WMO Standards for Hydromet Network Design

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1. Introduction

The World Meteorological Organization (WMO) is a specialized agency of the United Nations having following objectives (Article 2 of the Convention of WMO):

- To facilitate worldwide cooperation in the establishment of hydro-meteorological observational networks and other geophysical observations related to meteorology.
- To promote standardization of meteorological and related observations and to ensure the uniform publication of observations and statistics;
- To further the application of meteorology to aviation, shipping, water problems, agriculture and other human activities;
- To promote activities in operational hydrology and to further close cooperation between Meteorological and Hydrological Services; and
- To encourage research and training in meteorology and, as appropriate, in related fields and to assist in coordinating the international aspects of such research and training.

To promote the standardization of hydro-meteorological practices WMO published various guidelines and manual on standard practices. A partial list of these publications specifically related to precipitation and surface water is given in Annexure-I. For convenience, the general recommended practices and procedures are summarized below. These recommended practices and procedures should be implemented for developing hydro-meteorological services and activities:

i. The basic network of hydro-meteorological stations should provide the essential information and data to conduct an overall assessment of water resources at regional and national scale. The recommended minimum network densities are described in the subsequent sections.

ii. To obtain satisfactory information on mean values of the observed hydro-meteorological variables and their temporal variation, observational sites in the basic network should be operated for a relatively long period (at least 10 or more years)

iii. Hydro-meteorological stations for special purposes may be established for special investigations during a limited period in addition to the basic network of stations.

iv. Stations should be identified by name and geographic coordinates to avoid misunderstandings. An accurate and up-to-date directory of station characteristics is indispensable.

v. Uniformity in timing of the observations within a catchment area is desirable. Under exceptional conditions, e.g., floods, more frequent measurements of the appropriate hydro-meteorological elements should be made.

vi. For international exchanges, it is advisable to use the following time units in the Gregorian calendar year. Months derived from this year and the mean solar day from midnight to midnight, according to the zonal time.

vii. It is desirable to give descriptive statistics of the data, such as averages, maximum and minimum values, standard deviations, frequency distributions (tables or curves), etc. for easier interpretation of the phenomenon. A yearbook should contain complete information on all stations, including the name, coordinates, elevation, drainage area, observed phenomena, observation times, length of record, etc.

viii. For international use it is desirable to use the English (or French, Russian or Spanish) language and to employ only internationally recognized symbols, letters, abbreviations, and units;

ix. The observed and processed hydrological data will provide good understanding of the hydrological conditions of the region concerned. They will be helpful in improving or in establishing a forecast programme for hydrological purposes. A programme of this kind should include forecasts of water stages, stream flow, floods, and storm surges.

The sections below discusses the hydromet design aspects for the precipitation and surface water observational networks based on WMO No. 168, Guide to hydrological practices (Vol.1).

2. Density of Stations for a Network

The minimum network is meant for avoiding the serious deficiencies in developing and managing water resources on a scale proportionate with the overall level of economic development and environmental needs. Such a network will provide the framework for expansion to meet the information needs of specific water uses and it should be developed as rapidly as possible, incorporating existing stations. The concept of minimum network densities is intended to serve as a general guideline if specific guidelines are lacking. The design densities must be adjusted to reflect actual socio-economic and physio-climatic conditions. Mathematical analytical techniques should also be used, where data are available, to optimize the network density required to satisfy specific needs. WMO recommended minimum densities of various types of hydrological stations for different climatic and geographic zones based on the WMO basic network assessment project (WMO/TD-No. 671). These minimum densities for precipitation and stream flow networks and are shown in Table - 1.

Table – 1

Recommended minimum densities of stations (km^2 per station)
(WMO No. 168 Vol. 1)

Physiographic unit	Precipitation		Stream flow
	Non-recording	Recording	
Coastal	900	9000	2750
Mountains	250	2500	1000
Interior plains	575	5750	1875
Hilly/undulating	575	5750	1875
Small islands	25	250	300
Urban areas	-	10 - 20	-
Polar/arid	10000	100000	20000

It is impossible to define a sufficient number of zones to represent complete variation in hydrological conditions. However, areal and seasonal variation of rainfall provides the simplest and most precise criterion for the classification of zones. Each country could present a good map of annual precipitation and a minimum network could be developed from this. However, this would not help countries that need a network most as they have very few prior records, and the establishment of a good precipitation map is not possible. Also, the countries with very irregular rainfall distribution need to be considered as a special category. In such cases, it is not advisable to base the classification on this one characteristic.

Population density also affects network design. It is almost impossible to install and operate, in a satisfactory manner, a number of stations where population is sparse unless the stations are highly automated. Sparsely settled zones, in general, coincide with various climatic extremes, such as arid regions, polar regions or tropical forests. At the other extreme, densely-populated urban areas need a very dense rain gauge network for both temporal and spatial resolution of storms, for design, management and control of the storm-drainage systems and for other engineering applications.

