

Design and Review of Monitoring Networks

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1 Introduction

Assessment of freshwater resources, including the identification of potential sources and the determination of their capacity, dependability, and quality, are of primary importance to water resources planning and management. This entails the collection and analysis of substantial amount of long data records in the focus areas. Industrial development and growing domestic and agricultural water demands are increasing pressure on water resources and hence on the environment. This requires an appropriate hydrometric network to supply the adequate information.

An adequately designed network should be able to provide the desired information for different users and industries. For example, water resources managers deal with reservoir operations, which may include hydropower generation, water supply, and flood and drought management. For a better reservoir operation, the hydrometric network should be able to provide the following information: (1) the type of variables needed for flood control and hydropower generation and (2) the appropriate time interval of the variables observed (for example, hourly data for flood forecasting and monthly data for drought assessment). Other important requirements include the density of the network providing the records and the accuracy of the data for the end users. Data collection is the first step in the development of sound and sustainable environmental policy. Coordination of data collection activities is essential to maximize the information that can be derived from the collected data.

Some of the examples of the long-term benefits from good data include sound investment decisions in water supply, hydropower, irrigation and other projects, and the ability to provide timely warnings of drought and flood events to the population. Finally, it is unwise to cut funding on hydrometric network, when viewed over longer time scales.

The main objective of hydrological network design is to select an optimum number of stations and their optimum locations to measure the desired amount of information. Design and operation of a monitoring network is based upon two considerations:

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

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

The physics of the relevant processes must be known to estimate the scale of the spatial and temporal variability. To enable an optimal design of a monitoring network, it is helpful to know the following:

- sampling variables (what is to be measured),
- sampling locations (where to measure),
- sampling frequencies (when to measure),

- sampling accuracy (with what technique/equipment), and
- sampling duration (how long to measure).

These answers also determine the cost of establishing and running the network, such as the costs related to land acquisition, construction works, equipment procurement and installation, station operation, maintenance, and staffing of field stations and data centres. Once the relationship between the chosen effectiveness measure and costs have been established, the optimal network can be found, by weighting the two in a cost – effectiveness analysis. The network optimisation process is depicted in Figure 1.

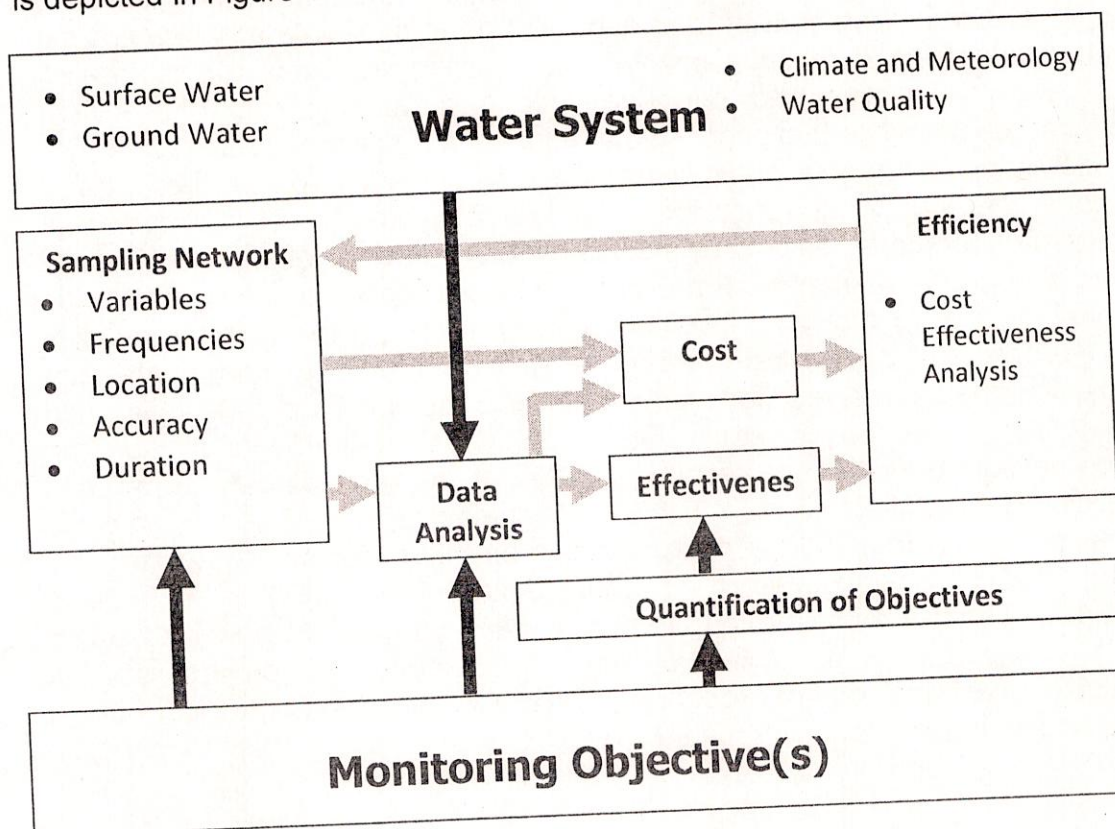


Figure 1: Network optimisation process

After the network becomes operational, it should be evaluated periodically to see whether the current objectives match with the output produced in a cost-effective manner. A network is seen as a dynamic system and not a static entity. This implies flexibility in establishing new stations and closing down these that are no longer needed.

2 Types of Networks

Density of a hydrological network is defined as the average area served by one hydrological station. It is important to distinguish between the following types of networks:

- Basic or primary or principal network, with a low density of stations, where measurements are continued for a long period of time. The principal or base stations provide the basis for statistical studies and should run continuously and indefinitely.
- Secondary network, with a density supplementary to basic network to meet accuracy demands, and where stations are operational for a short time to

establish a good correlation with principal stations. By moving secondary stations after a correlation has been established, one can cover an entire region/country with a dense network based on principal stations that operate continuously.

- Dedicated networks, put in place for a certain project whose objectives determine the network density and period of operation, and
- Networks for representative basins, to study certain phenomena in detail, say for research purpose.

It is emphasized that a part of the network should have a permanent character, to ensure that some basic information is continually gathered. The core network used/maintained by India Meteorological Department (IMD) or Central Water Commission (CWC) in India can be considered to be the primary or basic network. This network has a large coverage, though the density is limited and is in operation for a long period of time.

In addition to the basic network, stations may be established to better cope with the spatial variability of the observed variable. Once sufficient data have been collected at the secondary stations to establish relations with the primary stations, the added value of operating the secondary station should be re-examined. Spatial correlation reduces the information content in a set of data from the network taken at a particular time. For variables like rainfall, where temporal correlation is fairly weak, one more year of data may add on more information to the data set to compute some long-term statistics than one extra station does in case of non-zero spatial correlation.

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

3 Integration of Networks

In a typical national Hydrological Information System (HIS), the following networks are operational:

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

These networks are operated by various agencies. To avoid duplication of work and to reduce cost, the networks operated by the various agencies have to be integrated, technically and organisationally. The hydro-meteorological network has to be considered in conjunction with the surface water and groundwater networks. This will help among the other things, in rainfall-runoff and water balance computations. Organisational integration of the networks implies that the networks are complimentary and that regular exchange and reconciliation of field data takes place to produce authenticated data of high quality. Review of the networks is also to be done in close collaboration.

