Practical Approach for Design of Surface Water Gauging Network

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1. Introduction

Surface water gauging observations network is based upon two considerations, namely (a) the **observation objectives**, and the **physical characteristics of the systems** to be monitored. The identification of the objectives is the first step in the design and optimisation of observation systems. Related to this is the identification of the potential data users and their future needs. If there is more than one objective, priorities need to be set. Identification of objectives is also important because they determine the scale of changes to be detected in the data, the kind of information to be extracted from the data and therefore the way the data are analysed.

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

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

2. Definition of network design and objectives

A complete network design answers the following questions pertaining to the collection of hydrological data:

(a) What hydrological variables need to be observed?
(b) Where do they need to be observed?
(c) How often do they need to be observed?
(d) What is the duration of the observation programme? and
(e) How accurate should the observations be?

These quantities also determine the cost of establishing and running of the network, like the costs related to land acquisition, station construction, equipment procurement and installation, station operation, maintenance, data processing and storage and staffing of field stations and data centres.

Without a thorough understanding of the hydrological setting of the area in which the network is to be established, there is little chance that the resulting network will generate information in an effective manner. Hydrological understanding comes from both education and experience, but there is no substitute for experience when initiating a hydrological network in an area where little or no historical data are available. Because of measurement errors and errors caused by sampling in space and time, there will always be hydrological uncertainty. Perfect hydrological information can never exist. Probabilistic descriptions of these errors are the most effective means of dealing with the resulting uncertainty.

Socio-economic analysis which encompasses policy science and even politics plays a very important role in the realization of the potential benefits of water and, thus, also in the ultimate value of the data from the network. Though socio-economic analysis usually receives the least consideration in the design of the data network which probably attributable to two causes: the subject matter is difficult to treat in an objective, mathematical way; and to do so in a substantive manner require the synthesis of inputs from many disciplines beyond those of hydrology and water-resources engineering. Thus, a network design that includes a significant socio-economic analysis will probably be both expensive and time consuming. Nevertheless, it is wise to keep in mind the influence that the data have on the real world when designing a network — even if this must be done subjectively.

2.1 Objectives of network design

The objectives for an observation network be identified and decided before the designing is taken up. Some of the important objectives are listed below:

- Water resources assessment at basin or sub-basin scale
- Water resources assessment for administrative geographical unit
- Water resources project planning including:
    - Irrigation,
    - Domestic (domestic use, livestock watering),
    - Hydroelectric power and other power generation,
    - Environmental requirements,
    - Industrial requirements,
    - Navigation,
    - Tourism, recreation
- Flood management
- Assessing impacts of Climate Change on Water Resources

2.2 Inadequacy of data for Climate Change impacts studies

The inadequacy of hydrological date was observed by IPCC, which in its technical paper IV on "Climate Change and Water" stated that *Information about the water related impacts of climate change is inadequate – especially with respect to water quality, aquatic ecosystems and groundwater – including their socio-economic dimensions. Finally, current tools to facilitate integrated appraisals of adaptation and mitigation options across multiple water-dependent sectors are inadequate.*

3. The basic network

The worth of the data that derive from a network is a function of the uses that subsequently are made of them. Nevertheless, many of the uses of hydrological data are not apparent at the time of the network design and, therefore, cannot be used to justify the collection of specific data that ultimately may be of great value. In fact, few hydrological data would be collected if a priori economic justifications were required. However, modern societies have developed a sense that information is a commodity that, like insurance, should be purchased for protection against an uncertain future. Such an investment in the case of hydrological data is the basic network, which is established to provide hydrological information for unanticipated future water-resources decisions. The basic network should provide a level of hydrological information at any location within its region of applicability that would preclude any gross mistakes in water-resources decision making. To accomplish this aim, at least three criteria must be fulfilled:

(a) A mechanism must be available to transfer the hydrological information from the sites at which the data are collected to any other site in the area;
(b) A means for estimating the amount of hydrological information (or, conversely, uncertainty) at any site must also exist; and
(c) The suite of decisions must include the option of collecting more data before the final decision is made.

