land revenues are collected, based on agricultural production, the revenue departments also gather these data. Note that the boundaries of a water resources study rarely coincide with the administrative or political boundary and it is necessary to interpolate the data before it can be used as input.

Normally, the socioeconomic and agriculture data are compiled for two conditions: 'with' and 'without' project. It is improper to base the analysis on a comparison of conditions before and after project construction because a decline or improvement of present conditions might occur even in the absence of the proposed project. This factor

should be recognized while determining the impacts attributable to the project. Consistent assumptions should be applied to future conditions with and without the project so that comparability is assured. The net incremental benefit stream should be an accurate reflection of the project's income generating capacity, or its net contribution to real national income.

The socio-economic data to be collected depends on the nature of the project being studied as well as type of economy, i.e., developed or developing. Sample surveys are carried out to gather requisite data. The data required for an irrigation project should cover the following aspects.

Demographic and social characteristics

It is essential to ascertain the human resources available, since development proceeds through and on behalf of these. The survey should determine the size of the active and potential labor force for agriculture, together with that for the tertiary sector contributing to agricultural development. The population features as well as future projections are needed to estimate the present consumption pattern and future demand of agricultural products. The level of employment and the income of the entire agricultural and non-agricultural active population must be found. The idea is to estimate the present under-employment and the labor resources available for future development. It has been established that assured irrigation is instrumental in both mechanized large farms as well as manual labor-oriented small farms. Another important factor is migration prospects of the area, which, in turn, would lead to more reliable measurement of future population trends.

Land use and crop yields

Identification of areas, earmarked for annual crops, orchards, pastures, forests and non-cultivated along with the knowledge of the system of land tenure (owner occupancy, tenancy, share cropping), size of farms, and fragmentation, enables preparation of preliminary blueprints on the development possibilities. These details would also show the constraints on the availability of land for cultivation. Soil properties would determine the spectrum of crops which can be grown in the area.

To assess returns on investments in agricultural development, the rise in income resulting from investment is needed. It is essential to know the present cropping pattern, crop rotations, varieties grown, and yields for each crop. These data are used to optimize the cropping pattern and estimate irrigation water requirement.

Farm Budgets and Net Farm Income

Farm budget is a useful method to analyze agricultural economy and should represent conditions anticipated for a farm typical of the area. Where wide divergence in farming patterns is anticipated, the principal patterns may be noted. The budget should cover the following factors: i) farm investment (size of farm, value of land, building, value of farm equipment and livestock); ii) farm production (area and yield of principle crops, and

production of live-stocks); iii) farm expense: details of farm expenses to produce and market the farm products; iv) gross farm income (total annual receipts from sale of crops, livestock and live stock products, and value of farm products consumed by the farm family); and v) net farm income which is difference between gross farm income and farm expense.

By means of sample surveys, it is possible to ascertain the inputs and equipment used by farmers, such as fertilizer, seeds, labor, machinery, breeding stock, etc.

Agricultural supporting services

This covers extension services, research, storage and processing facilities, credit, transport, etc. It will be necessary to assess the importance and the part played by public and private bodies and co-operatives in distributing the inputs and equipment commonly used. A study should be made how the agriculture output of the area is marketed and what long-term storage capacities are. The volume and price trends of markets should be analyzed and forecasted.

It is also essential to know the present agricultural credit and insurance facilities, the details of loans, and the indebtedness of farmers to deduce the amount of time needed by farmers to adapt to irrigation and intensive agriculture.

2.8.5 Water Use and Demand Data

The need for water for various sectors has been quantified in Chapter 1 and continent-wise historical water withdrawal, consumption, and projections have been given in Table 1.1. Since water is a reusable commodity, water use and water abstraction are two different things. The reuse of water is increasing globally and this is likely to grow further. Each drop of the Colorado River water is used 6-7 times before it reaches the sea (Biswas, 2000).