4 Steps in Network Design

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

1. **Institutional set-up:** review of mandates, roles and aims of the organisations involved in the operation of the HIS. Where required, communication links should be improved to ensure co-ordination/integration of data collection networks.
2. **Data need identification:** with the aid of a questionnaire, the existing and potential future data users are approached to identify their data needs.
3. **Objectives of the network:** based on the outcome of step 2, a Hydrological Information Need (HIN) document is to be prepared which lists out a set of objectives in terms of required network output. The consequences of not meeting the target are to be indicated.
4. **Prioritisation:** a priority ranking among the set of objectives is to be made in case of budget constraints.
5. **Network density:** based on the objectives, the required network density is determined, taking in view the spatial (and temporal) correlation structure of the variable(s).
6. **Review of existing network:** the review covers existing network density versus the required one as worked out in step 5, spreading of the stations in conjunction with the hydrometric and groundwater network, available equipment and its adequacy for collecting the required information, and adequacy of operational procedures and possible improvements.
7. **Site and equipment selection:** if the existing network is inadequate to meet the information demands, additional sites have to be selected as well as the appropriate equipment.
8. **Cost estimation:** costs involved in developing, operating and maintaining the existing and new sites as well as the data centres have to be estimated.
9. **Cost-effectiveness analysis:** cost and effectiveness are compared. Steps 5 to 8 are repeated in full or in part if the budget is insufficient to cover the anticipated costs.
10. **Implementation:** once the design is approved, the network is to be implemented in a planned manner where execution of civil works, equipment procurement and installation and staff recruitment and training is properly tuned to each other.
11. The network should be **reviewed** after 3 to 5 years to see if new data needs have developed. The above listed procedure should then be repeated again.

WMO has suggested that an optimum network should not be attempted until a minimum number of stations has been established. This minimum network is intended as a first step to satisfy the most serious gaps from the perspective of water resources development. Because of the small density of the minimum network, it is important that the records at all stations are of good quality. New observation stations should be started and comparative observations made for at least 10 years to obtain the long-term normal of the new station. Once a significant correlation has been established between new and old stations, old stations that are no longer suitable can be removed from the network to move toward greater network optimization.

5 Data Need Assessment

Step 2 in the network design/review involves an assessment of what is really required by the users. Often, this aspect is overlooked and it is assumed that the information being provided is the same as required by the users. Needs of users may change with time and HIS would fulfil its commitment only if there is a periodic review of the changing needs of the users. It is possible to make a direct link between the objectives of water resource management and use functions of the water system and the type of data that is needed from the HIS (see Table 1).

Table 1: Data requirements from HIS

Objective/function	Data requirements from HIS (examples)
Protection: - flooding - drainage	- design studies (e.g. embankments along rivers and canals, culverts and bridges to bypass floods under roads-railways) require data on temporal and spatial distribution of extreme rainfall, on discharge extremes and river stages; - flood early warning systems require the same kind of information.
Ecological sound water systems: - ecology - forestry - erosion	- assessment and habitat studies require data on the natural river stage and flow dynamics, flow velocities, variation of groundwater levels, water quality and of anthropogenic effects; - forestry/erosion require data on rainfall, evaporation, variation of river stage/groundwater levels and on quality.
Drinking water supply/ Municipal water supply	resource assessment and design studies require data on water quantity and quality. e. g. temporal distribution of river flows, groundwater levels.
Agriculture - irrigation - rain-fed agriculture	- assessment and design studies (reservoirs, intakes, irrigation schemes, etc.) require data on water quantity and quality, including extreme rainfall and river flows (spillways), historical river regime (reservoirs) and sediment transport. - for the operation planning of the system, data on water demands, rainfall, river stages and flows (quantity and quality) are needed. Real-time data and forecasts are, however, not provided by the HIS.
Fisheries	Assessment and suitability studies require data on water depth, flow velocities and water quality.
Hydropower production	- the design and operation of micro, mini and macro-hydropower systems, often in combination with water use for irrigation and flood mitigating measures require data on water quantity and quality data, including extreme rainfall and river flows (spillways), historical river regime (reservoirs) and sediment transport. - for the operation of the system data on water demands, rainfall, river stages and flows (quantity and quality) in real-time and as forecasts are needed. Such data are however not provided by the HIS.
Shipping	Design and maintenance require information on water depth, flow velocities. Sedimentation (note: inland shipping is of minor importance in India).

Objective/function	Data requirements from HIS (examples)
Industrial water supply	Availability studies (for process and cooling water) require information comparable to drinking water supply.
Discharge of effluents	Licensing and monitoring require data on flows, various water quality parameters.
Recreation	Assessment studies and protection require on water quality conditions, water levels and flow velocities.

5.1 Objectives, functions and activities of Water Resource Management

Based on the National Water Policy and overlying strategic plans, a concise objective of the water resources development can be formulated. The objectives of water resource management (see box) and use functions of the water system are linked to the type of data that is needed from the HIS.

Objectives of WRM:

- to support various water use functions,
- to protect human life and economic functions against water related disasters,
- to maintain ecologically sound water-systems.

Use functions:

- drinking and municipal water supply
- irrigation
- hydropower production
- industrial water supply
- fisheries
- navigation
- discharge of effluents (incl. cooling water)
- recreation, ...

An efficient procedure to assess the data needs is through small interview teams who explore the mandates and data needs of the potential data users. In the interview teams both surface and groundwater organisations should be represented. To guide and streamline the discussions a questionnaire may be prepared, to be filled in during visit to the data user, addressing the following items:

- description of data user (name, sector, mandate, services provided, staffing and financing).
- water system use (present and future) with respect to quantity and quality, and responsibility.
- data use and requirements (variables, type, location frequency of measurement, in what form, accuracy, consequences if not available, summary of present status of data supply).

A list of potential users of hydrologic data is given in Table 2.

6 Rainfall Network

6.1 Measuring Objective

The major uses of rainfall data are for water resources planning, hydrologic design, management of water projects, disaster warning systems, and research.

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

Table 2: List of potential hydrological data users

1. Governmental organizations - Surface Water Departments: Federal/ local - Ground Water Department: Federal/ local - Meteorological Department - Pollution Control Department - Ministry of Environment and Forest/ Public Health Department/ Water Supply and Sewerage Department - Geology and Mines Department - Hydro and Thermal Power Producers - Industries and Commerce Department - Agricultural Ministry - Fisheries and Forestry Department - Ministry of Transport / Railways - Tourist Board - Universities, ...	2. Non-governmental organizations - Chambers of Commerce - Water Users Associations - Farmers Development Agencies - Environmental Protection Organisations - Tourist Organisations, - ... 3. Private sector - Industries: e.g. Paper Mills, Cotton Mills, Beverages, Metals, Capital Goods, Consumer Goods, ... - Engineering Consultants - Contractors, etc.
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For design of structures, statistics of short duration rainfall (e.g. quarterly, hourly or daily) are to be estimated. Rather than focussing on the average amounts, here the interest is in the extremes and their areal extent. Generally the spatial correlation structure of short duration rainfall (minutes or hours) differs much from the long duration rainfall. This feature has important implications for the required network density and also for the type of equipment to be used for rainfall measurement.