3.1 The minimum network

In the early stages of development of a hydrological network, the first step should be the establishment of a minimum network. Such a network should be composed of the minimum number of stations which the collective experience of hydrological agencies of many countries has indicated to be necessary to initiate planning for the economic development of the water resources. The minimum network is one that will avoid serious deficiencies in developing and managing water resources on a scale commensurate with the overall level of economic development of the country. It should be developed as rapidly as possible by incorporating existing stations as appropriate. In other words, a minimum network will provide the basic framework for network expansion to meet future needs for specific purposes. It is emphasized that a minimum network will not be adequate for the formulation of detailed development plans and will not meet the numerous requirements of a developed region for the operation of projects and the management of water resources.

3.2 Expanding the information base

Once the minimum network is operating, regionalized hydrological relationships, interpreted information, and models can be formulated for estimating general hydrological characteristics, including rainfall and runoff at any location in the area. The basic network of observing stations should be adjusted over time until regional hydrological relationships can be developed for ungauged areas that provide the appropriate level of information. In most cases, this adjustment will result in increase in the densities of hydrologic stations. However, this is not always the case.

Owing to the broad dependence on the stations in the basic network, it is very important that the records from all of these stations be of high quality. Even if the installation of a station is adequate, its records may be of little value if it is not operated correctly. Continuous operation may be difficult — especially over a period of 20 years or more. A minimum network, in which stations are abandoned or irregularly observed, will have its effective density reduced and is, therefore, no longer an adequate minimum network. For that reason, care should be taken not only in establishing, but also in providing for the continuing operation of these stations and for monitoring the reliability and accuracy of the collected records.

4. Integrated network design

The hydrological cycle is a continuum, and its inter-connections permit the partial transfer of information obtained in one part of the cycle to another. The efficiency of such transfers is proportional to the degree of hydrological understanding that is captured in the models that are used to route the water (and the information) between the parts of the cycle. For example, precipitation records on or near a gauged drainage basin permit the reconstruction of streamflow records during periods when the stream-gauge malfunctions if a valid precipitation-runoff model has been calibrated during times when all gauges were functioning properly.

To date, little has been done to include these interactions in network designs in an explicit manner. Ideally, the complementarity between the raingauges and the stream gauges that are operated in a flood-forecasting network could be used in designing a network for water-resources assessment, for example. If the economic tradeoffs between the two networks could be defined, they could be optimized together and peak efficiencies in information generation could be attained for both. In spite of this technological shortcoming, networks should be designed iteratively, and the outcomes of an existing design should become starting points for subsequent designs. By extension of the above example, this can be illustrated. The flood forecasting network will probably have stream gauges and precipitation gauges at rather specific locations to meet its information needs. Because the water-resources assessment will generally have less specific requirements for its information sources, it will be likely that many of the gauges of the flood-forecasting network can be incorporated into the assessment network and used as initial given conditions for its design.

4.1 Stations for operational purposes

Stations may be established for such specific purposes as reservoir operation, irrigation, navigation, water quality monitoring, flood forecasting, or research. Benchmark or reference stations would also belong to this category. The length of operation of special stations is related to the purpose for which they were installed. In some cases, the specific purpose to be served may require observations on only one particular aspect of an element, or be confined to one season of the year. For example, a hydrometric station may consist of a crest gauge for recording only the maximum flood peak or a storage gauge for measuring the total precipitation during a season. Although such stations may perform a valuable function, they do not provide the data required for general hydrologic analyses. Consequently, such stations may or may not be included in a basic hydrological network.

5. Conducting a network analysis

Network should be reviewed periodically to take advantage of the reduction in hydrological uncertainty brought about by the added data since the last network analysis and to tune the network to any changes in the socio-economic environment that may have transpired. Figure given below lays out the steps that should be taken in conducting a review and redesign of an existing hydrological network. The steps of the analysis are discussed individually below.