Water use denotes the quantity of water that is withdrawn from waterbodies such as rivers, lakes, and aquifers, for supply to fields, cities, industries, or for ecological and environmental needs. The consumptive use of water is that quantity which is evaporated, transpired, incorporated into crops, or consumed by humans or animals. This water is not immediately available for further use. For some purposes, such as hydropower generation, navigation, and recreation, water is used where it is available (river or lake) but is not withdrawn. But all purposes cannot be served this way and the offstream uses, such as municipal water supply, irrigation, and industrial use, require that water be diverted from the source. A part of diverted water may come back to the river, lake or aquifer as return flow and is available for subsequent use.

The collection of the water-use data is a complex task. Problems stem due to scarcity of data, especially at the individual activity level (a farm, industrial enterprise, or household). The water-use data requirements vary according to the approach employed to represent water use in the planning effort. There are two broad approaches. The first requires data on a set of several inputs to each water-use activity (including the water itself),

each activity's associated prices and costs, and a set of total outputs, including outputs of pollution, with their associated prices and costs. Such data can only come from repeated observation of the same water-user over time (say, monthly totals over several years) or simultaneous observation of many users of the same sort at the same time. For self-evident reasons, the first source is known as a time series, and second as a cross section. Under certain conditions, the time series and cross-sectional data can be pooled, so that several inadequate data sets may be combined into one with enough size and variation to be helpful. But, under all circumstances, extreme care must be exercised in interpretation of the available statistical information.

The second approach is determined by the process for which water is used. It requires data on what is going on within and among the many unit processes of a single water-use activity. This approach amounts to a summation of all individual water demands which can produce a large number of alternative activity designs. These designs, in turn, can be used to define water-use relations and unit water-use coefficients for specific activities, such as steel rolling, paper production, household water use, and the like.

Water resources planning needs both hydrologic and non-hydrologic data. These two broad data sets should always be mutually consistent. Spending unjustified time and resources, for instance, for refinement and improvement of the hydrologic database at the expense of the depth and scope of other non-hydrological data should always be avoided. In other words, one need not try too hard to improve one set of data if another set of equal importance, for whatever reasons, is deficient. One of the common problems which make data acquisition difficult is that hydrologic data are always collected within the watershed boundaries, while non-hydrologic data usually refer to different spatial units that follow political and economic subdivisions of the area under consideration. Adjustments must be made to make all project data compatible in time and space.

Water demand and water use are interrelated concepts, the link being the price of water. Sometimes, these terms are erroneously used interchangeably. The traditional approach has been supply side management but the growing water scarcity has forced consideration of demand management as a viable and desirable option. The tools and techniques of water-demand management have been classified in three categories by WMO (1994): economic, structural, and socio-political. The first category is centered on realistic water pricing. Structural techniques involve infrastructure to effect better control on water demands. The last category includes policies to encourage water conservation.

The data about municipal and industrial water supply can be obtained from municipal water works department or from private suppliers (if the services are in private hands). The procedures to estimate of water requirements for agriculture, hydropower, etc. and their future projections have been described in Chapters 9 and 10. WMO (1994) has also discussed techniques for estimation of water requirements for many purposes.

2.8.6 Data Gathered during System Operation

It is important to note that the data collection and analysis should not stop after the

construction of the project. Rather data collection is a continuous activity and it should continue during the actual operation of the system although the type of data collected may undergo some change. During the operation of a water resources project, the precipitation and discharge gaging stations should continue to function to the extent feasible. Sometimes, stream gaging stations that are located in the vicinity of a dam or a barrage are relocated. The following data should be regularly measured during the operation of a project to provide useful information for improvement in the present and subsequent projects:

- a. **Reservoir working table:** For each reservoir, a detailed working table is prepared for each time period. The time period can be daily for the low flow season and multi-hourly during high flow season. This working table gives data about initial reservoir level and storage, inflow, release from different outlets, evaporation and other losses, spill and final reservoir level /storage. The release details can include the magnitude of demand and volume of actual release for each purpose. The table should also indicate how many outlet gates were opened and by what amount. If the project generates hydropower, the amount of power produced should also be indicated.
- b. Usually a pan evaporimeter is installed at the dam site and the data is used to estimate evaporation losses from the reservoir by applying a suitable pan coefficient. It would be ideal if a meteorological station is set up at the dam site and the data of other meteorological variables, such as temperature, wind velocity, sunshine hours, humidity, etc., are measured. A better estimation of evaporation from a large reservoir is obtained if another pan is installed near the upstream end of the lake.
- c. **Crop data:** This consists of the cropping pattern in the command, sowing and harvesting time, water supplied to crops and crop yield.
- d. It is advisable to carry sedimentation surveys of major projects from time to time. The frequency of such surveys depends on the annual loss of storage due to sedimentation and normally varies from 5 to 10 years; higher sedimentation rates necessitate frequent surveys.
- e. If an inflow forecasting mechanism exists, it is recommended to note the actual inflows against forecasts issued at various times. At the end of the flood season or water year, a comparison should be made to determine the efficiency of the forecast model. Suitable ways to improve this efficiency, if necessary, should be identified.
- f. It has been noticed that in many command areas, the water table shows a rising tendency after surface irrigation is introduced. In all such command areas, ground water table should be monitored at several places. If a rising tendency is noted, suitable remedial measures should be initiated without any delay.
- g. For flood control projects, a detailed map should be prepared for each year showing the area inundated and the depth of flooding. An estimate of flood damage to agriculture area and urban areas should also be made.

2.9 WATER RESOURCE INFORMATION SYSTEM

A Water Resource Information System (WRIS) is a means to manage current and historical hydrological and related data in an organized form. The principles of a WRIS are clearly reflected in the title itself. 'Water resources' indicates that the attention is limited to states, storages, and fluxes of water in space, time, and phase. Hydrometry is concerned with the measurement of these states, storages, and fluxes. 'Information' is data which has been manipulated and processed to give them meaning and purpose. By definition, information serves a function and is created not simply because there is something to be measured or because of curiosity. Three key features of information are: reliability, availability, and presentation. A WRIS is not simply a data collection or archive, it is a logical and structured system to collect, process, store, and disseminate water resources data.

A WRIS comprises the infrastructure of physical and human resources to collect, process, store and disseminate data on (geo-)hydrological and hydrometeorological variables. The physical infrastructure includes observation networks, laboratories, and data processing and storage centers. Large funds and efforts are required for operation of a WRIS. Therefore, the efficiency of the system should be such that the data are easily available to the users and the analysis leads to optimal utilization.

The primary role of a WRIS (see Fig. 2.22) is to provide reliable data sets for planning, design and management of water resource and for research activities. The system should function in such a manner that it provides the information to users in time and in proper form. Sometimes, the scope of WRIS is extended to provide data to users on a real-time basis for short-term forecasting or operational purposes.

The data collected for different hydrometeorological phenomenon through this network is called the raw or observed data. The raw data have to be processed to ensure the reliability of the resulting information. Both raw and processed data sets have to be properly stored -- processed data for dissemination and raw data to permit inspection and revalidation in response to queries from users. Note that the users have a central role in a WRIS.

Since most of water-related development activities are controlled by the government sector in a majority of countries, the main agencies that observe hydrometeorological data are the data users themselves (DHV, 1999). Therefore, the network and frequency of data collection are governed by their own needs. Other data users, such as researchers, may find that data, if available, are inadequate in spatial and temporal coverage, are of varying/inadequate reliability and are scattered at many locations. Importantly, the data that is once missed is not available later on. To obviate all these, there must be a strong linkage between data collectors and the end users and a periodic review of the WRIS.

The activities under WRIS can be broadly classified in the following categories:

- i. Assessing the user needs;
- ii. establishing an observational network and operating it;

- iii. data collection, validation, processing, and reporting;
- iv. management of historical data;
- v. data transmission, storage, and dissemination; and
- vi. institutional and human resource development.