For actual management decisions, the interest is particularly in data on a real - time basis for purposes such as reservoir operation and flood forecasting. Historical data are required here for the design of rule curves and operation strategies and for model development.

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

Clearly, different objectives lead to different information needs and, given the variation of the spatial correlation structure of rainfall with duration, to different network densities.

6.2 Measure of Effectiveness

The typical objective of the rainfall network is to give reliable estimates of areal rainfall. Thus there is a need of integration of the networks. Upstream of every stream gauging station, sufficient rain gauges should be operational to estimate the areal rainfall with desired accuracy. With respect to areal rainfall, generally the interest is in:

- Areal estimates for a storm or defined time period, and/or
- Long-term mean values.

Due to the presence of spatial correlation among the point rainfall stations and weak or no serial correlation, these objectives will lead to different networks and duration of operation. If spatial correlation is absent then each point rainfall data in space would equally contribute to the improvement of the long term mean areal rainfall estimate, provided the rainfall field is homogeneous. However, correlation reduces the

effective number of data, since information in one data is to some extent already included in others. Hence, due to the spatial correlation, data points in time are more effective than data points in space to improve the long term areal mean. Hence, a less dense network operated for a longer time is more cost-effective than a denser network providing the same number of rainfall data. A reduction in the network density, however, adversely affects the quality of the individual areal estimates. The latter is better served with a higher network density, though this may be sub-optimal to estimate the long-term mean.

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

6.3 Network Design

A number of performance measures can be used to assess the adequacy of a network design, e.g. root mean square error (RMSE) between the actual and estimated values, and Nash-Sutcliffe efficiency. To compute root mean square error, one has to describe the spatial correlation structure of the rainfall field. For rainfall, often the following exponential function applies (see Figure 2):

$$r(d) = r_0 \exp(-d/d_0) \quad (1)$$

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

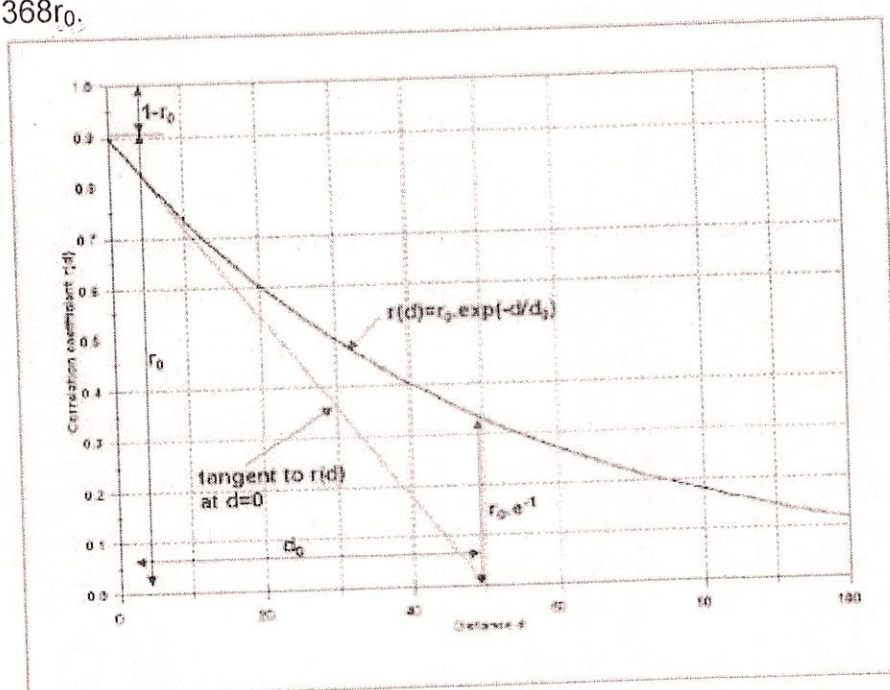


Figure 2: Exponential spatial correlation function

This model includes two parameters, r_0 and d_0 . The value for r_0 being less than 1 is generally attributed to measurement errors and/or microclimatic effects. The

parameter d_0 increases usually with the aggregation level of the rainfall. If the gauges are about evenly spread over the catchment then the relative root mean square error in the areal estimate reads (Kagan, 1972):

$$Z_{areal} = \frac{\sigma_e}{P_{av}} = C_v \sqrt{\frac{1}{N} \left(1 - r_0 + \frac{0.23}{d_0} \sqrt{\frac{S}{N}} \right)} \quad (2)$$

where, Z_{areal} = relative RMSE in areal RF estimate, σ_e = error variance of areal RF estimate, P_{av} = areal average RF, C_v = coeff. of variation of point RF, S = catchment area, and N = number of gauging stations.

The relative RMSE is seen to be a function of:

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

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

- It should be recalled that Z is the root of the mean square error and, in specific cases, errors twice and even three times as high as Z are possible.
- In the above equation a uniformly spaced rainfall network was assumed. If the distribution is less even, the error variance and Z will be somewhat larger. Then technique such as kriging can be applied for error analysis.

The effects of the various parameters C_v , r_0 , d_0 and S on Z_{areal} and N are shown in the Figures 3 to 5. Figure 3 shows that the temporal variation of rainfall has a large impact on the required network density. Variation coefficients are high for short duration rainfall data and diminish gradually when the interval gets larger. Also pre-and post-monsoon monthly rainfall data show generally high coefficients of variation. In such cases either higher Z_{areal} -values have to be accepted or a denser network is to be applied.

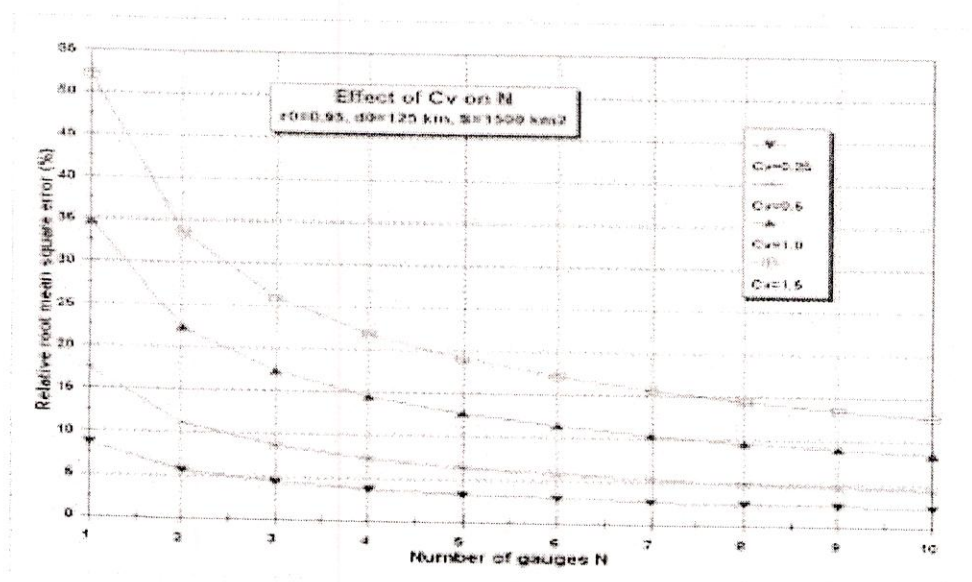


Figure 3: Estimation error as function of C_v and N

Figure 4 illustrates the effect of inaccurate measurements (relatively low values of r_0 , see equation 1) on the estimation error and the consequences for required density of the network. Accurate measurements pay off !!