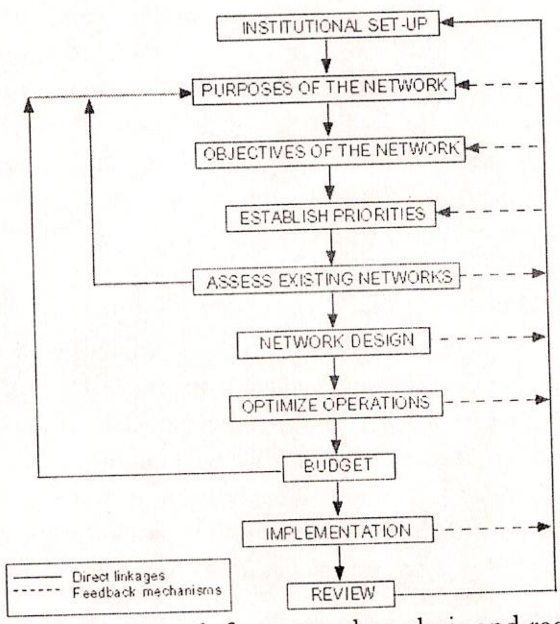

Figure — A framework for network analysis and redesign

5.1 Institutional set-up

The roles and aims of all of the organizations involved in various aspects of water resources management should be defined and identified (particularly legislative responsibilities). Communication links between these organizations should be improved to ensure coordination/integration of data-collection networks.

5.2 Purposes of the network

The purposes of the network in terms of the users and uses of the data should be identified. Data users and uses can vary temporally and spatially. There is also a need to identify potential future needs and incorporate these into the design as well.

5.3 Objectives of the networks

Based on the purpose of the network, an objective or set of objectives can be established in terms of the information required. An indication of the consequences of not being able to provide this information may prove useful later.

5.4 Establish priorities

If there is more than one objective, priorities need to be set for later evaluation. If all objectives can be met within the budget, then this is not needed. However, if they cannot, then the lower-priority objectives may not be met fully.

5.5 Assess existing networks

Information on the existing network should be compiled and interpreted to determine if the current networks fulfill the objectives. This may include comparisons with other basins and/or networks.

5.6 Network design

Depending on the available information and the objectives defined, the most appropriate network-design technique or techniques should be applied. This may be simple hydrological characteristics, regression relationships, or more complex network analysis using generalized least squares methods.

5.7 Optimize operations

A significant portion of the cost of data collection is contained within the operational procedures. This includes the types of instruments, frequencies of station visits, and structure of field trips. The minimum-cost operational procedures should be adopted.

5.8 Determine costs

Based on the identified network and operational procedures, the cost of the operation of the network can be established. If this is within the budget, the next step can be followed. If not, either additional funding must be obtained or the objectives and/or priorities need to be examined to determine where costs may be reduced. The process adopted should allow the designer to express the impact of insufficient funding in terms of not meeting objectives or reduced information and net impacts.

5.9 Implementation

The re-designed network needs to be implemented in a planned manner. This will include both short- and long-term planning horizons.

5.10 Review networks

Since a number of the above components are variable in time, a review can be required at the instigation of any particular component — for example, changes in users or uses or changes in the budget. To be ready to meet such changes, a continuing review process is essential.

6. Density of stations for a minimum network

As mentioned earlier, the minimum network is one that will avoid serious deficiencies in developing and managing water resources on a scale commensurate with the overall level of economic development and environmental needs of the country. It should be developed as rapidly as possible, incorporating existing stations, as appropriate. In other words, such a network will provide the framework for expansion to meet the information needs of specific water uses.

The concept of network density is intended to serve as a general guideline if specific guidance is lacking. As such, the design densities must be adjusted to reflect actual socio-economic and physio-climatic conditions. Computer-based mathematical analysis techniques should also be applied, where data are available, to optimize the network density required to satisfy specific needs. In the following sections, minimum densities of various types of hydrological stations are recommended for different climatic and geographic zones.