The item (v) is relevant to this chapter and is discussed next.

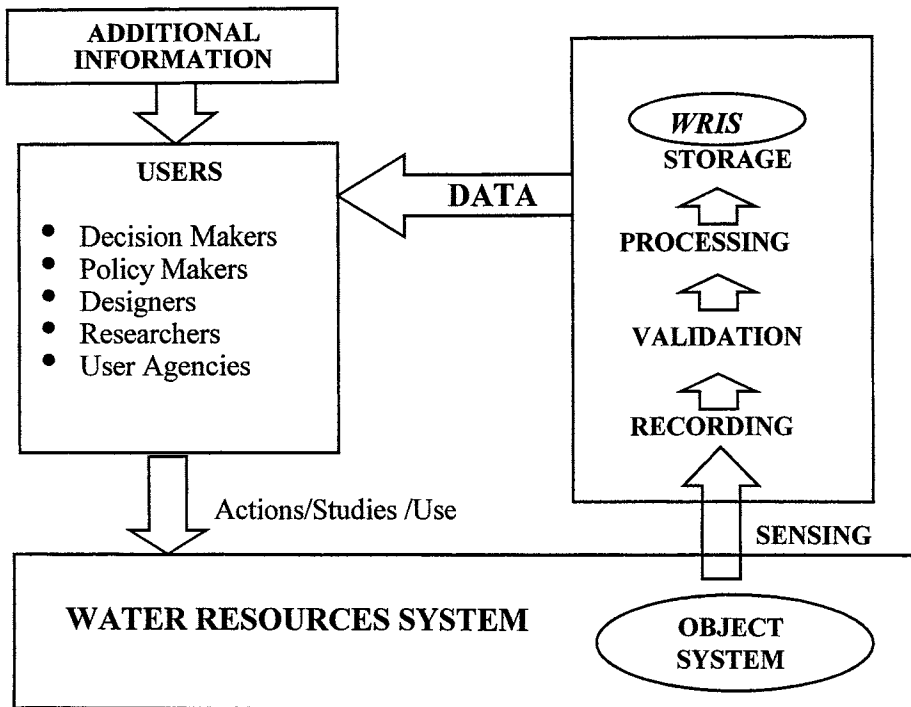


Fig. 2.22 Schematic diagram of a water resources information system [adapted from DHV (1999)].

2.9.1 Data Transmission

WMO (1994) has given the classification of data transmission systems:

1. Manual with the observer at a station sending data to the central office.
2. Manual/semi-automatic system where the central office manually interrogates the automatic field stations through telephone, radio, etc. and receives the data.
3. Pre-program and time system where automatic equipment initiates the transmission of observations.
4. Automatic event indicator and the station automatically transmitting the specified change of variable to a central location.

5. Automatic system with station transmitting and central office recording data continuously.

The possible choices of transmission links are:

- a) Dedicated land lines are used when distances are short and commercial lines are not readily available.
- b) Commercial telephone lines are used wherever feasible. Two-way communication and data transmission is possible. With improvements in information technology, very good voice quality and high band rates of data transmission are possible.
- c) High frequency radio links are used when land lines are not available or topography is difficult. The installation cost can be high.
- d) A significant development of last few decades has been the use of satellites for data transmission. A satellite-based system consists of Data Collection Platforms (DCP) that are installed at hydrometeorological stations. DCPs are (rechargeable) battery-operated devices that collect, encode, and communicate the data of the station to a central location through a satellite link. This system is very useful for remote and difficult-to-access locations.

The choice of a particular transmission system depends on a) the frequency of data observation and the urgency of data, b) the additional benefits of having forecasts based on telemetered data, c) robustness and reliability of the system, particularly in inclement weather, and d) availability of finances, infrastructure and manpower to efficiently run the system.