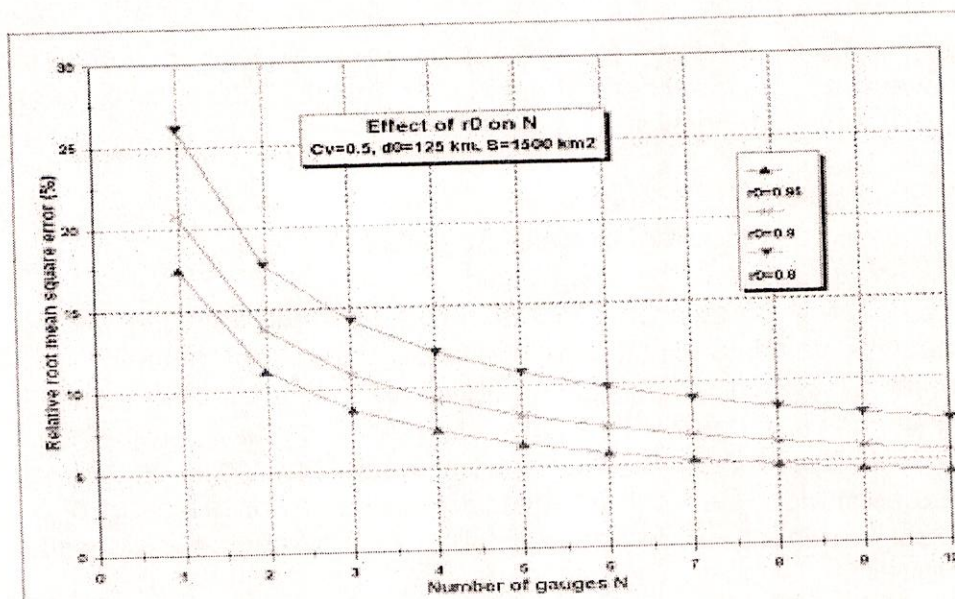


Figure 4: Estimation error as function of r_0 and N

In Figure 5 the effect of the characteristic correlation distance d_0 on Z_{areal} and N is given. It clearly shows, as expected, that a stronger spatial correlation reduces the network density required to reach Z_{areal} target. The distance d_0 generally increases with the duration, whereas C_v reduces when looking at a larger interval, but both with a similar effect on the required network density. This may be taken into consideration when deciding on the interval for which the network has to give a specified accuracy.

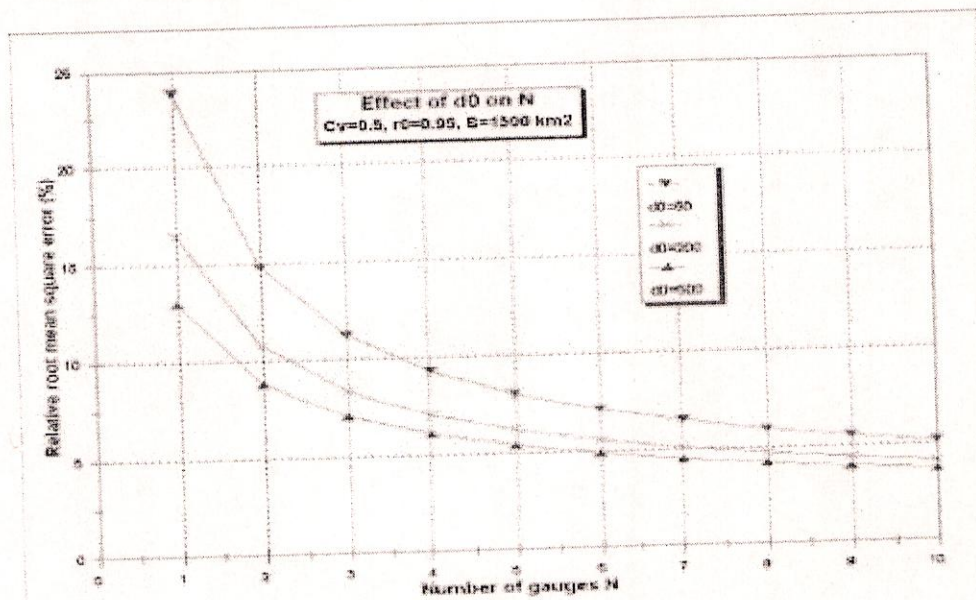


Figure 5: Estimation error as function of d_0 and N

Figure 6 shows the effect of the size of the basin on the required network

density. The general tendency is that for the same accuracy, a smaller catchment needs a denser network than a larger one. Figure 6 is to be fully understood, as one may be tempted to enter for S in equation (2) the entire catchment area, which leads to too optimistic results. Upstream of every stream gauging station sufficient rain gauges should be available to estimate the areal rainfall with a specified accuracy. The minimum stream gauge density in the plains is approximately one gauge per $2,000 \text{ km}^2$ and one per $1,000 \text{ km}^2$ in the hilly areas. Hence those are the catchment sizes to be considered while applying equation (2).

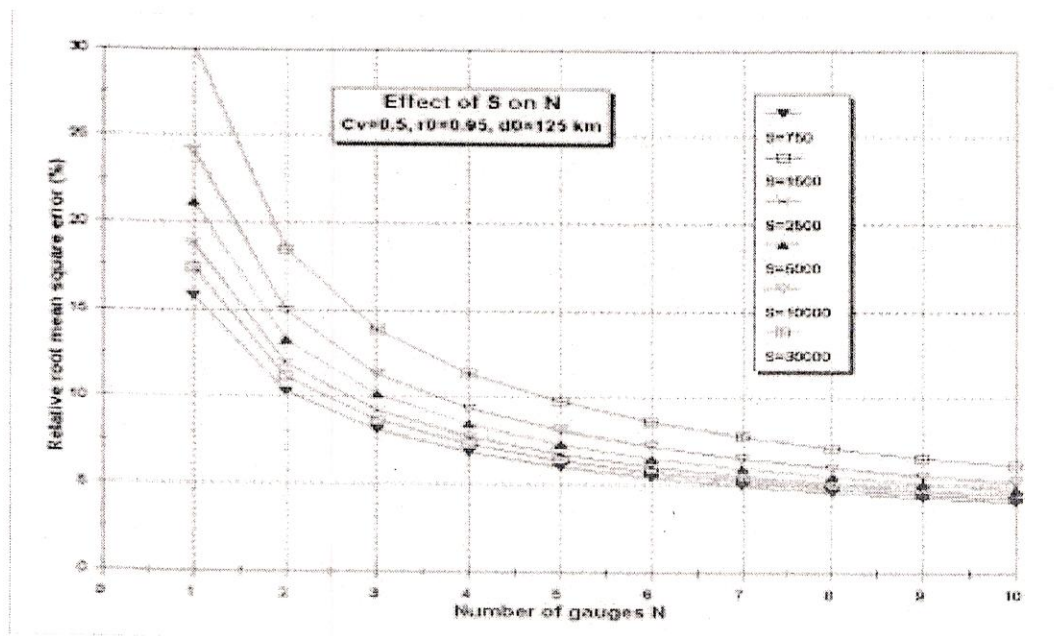


Figure 6: Estimation error as function of S and N

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

Example 1: Rainfall network design in a basin

Consider a catchment in a homogeneous area with altitudes below 600 m (hence orographic effects are not expected). Design the rainfall network to provide monthly, seasonal, and annual areal rainfall with a relative RMSE of not more than 10% ?