Population density also affects network design. It is almost impossible to install and operate, in a satisfactory way, a number of stations where population is sparse. Sparsely-settled zones, in general, coincide with various climatic extremes, such as arid regions, polar regions, or tropical forests.

Six types of physiographic regions have been defined for minimum networks:

(a) Coastal;
(b) Mountainous;
(c) Interior plains;
(d) Hilly/undulating;
(e) Small islands (surface areas less than 500 km2); and
(f) Polar/arid.

The minimum densities for streamflow stations are given in Table-1 below. These norms are not applicable to the great deserts with no defined stream networks (such as the Sahara, Gobi, Arabian and Korakorum deserts) and great ice fields (Antarctic, Greenland, Arctic islands).

Physiographic unit	*Minimum density per station (area in km^2 per station)*
Coastal	2750
Mountainous	1000
Interior plains	1875
Hilly/undulating	1875

Small islands	300
Polar/arid	20000

Table-1 Recommended minimum densities of streamflow stations (WMO)

In general, a sufficient number of streamflow stations should be located along the main stems of large streams to permit interpolation of discharge between the stations. The specific location of these stations should be governed by topographic and climatic considerations. If the difference in flow between two points on the same river is not greater than the limit of error of measurement at the station, then an additional station is unjustified. In this context, it must also be stressed that the discharge of a small tributary cannot be determined accurately by subtracting the flows at two mainstream gauging stations which bracket the mouth of the tributary. Where the tributary flow is of special interest in such a case, a station on the tributary will be required. It will usually take its place as a secondary station in the minimum network. Wherever possible, the base stations should be located on streams with natural regimes. Where this is impractical, it may be necessary to establish additional stations on canals or reservoirs to obtain the necessary data to reconstruct the natural flows at the base stations. Computed flows past hydroelectric plants or control dams may be useful for this purpose, but provisions will have to be made for calibration of the control structures and turbines and for the periodic checking of such calibrations during the life of the plants.

Stations should be located on the lower reaches of the major rivers of the country, immediately above the river mouths (usually above tidal influence), or where the rivers cross borders. Stations should also be located where rivers issue from mountains and above the points of withdrawal for irrigation water. Other hydrometric stations are situated at points, such as where the discharge varies to a considerable extent, below the points of entry of the major tributaries, at the outlets from lakes, and at those locations where large structures are likely to be built. To ensure adequate sampling, there should be at least as many gauging stations on small streams as on the main streams. However, for small streams, a sampling procedure becomes necessary as it is impracticable to establish gauging stations on all of them. The discharge of small rivers is strongly influenced by local factors. In highly developed regions, where even the smallest watercourses are economically important, network deficiencies are keenly felt even on streams draining areas as small as 10 km2.

Stations should be installed to gauge the runoff in different geologic and topographic environments. Because runoff varies greatly with elevation in mountains, the basic network stations must be located in such a way that they can, more or less evenly, serve all parts of a mountainous area, from the foothills to the higher regions. Account should be taken of the varying exposure of slopes, which is of great significance in rough terrain. Similarly, consideration should be given to stations in districts containing numerous lakes, whose influence can be determined only through the installation of additional stations.

6.1 River stages

Stage (height of water surface) is observed at all stream-gauging stations to determine discharge. There are places where additional observations of water level only are needed as part of a minimum network:

(a) At all major cities along rivers, river stages are used for flood forecasting, water supply, and transportation purposes; and
(b) On major rivers, at points between stream-gauging stations, records of river stage may be used for flood routing and forecasting purposes.

6.2 Lake and reservoir stages

Stage, temperature, surge, salinity, ice formation, etc., should be observed at lake and reservoir stations. Stations should be established on lakes and reservoirs with surface areas greater than 100 km2. As in the case of rivers, the network should sample some smaller lakes and reservoirs as well.

6.3 Sediment discharge and sedimentation

Sediment stations may be designed either to measure total sediment discharge to the ocean or to measure the erosion, transport and deposition of sediment within a country, basin, etc. In designing a minimum network, emphasis should be placed on erosion, transport, and deposition of sediment within a country. An optimum network would contain a sediment station at the mouth of each important river discharging into the sea.