With growth in information technology, the trend is towards automatic observation, transmission and storage of data, particularly in developing countries. Multi-parameter data loggers can measure, store, and transmit data observed by several observation sub-systems. These days, the data loggers are small, rugged, and have small power requirement. These may be battery or solar-power operated. The automatic transmission of data is usually in coded form. WMO has evolved codes related to hydrometeorological data. They have also launched an elaborate system for data observation and transmission through the World Weather Watch (WWW) programme (www.wmo.ch/web/www).

2.9.2 Data Storage and Retrieval

The vast amounts of data which are observed by incurring huge efforts and resources should be stored in such a way that they are easily obtainable and safe from weather and other harmful agents. Also, it is much more useful if the basic data is processed into various useful forms and kept ready to be used by the end users. This can save a lot of money and effort of the user agencies and they would be encouraged to use the data to solve different water resources problems. Archival of data is important in any field. When done in a proper manner, it enables the end users to exploit its potential of data in an efficient way and thus eliminate the tedious task of manually handling voluminous data.

Everyday, vast quantities of water resources data are collected all over the world. In this computer era, the archival of data may be accomplished in a very efficient and economic way. The basic and other processed information may be stored on computer media and the same may then be quickly made available to intended users. Hard copies in the form of data year-books may also be brought out for use by practising engineers, planners and managers. These water year-books can also be made available to the users on computer. Besides the processed data, it is advisable to store the raw data as well because it may be needed for research purposes and it might be realized at a later date that the data validation procedures had missed some aspects.

A typical setup for water resources data management is depicted in Fig. 2.23. The main components are: a) data entry module to input data from various sources in the database, b) user interface for data editing, display, and management, and c) applications that can retrieve data or write to the data base.

Due to large volumes of water resources data, it is necessary that the data are stored such that minimum space is needed. It is estimated that the storage of graphical data on micro films requires only about 1/300th of the storage space needed for the original data. Till recently, the digital data were archived on magnetic tapes. However, the life of these tapes is limited and these are to be stored in controlled environment. The current trend is to archive the data on CD-ROMs each of which can hold 600MB of data and do not require stringent environmental conditions for storage. The problem is considerably less severe now since high capacity hard disks are available and the cost of hardware has dropped drastically. Of course, the volume of data that are being generated each day is also progressively increasing.

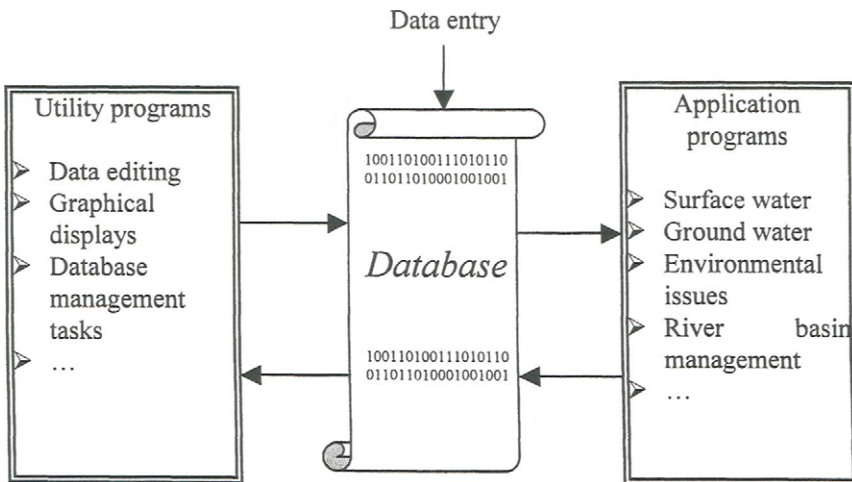


Fig. 2.23 Management and use of hydrological database.