Solution: Some 9 rainfall stations fairly equally spread over the area are selected. Monthly and annual point rainfall series, derived from daily observations in the period 1970-1995 are used for the analysis. The annual rainfall in the study area is 1435 mm. The characteristics of the monthly point rainfall series are shown in Figure 7. Typically, the rainfall in the basin is concentrated in the monsoon season, with July and August being the wettest months, both with a long-term average rainfall of approximately 400 mm. In the same figure, the coefficient of variation of the monthly point-rainfall series is shown. It is observed that the C_v values for the monsoon months are lowest, and are approximately 0.5. The C_v values in the non-monsoon season range from 1 to 3.5. The 90% reliable C_v values (the values which are not exceeded at 90% of the stations) are also shown. From Figure 7 it is observed that apart from December, the variation in the C_v values is very small. Hence the assumed homogeneity is justified. The C_v value for the annual point-rainfall series is 0.29 (against 0.23 for the areal average series). It shows that the variation for the larger interval is about half the value of the monthly

series. The C_v statistics are summarised in Table 3.

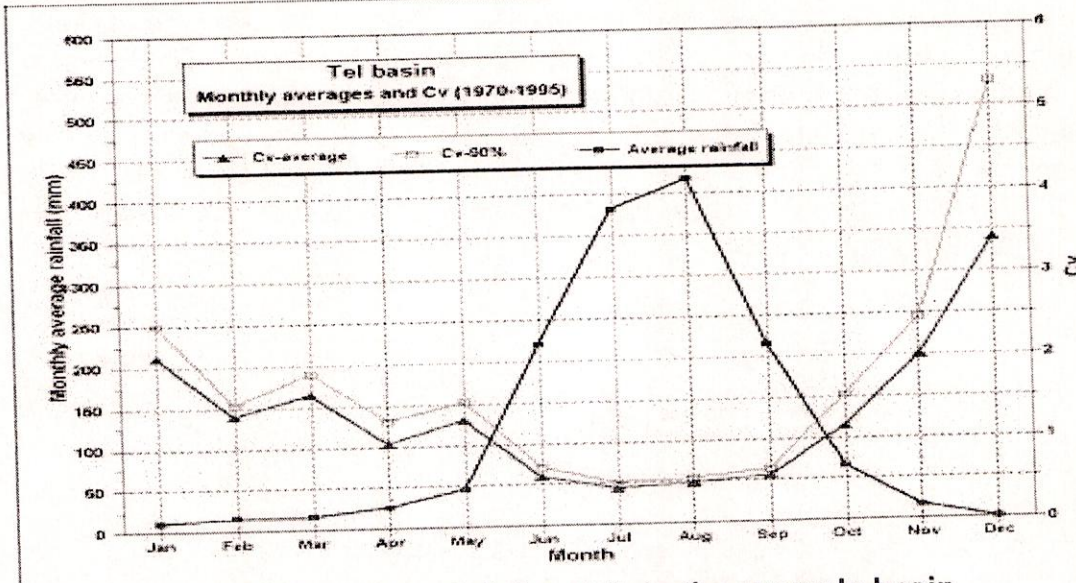


Figure 7: Average monthly rainfall and C_v in the example basin

Table 3: Summary of rainfall network design statistics and rain-gauge density requirements for different measures of effectiveness

Tel-basin Design $S=2000 \text{ km}^2$	Month				Year
	June	July	August	Sept	
C_v average	0.60	0.44	0.48	0.56	0.29
C_v 90%	0.71	0.51	0.55	0.64	0.33
r_0	0.975	0.85 (0.90)	0.95	0.95	0.90
d_0 (km)	140	150	125	150	200
$Z_{\text{areal}} = 0.1$ (10%): S/N in km^2/gauge	780	560 (800)	830	710	1670
$Z_{\text{areal}} = 0.05$ (5%): S/N in km^2/gauge	270	150 (210)	270	220	480

Given that nearly all rainfall takes place in the period June to September, the analysis is concentrated only on these months and on the annual data. The correlation coefficients between the 9 stations for the selected months and of the annual data have been computed and to reduce the scatter have been averaged over intervals of 10 km distance. These are plotted, as an example in Figure 8 for the month of August.

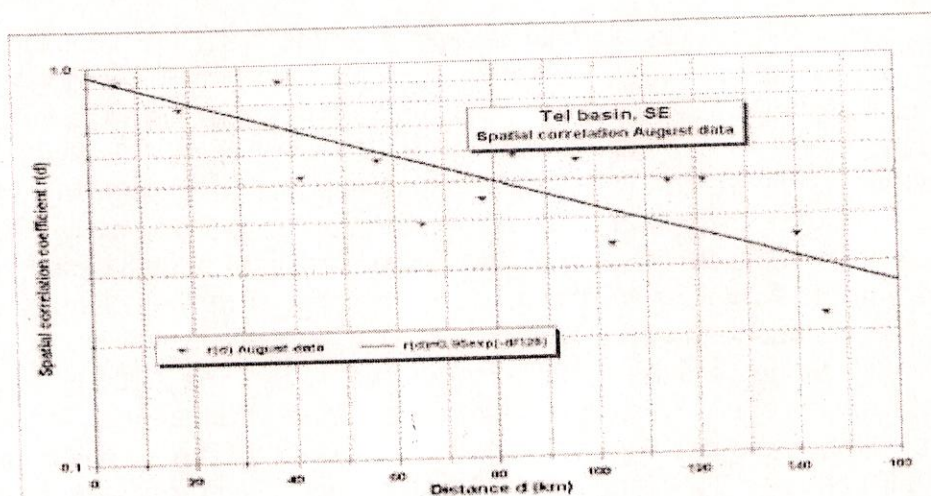


Figure 8: Spatial correlation structure in the example basin for August.

The estimates for r_0 and d_0 for the monsoon months and annual data are presented in Table 3. July data appears to have $r_0 = 0.85$, indicating large measuring errors or strong microclimatic variability. The d_0 values of the monsoon monthly rainfalls are typically in the order of 125-150 km. The annual series shows a larger spatial correlation, with $d_0 = 200$ km. Assuming a design basin area of $S = 2,000 \text{ km}^2$ in view of hydrometric network demands, the required network densities have been computed for each month and for the annual series for Z_{areal} value of 10%. The results are presented in Figure 9 and Table 3. It is observed that the month of July puts the largest pressure on the network. To estimate the areal rainfall in July for units of approximately $2,000 \text{ km}^2$ with on average an error less than 10% one gauge per 560 km^2 would be required. This is primarily due to the low accuracy of the rainfall measurements in that month.

In Table 3 within brackets also the density requirement is indicated if the measurements of July would be improved to an error variance $<10\%$ of the series variance, ($r_0 = 0.9$). It is observed that this would reduce the required network density for that month by 30%. Hence, investment in better observation practice really pays off.