Sediment transport by rivers is a major problem in arid regions, particularly in those regions underlain by friable soils and in mountainous regions where, for engineering applications, the amount of sediment loads should be known. The densities are given in Table-2 below serve as guides in considering a basic network.

Physiographic unit	*Minimum density per station (area in km^2 per station)*
Coastal	18 300
Mountainous	6700
Interior plains	12 500
Hilly/undulating	12500
Small islands	2000
Polar/arid	200000

Table-2 Recommended minimum densities for sediment stations (WMO)

Emphasis should be placed on those areas where erosion is known to be severe. After a few years of experience, it may be desirable to discontinue sediment measurements at those stations where sediment transport no longer appears to be of importance. Sediment-transport data may be supplemented by surveys of sediment trapped in lakes or reservoirs. Echo sounding devices are useful for this purpose. However, information obtained in this way is not considered a substitute for sediment-transport measurements at river stations.

6.4 Water quality stations

The usefulness of a water supply depends, to a large degree, on its chemical quality. Observations of chemical quality, for the purposes of this Guide, consist of periodic sampling of water at stream-gauging stations and analyses of the common chemical constituents. The number of sampling points in a river depends on the hydrology and the water uses. The greater the water quality fluctuation, the greater the frequency of measurement required. In humid regions, where concentrations of dissolved matter are low, fewer observations are needed than in dry climates, where concentrations, particularly of critical ions such as sodium, may be high. As a minimum network, records of water quality should be obtained at the densities as shown in Table-3 below.

Physiographic unit	*Minimum density per station*

	(area in km^2 per station)
Coastal	55000
Mountainous	20000
Interior plains	37500
Hilly/undulating	47500
Small islands	6000
Polar/arid	200000

Table 3 Recommended minimum densities for water quality stations (WMO)

7. Steps for Network Design

Network design should be done basin wise, irrespective of size of basin. The Geographical Information System (GIS) is an excellent tool for designing various parameters of observation network. The GIS map of 1:50,000 scale would be preferred however in absence of this 1:250,000 scale maps may also be used. Following are the steps for designing the network:

- Mark the complete river network of the country;
- Lay watershed map layer on the basin map;
- Demarcate coastal, mountainous, interior plains, hilly & undulating regions and small islands on the map;
- Mark existing (including closed or project specific) observation sites;
- Lay infrastructure including road/rail network, GSM network and inhabited localities;
- For the rivers originating with in the country: Identify first site on each and every river/tributary where the catchment area is nearly equal to as suggested in above the tables for that specific physiographic unit;
- For the rivers coming from neighbouring countries: Identify one site on each and every river/tributary as near as possible to the international border considering easiness in communication connectivity and workout catchment area up to that point;
- Find out next location where catchment area has increased as per minimum density norm. Check the location for easiness in communication connectivity and workout catchment area up to this location;
- Adjust the locations to suit the requirements of the existing/planned water resources projects; and
- Repeat above two steps up to international border in downstream or up to the outfall into the sea;
- A reconnaissance survey would be necessary before finalizing the location of each of the sites;
- Identification of site-specific observation methodology & instrumentation, data collection frequency;
- Review observation methodology & instrumentation, data collection frequency at existing sites;
- Suitability analysis for observing water quality parameters; and
- Suitability analysis for observing silt parameters.

8. Conclusion

The networks for observing different parameters of the hydrological cycle and other related weather parameters are deficient in general. The stations for water quality monitoring also need to be reviewed for river waters, ground water and for stored water in tanks, ponds or reservoirs. There are statistical techniques available for analysing existing networks and suggesting modifications to achieve desired degree of accuracy in making assessment, however with the increasing uncertainties in all the constituents of hydrological cycle due to climate change, it is suggested to follow WMO norms for designing the networks for hydrometric hydro-meteorological parameters taking criteria for minimum densities. The review of network is a dynamic process and should be undertaken at a suitable period, say 10 years.

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