In order to reduce the requirement of storage space, some type of data compression is applied. WMO (1994) has described such procedures. A number of data compression

algorithms have been developed recently. For example, daily rainfall is measured to an accuracy of 0.1mm. Rather than storing it as a real number which requires 4 bytes, the values can be multiplied by 10 and stored as an integer requiring only 2 bytes. The daily data of one month when rainfall was zero need not be stored as 30 zeros. An efficient way is to use notation '30*0'. The database files are not normal ASCII files that require larger space; these are special types of files. The suitability of a particular compression technique will depend on the characteristics of the data.

An efficient data retrieval system is also necessary so that the requisite data are quickly fetched from the database. A good retrieval system should provide the user a combination of options to select the data using criteria, such as by variable, basin, station, time period or range of values. The user should also have a control on the format of the output, i.e. tabular, plot or ASCII data files that can be directly input to another software. If graphs are displayed on the monitor, the user should have an option to print them or store on hard disk for later use. Adequate security measures should also be built in the retrieval system so that only authorized users have access to the database. Among the authorized users also, there should be various categories. Most users are given read-only access and they cannot do any modification to the database. A limited group of users are given all privileges, i.e., they can read, modify and delete data from the database. It is useful to have a log of all users who have accessed the database and the operations that they have performed so that the source can be identified in case of any mishap.

2.9.3 Data Dissemination

The basic objective of creating databases and storing data in an efficient manner is to encourage the use of data for planning, design, management, and research purposes. Therefore, there should be no hurdle in accessing the data by genuine users. Dissemination of information goes a long way to achieve this objective. The first and foremost step in the dissemination process is an up-to-date catalog of database. WMO (1994) has outlined a data catalog format and summary reports. The catalogue of data held in various databases should be updated periodically.

Many organizations routinely publish basin-wise data-year books. A typical water year book consists of description of the basin, its topography, soils, land use etc., major rivers, and salient features of various water resources projects. Maps are included to illustrate all these features. The data section contains typically precipitation, streamflow, evaporation, and ground water data. Periodically, special reports may be published giving long-term statistics of stations or highlighting special or unusual events, such as floods or droughts.

Of late, many organizations have started dispensing with paper publishing due to high costs and handling problems. With the bulk of data now available in digital form in a WRIS, the hard-copy publication is not considered as an efficient means of data dissemination. A water-year book can be conveniently published on a computer media, such as CD-ROMs which are cheaper to produce and easier to handle. A browser may also be supplied to handle data search, display and print facility. This trend is likely to accelerate

further. An important thing to remember is that the format and content of publications should depend on the need of users. The contents should be so designed that the need of most data users are answered and the efforts to handle data requests are reduced. The contents may also depend on the frequency of publication. The price of publication should be fixed such that it is not a burden on the organization and is affordable to the users.

Finally, in this age of computers and Internet, it is appropriate that many international organizations have established databases that can be accessed through Internet. The Global Runoff Data Centre (GRDC) at the Federal Institute of Hydrology, Germany, has a large archive of surface water data. The center was established under the auspices of WMO and mechanisms have been evolved to supply data to a user. INFOHYDRO of WMO is metadatabase that does not actually contain any data but facilitates quick dissemination of information about institutions and agencies dealing with hydrology and catalogs of data. A similar service for climate data is INFLOCLIMA.

2.10 CLOSURE

Two basic tools for integrated management of the environment are modeling and environmental data. Both tools were available and valid in the past; however, the recent requirements for integrated environmental management have also led to a significant evolution of both modeling procedures and data management systems. Current literature provides vast amounts of studies on modeling of different environmental processes. However, issues related to data management systems are barely touched in a comprehensive framework. Data requirements and data availability are mentioned merely as subtopics in most environmental studies although it is well recognized that data constitute the basis for all environmental management activities. Most developed countries have well-established databases which can be accessed easily by the users. Developing countries, on the other hand, do not have extensive data banks and these many not be easily accessible by the users. There is a need for harmonization or standardization in development of databases so that data exchange can be facilitated on regional and global levels.

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