In Table 3, the required network density for Z_{areal} value of 5% is also indicated. It shows that to double the accuracy, a network which is almost 4 times as dense would be required. Hence, the Z_{areal} value has to be carefully chosen and the financial implications of different Z_{areal} values have to be evaluated. Note that the WMO norm for plain areas is one gauge per 500 km^2 (Table 4). For this basin, the density requirement matches with the required density for monthly values if a 10% error in monthly areal rainfall estimates is considered to be acceptable.

Table 4 Recommended minimum densities of stations (area in km^2 per station) [Source: WMO (2008)].

Physiographic unit	Precipitation		Evaporation
	Non-recording	Recording	
Coastal	900	9000	50000
Mountains	250	2500	50000
Interior plains	575	5750	5000
Hilly/undulating	575	5750	50000
Small islands	25	250	50000
Urban areas	-	10-20	-
Polar/arid	10000	100000	100000

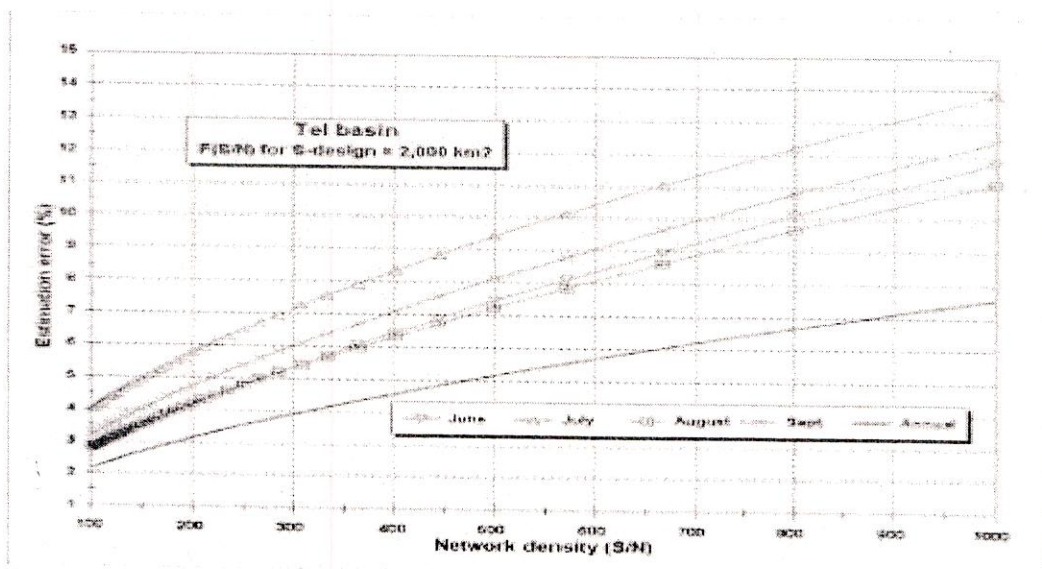


Figure 9: Network requirements for $S = 2,000 \text{ km}^2$

Minimum network density

Based on world-wide experiences, WMO (1994) has presented a general guide for the required density of precipitation stations. An absolute minimum density for different physiographic units is given in Table 4. WMO (1994) does not mention the criteria applied in the preparation of this Table and the accuracy of the results obtained. According to Table 4, at least 10% of the network stations should be equipped with a recording rain gauge.

The network required to get a sufficiently accurate areal estimate for time interval less than one month will be much denser in view of the greater variability and smaller spatial correlation. If such a dense network is likely to be too costly, for short duration rainfall per climatic zone a representative basin may be selected in which a network could be operated with a density that fulfils the short duration rainfall requirement.

The evaluation of a network has two aspects: (1) number of gauges and their location (space evaluation) and (2) time interval for measurement (sampling interval) for each gauge. Approaches which have been commonly used for network evaluation are: (1) statistically based methods, (2) information theory-based methods, (3) user survey approach, (4) hybrid method, (5) physiographic components, and (6) sampling strategies. Statistical methods are mostly applicable to homogeneous hydrologic regions within which regionalized estimates may be derived. Statistical methods typically assume that the basin response, land use, and climate remain the same over time. In general, the statistical methods are essentially based on the minimization of variance. In the past, network design approaches relied largely on statistical methods.

Geostatistical interpolation methods are stochastic methods, with kriging being the most well known in this category. Kriging methods are gradual, local, and may or may not be exact (perfectly reproduce the measured data). The kriging process is composed of two parts: analysis of this spatial variation and calculation of predicted values. Spatial variation is analyzed using variograms, which plot the variance of paired sample measurements as a function of distance between samples. An appropriate parametric model is then typically fitted to the empirical variogram and utilized to calculate distance weights for interpolation. Kriging selects weights so that the estimates are unbiased and the estimation variance is minimized. After a suitable variogram model has been selected, kriging creates a continuous surface for the entire study area using weights calculated on the basis of the variogram model and the values and location of the measured points.

Cross validation is frequently used to compare the prediction performances of the three geostatistical interpolation algorithms with the straightforward linear regression of rainfall against elevation and three univariate techniques: the Thiessen polygon, inverse square distance, and ordinary kriging. Larger prediction errors are obtained for the two algorithms (inverse square distance and Thiessen polygon) that ignore both the elevation and rainfall records at surrounding stations. The three multivariate geostatistical algorithms outperform other interpolators, in particular the linear regression, which stresses the importance of accounting for spatially dependent rainfall observations in addition to the collocated elevation. Last, ordinary kriging yields more accurate predictions than linear regression when the correlation between rainfall and elevation is moderate (less than 0.75 in the case study). It is observed that for low-density networks of rain gauges, geostatistical interpolation outperforms techniques, such as the inverse square distance or Thiessen polygon, that ignore the pattern of spatial dependence which is usually observed for rainfall data: the mean square error of kriging prediction is up to half the error produced using inverse square distance.

Prediction can be further improved if correlated secondary information, such as a digital elevation model, is taken into account.

Quantification of any hydrologic resources and/or processes can be performed with only limited accuracy, and thus plans for hydrologic control and development usually face serious problems due to this lack of appropriate information. An optimum rain gauge network will vary with location and the purpose for which the data is collected. A basic problem in designing networks arises because hydrometeorological variables cannot be sufficiently explained in terms of a mathematical model in which the magnitude of a variable is a time-invariant function of the magnitude of the variable at another point. The key to performing this type of integration is the ability to deal with the uncertainties that exist in both the hydrologic and water resources decision processes.

Various studies have found that errors in areal average rainfall intensity estimated from a rain gauge network may be caused by (1) inadequate temporal resolution, (2) inadequate spatial coverage or configuration, (3) inadequate gauge density, and (4) instrument error. A key objective of rain gauge network design is to determine the effects of rain gauge sampling (both the number of gauges and location) on the uncertainty of precipitation variables or hydrologic variables computed from precipitation estimates. The effect of gauge density is one of the important factors in the estimation of uncertainty.

7 River Gauging Networks

7.1 Measurement Objectives

A river gauging network is a system of river gauging stations in a river basin to measure river stage and discharge. The network provides hydrologic data needed for:

- planning, design and management of water and other natural resources of the river basin, and
- design and management of flood protection measures in flood prone areas.

Water management requires, generally, annual or monthly flow data, whereas for design of structures, discharge and/or water level extremes are important. Hence, the network and measurement technique depends on the end use of the data. The data should enable accurate estimation of the relevant characteristics of the hydrological regime of the river basin. In case no clarity is available one should be able to fully reproduce the entire flow regime at a number of locations along the river at such distances that the interpolation error remains sufficiently low.

7.2 Measure of Effectiveness

To enable an optimal design of the monitoring system a measure is required, which quantifies the effectiveness level. This measure depends on the monitoring objectives and can be related to an admissible error, e.g. in the mean flow during a certain period, monthly flow values for water balances, extreme flows and/or river stages, etc. This error is a function of the sampling locations, sampling frequency and sampling accuracy, i.e. where, when and what are river/reservoir stages and flows to be measured.

7.3 Network Design Consideration

Here we discuss a number of aspects which are related with actual design of the hydrometric network:

- Classification of stations,
- Minimum networks,
- Networks for large river basins,

- Networks for small river basins,
- Networks for deltas and coastal flood plains,
- Representative basins,
- Sustainability,
- Duplication avoidance, and
- Periodic re-evaluation.

Classification

Stations in a stream gauging network can be classified in the following groups:

Primary stations maintained as key stations, principal stations or bench mark stations, where measurements are continued for a long period of time to generate representative flow series of the river system and provide general coverage of a region.

Secondary stations which are essentially short duration stations intended to be operated only for such a length of time which is sufficient to establish the flow characteristics of the river or stream, relative to those of a basin gauged by a primary station.

Special purpose stations usually required for the planning and design of projects or special investigations and are discontinued when their purpose is served. The purpose could vary from design, management and operation of the project to monitoring and fulfilment of legal agreements between co-basin states. The primary as well as secondary stations may also, in time, serve as special purpose stations.

In designing a network all types of stations must be considered simultaneously.

Minimum networks

A minimum network should include at least one primary streamflow station in each climatological and physiographic area. A river or stream which flows through more than one administrative unit should be gauged at the border. At least one primary gauging station should also be established in the basins which have potential for future development.

A minimum network should also include special stations. Where a project is of particular socio-economic importance to a region, it is essential that a gauging station is established for planning, design and possibly operational purposes. Sometimes special stations are required to fulfil a legal requirement, e.g., to monitor releases to follow a court order. Benefit - cost ratios for special stations are usually the highest.

Networks for Large River Basins

A primary station might be planned at a point on the main river where the mean discharge attains its maximum value. For rivers flowing across the plains, this site is usually in the downstream part of the river, immediately upstream of the point where the river normally divides itself into branches before joining the sea or a lake or crosses a national border. In the case of mountainous rivers, it is the point where water leaves the mountainous reach and enters the plain land. Subsequent stations are established at sites where significant changes in the volume of flow are noticed viz., below the confluence of a major tributary or at the outflow point of a lake, etc.

If a suitable location is not available below a confluence, the sites can be located above the confluence. While establishing sites downstream of a confluence, care should be taken to ensure that no other small stream joins the main river so as to avoid erroneous assessment of the contribution of the tributary to the main river. In the case of a large river originating in mountains, though the major contribution is from upper

regions of the basin, several stations may have to be located in the downstream stretch of the river. Such stations are intended to provide an inventory of water loss from the channel by way of evaporation, infiltration, and by way of utilisation for irrigation, power generation, industrial and other domestic needs.

The distance between two stations on the same river may vary from about 25 to several hundred kilometres, depending on the size of the river. The drainage areas computed from origin up to consecutive observation sites on a large river should preferably differ by more than 10% so that the difference in flow is significant. The uncertainties in discharge values, particularly for high flows, are unlikely to be less than $\pm 10\%$. However, every reasonable attempt should be made to minimise these uncertainties.

The above uncertainties may affect the location of stations. When tributary inflow is to be known it is generally better to gauge it directly, rather than deriving the flow from the difference of a downstream and an upstream station along the main stream. A more accurate discharge record for the main stream is obtained by monitoring the feeder rivers also rather than the main river alone; however this requires additional cost.

Networks for Small River Basins

The criteria mentioned in the previous paragraph are applicable to a river basin having a large area and well developed stream system. A different approach is to be adopted to deal with small independent rivers, which flow directly into the sea, as in the case of west flowing rivers of Kerala and Maharashtra and some east flowing rivers of Tamil Nadu. In such cases, the first hydrological observation station might be established on a stream that is typical of the region and then further stations could be added to the network to widely cover the area. Streams in a particular area having meagre or lower yields should not be avoided for inclusion in the network. Absence of a station on a low flow stream may lead to the wrong conclusions on the water potential of the area as a whole, evaluated on the basis of the flow in the high flow streams. Thus, great care is to be exercised in designing the network to ensure that all distinct hydrologic areas are adequately covered. It is not possible to operate and maintain gauging stations on all the smaller watercourses. Therefore, representative basins have to be selected and the data from those are used to develop techniques for estimating flows for similar ungauged sites.

Networks for deltas and coastal floodplains

Deltaic areas where gradients are usually low and channels bifurcate, are often important as water use is productive and thus these areas need monitoring. This is particularly important, as deltas are dynamic systems, i.e. they are continually changing. However, the type of network required may differ from more conventional river basins. It is often not possible due to the low gradients to locate stations with stable stage-discharge relationships, i.e. variable backwater effects can occur due to tidal influences and/or changes in aquatic vegetation growth. Stage readings should be made at all principal off-takes/bifurcations or nodes in the system. These should be supplemented by current meter gaugings when required.

Representative basins

When gauging stations are included in a network to obtain representative data from a particular physiographic zone, it is advisable to choose the basins with least human intervention which means that the basins are close to their natural state. It is better to avoid basins with significant existing or proposed water abstraction and/or land use

changes.

Sustainability

Sustainability of the network is of paramount importance. Many benefits of a gauging network will be lost if it is not sustainable. The problems that arise in implementation and operation of a network are of a network and totally different than those in design a network of stations. Many-a-times, there is a tendency to have as many stations as possible in designing the network. However, frequently there are networks where stations fail to work well due to lack of financial support, skilled manpower and logistic support. It is far better to operate and maintain 10 gauging stations well than to operate and maintain 20 stations badly – better quality data from fewer stations is preferable to a poor quality of data from a greater number of stations.

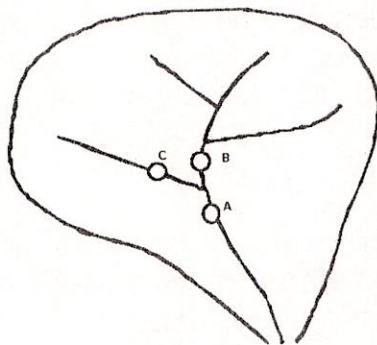
Duplication avoidance

Since, generally more than one organisation is responsible for the establishment of gauging stations, it is essential that the activities are co-ordinated so they complement each other and duplication of efforts is avoided.

Periodic re-evaluation

Gauging station networks require periodic re-evaluation. The developments that take place in the basin, like construction of new water resources development projects and industrialisation of the area, may warrant addition or closure of stations. For example river reaches are often polluted due to the discharge of effluents from industry. Therefore, a need may arise to establish stations to assist with water quality monitoring and pollution assessments.

Example 2: Consider the basin shown in the sketch. It is desired to know the flow in the main river and in its headwater rivers. What would be the best strategy if the flows at the locations are estimated at: $A = 100 \text{ m}^3/\text{s}$; $B = 80 \text{ m}^3/\text{s}$, and $C = 20 \text{ m}^3/\text{s}$. Measuring procedures are such that at each location a 10% error is made



Solution: The following are the options for flow estimation:

1. $A = B + C$
2. $B = A - C$
3. $C = A - B$

Assuming that the measurement errors made at each location are independent, it follows:

1. $\sigma_A = (8^2 + 2^2)^{1/2} = 8.25 \text{ m}^3/\text{s}$, so the relative error in the flow at A is $8.25/100$ or 8%.
2. $\sigma_B = (10^2 + 2^2)^{1/2} = 10.2 \text{ m}^3/\text{s}$, so the relative error in the flow at B is $10.2/80$ or 13%.
3. $\sigma_C = (10^2 + 8^2)^{1/2} = 12.81 \text{ m}^3/\text{s}$, so the relative error in the flow at C is $12.81/20$ or 64%.

64%.

It follows that the best option from an accuracy point of view would be to have stations at B and C even if only the flow at A is to be known. However, measuring flow at B and C if only A is to be known requires two stations to be kept operational, so the solution might not be cost-effective. Furthermore, the sum of B and C will be slightly less than A because due to backwater effects, the stations B and C cannot be located too close to the confluence.

From the experience, it is also observed that estimating flows as the difference of two large values ($C = A - B$) will result in an inaccurate estimate.

7.4 Network Density

The World Meteorological Organisation developed guidelines on minimum hydrological network densities. Their guidelines and potential use and limitations are presented in this section. Furthermore, prioritisation system is introduced to rank the importance of stations. Finally, comments are given on the use of statistical and mathematical optimisation techniques for hydrometric networks.

WMO recommendations

The recommendations of the WMO (World Meteorological Organisation) on the minimum density of a streamflow network for regions with different physiographic features are reproduced in Table 5 below.

Table 5 Recommended minimum densities of river gauging stations (area in km² per station) [Source: WMO (2008)].

Physiographic unit	Streamflow	Sediments	Water quality
Coastal	2750	18300	55000
Mountains	1000	6700	20000
Interior plains	1875	12500	37500
Hilly/undulating	1875	12500	47500
Small islands	300	2000	6000
Urban areas	-	-	-
Polar/arid	20000	200000	200000

It is not possible to provide specific, general guidelines on an appropriate network density. The WMO recommendations are very general guidelines which if adopted for some large river basins could result in a dense network. The network density must ultimately be based on the network objectives, the temporal and spatial variability of river stages and flow and on the availability of finance, manpower and other resources.

Prioritisation system

It is suggested that in the first instance the "ideal" network size is determined. In determining the network all potential users of the data should be consulted. Each station in the "ideal" network should be prioritised. In order to do this a simple prioritisation system is useful. This prioritisation system could be a simple one such as follows:

Category	Priority	Relative Importance
A	High	Major, multi-purpose water resources development site, State

		boundary river, operation of major scheme, major ungauged basin, heavily polluted major water supply source.
B	Medium	Medium scale water resources development project site, secondary basin, industrial development area, i.e. potential water quality problems).
C	Low	Minor irrigation project site, secondary gauging station on tertiary tributary, major water course but already extensively gauged.

The above categories and priorities are merely highlighted by way of example. Each organisation needs to set its own priorities based on its own policies and objectives. In prioritising sites, the following questions should be asked:

- What are the socio-economic consequences of not collecting streamflow data at the site?
- What are the alternatives to establishing a streamflow gauging station at the site under consideration?

An estimate of the number of stations which can be realistically maintained by the organization should be made. When deriving this estimate the following factors should be considered:

- The recurrent budget implications;
- Short and long-term manpower requirements and availability of suitably skilled personnel;
- Capacity of instrument repair, spare part provision and calibration facilities;
- Long-term availability of logistic support facilities.

The ideal and realistic network size estimates should be compared. If necessary the size of the ideal network should then be reduced by removing the lower priority stations.

This approach is based on users' need to continue/ discontinue gauging stations depending upon the type of data requirement in the basin. Initially, the questionnaires are developed by giving importance to a set of parameters, for example, length of record, accuracy of flood prediction, and usefulness of data for water resources projects in the region. Emphasis to these parameters is assigned depending upon the importance of the parameters in the region. This analysis by its nature is subject to a certain amount of personal judgment. So it is important to take feedback from different sectors and users, for example, hydrologists, meteorologists, and agronomists, as well as planning commissions, state, and federal agencies. Individual stations are assessed in terms of the extent to which they contribute to the full set of priority considerations. The higher the total weight/points accumulated by a particular station, the higher is the relative value or benefits derived from that station, and it is important to maintain those stations. Gauges that received the lowest total scores in the relative worth analysis are identified as possible candidates for discontinuance if budgetary considerations required such an action. Different combinations of stations can be compared on the basis of their importance in the region within the specified budgets to find the best combinations.

8 Statistical and mathematical optimisation

The streamflow network should provide information for the location indicated by the hydrological data users. At a number of locations no stations will be available. Hence the information is to be obtained from the network by interpolation. If the interpolation

error in estimating a flow characteristic is too large than additional stations or a re-design should be considered. These techniques are most applicable to already well established networks, where the data have been rigorously quality controlled and are readily available in computer compatible form. However, they are less readily applied to heavily utilised, over-regulated catchments like many of the larger river basins in India. These techniques are a tool to assist with network design. They are not straightforward to apply and do not totally obviate the need for the pragmatic, common sense approach.

9 Recent Advances in Hydrometry

Recent advances in information technologies and electronics have resulted in a new generation of hydrometric instruments. Hydroacoustic instruments, perhaps the best example of the new generation of instruments, are having a dramatic effect on how flow measurements are made. The most important development in streamflow measurement in recent decades has been the deployment of acoustic Doppler current profilers (ADCPs). The ADCP measures water currents with sound, using a principle of sound waves called the Doppler effect. ADCP uses acoustic energy, typically in the range 300–3000 kHz, to measure water velocity throughout most of the water column by measuring the shift in the frequency of the acoustic signals reflected from materials suspended in, and moving with, the water. The ADCPs have several advantages over other methods. The ADCP measurement is fast, made in a matter of minutes rather than hours, and is equally accurate. In addition, the ADCP allows measurements in environments where conventional mechanical current meters are inappropriate or unreliable, such as in tidally affected flows, highly unsteady flows, and flood flows that may not have been measurable. Precisely, ADCPs are used to measure continuous profiles of water velocity. Thus, the vertical velocity distribution is no longer assumed but rather measured for all the near-bed and near surface, thereby providing more accurate measurements of stream flow. An additional advantage is that the ADCP measures the flow field in the stream channel in three dimensions, which provides a far more accurate and detailed view of velocity and flow profiles.

The possibility of measuring and monitoring surface water from space seems real now. Space-based instruments hold promise for measuring elevations and perhaps even flow rates of rivers around different part of the world. In the long run, space-based will be highly useful for hydrologic monitoring.

Recent works have shown that weather radar can provide an estimation of rainfall rates with good spatial and temporal resolution. Rainfall estimation using satellite measurement (mainly thermal infrared images) gives satisfactory results. Satellite rainfall estimation algorithms must be calibrated and validated using rain gauge networks which are usually very scarce in important parts of the world, which are facing different water-related disasters due to lack of proper water resources planning and management.