From these considerations, a limited number of larger zones have been defined for the definition of density norms in a somewhat arbitrary manner adopting some general rules. Six types of physiographic regions have been defined for minimum networks. These are Coastal, Mountainous, Interior plains, Hilly/undulating, small islands (surface areas less than 500 km^2), Polar/arid regions.

It is necessary to group the areas for polar/arid region, in which it does not seem possible to achieve completely acceptable densities because of sparse population, poor development of communications facilities, or for other economic reasons.

3. Precipitation Stations

The major uses of rainfall data are generally for:

- water resources planning, and design
- management and research

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

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

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

Research needs intensive data to improve the understanding of certain processes or phenomena. The research generally concentrates on small river or water resources management systems. The type of data required for research varies from study to study but is often comparable with the requirements for design. It follows that different objectives lead to different information needs and to different network densities unless concessions are made towards the required accuracy.

The small number of stations in the minimum network can furnish the most immediate needs, if one follows certain principles of installation and use, In general, precipitation gauges should be as uniformly distributed as is consistent with practical needs for data and the feasible locations for observers. In mountainous regions, attention must be given to vertical zonality by using storage gauges to measure precipitation at high altitudes. Precipitation gauges may be designed specifically to measure snow-water equivalent. Periodic manual snow surveys may be used to supplement the network, but they should not be counted as part of the network.

To ensure that precipitation data are available for extending stream-flow records, flood-forecasting or hydrological analysis, coordination of the locations of the precipitation gauges with respect to those of the stream gauges is of great importance. Precipitation gauges should be located so that basin precipitation can be estimated for each stream-gauging station. These will usually be located at or near the stream gauge and in the upper part of the gauged drainage basin. A precipitation gauge should be located at the site of the stream gauge only if the observations will be representative of the general area. There can be cases in which it is desirable to locate the precipitation gauge some distance away from the stream gauge, as for instance when the stream gauge is in a narrow, deep valley.

4. Hydrometric Network

A hydrometric network is a system of river gauging stations in a river basin at which river stage and discharge are measured. The network provides hydrologic data needed for:

- the planning, design and management of conservation and utilisation of the waters and other natural resources of the river system
- for design and management of flood protection measures in flood prone areas

Water management requires, generally, decadal or monthly flow data, whereas for designs discharge and/or water level extremes are of importance. Navigation would be interested in exceedance durations of water levels to be able to assess the Least Available Depth. Hence, it depends on the use of the data which information is to be collected. 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. Gauging sites in rivers or other open water areas should anyway be located on places where changes are obvious, such as:

1. Immediately d/s of an international boundary
2. Diversion for public supply of large town
3. Important fishing, recreation and amenity zone
4. Diversion for large scale agriculture irrigation
5. Freshwater tidal limit of major river
6. Diversion for large industrial supply
7. D/s of industrial effluent discharge and important tributary influencing main river
8. Baseline station, water in natural state

These criteria for monitoring sites for rivers are shown in Figure - 1 below.

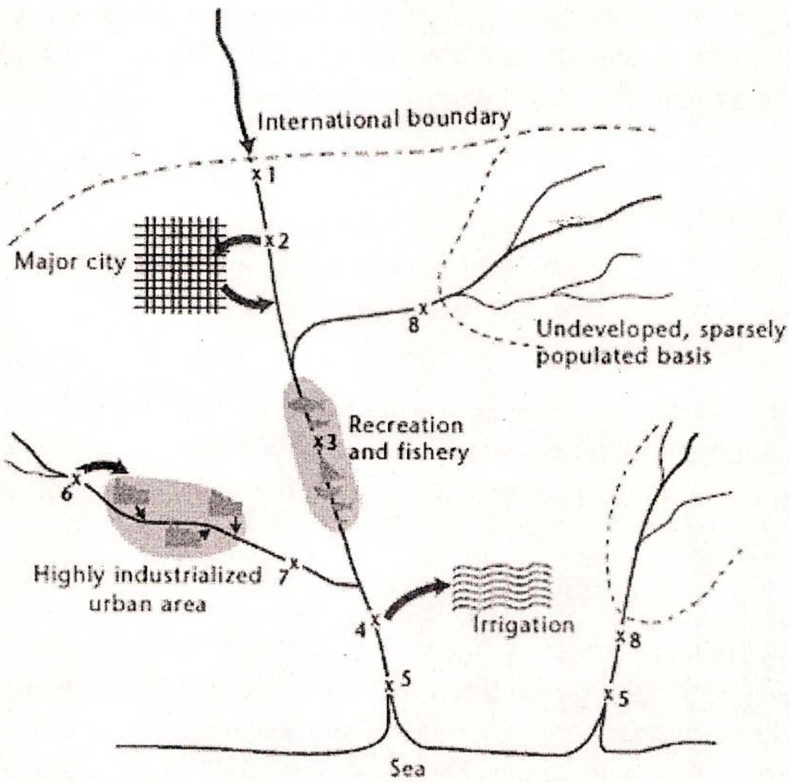

Figure - 1: Criteria for monitoring sites: rivers (WMO No. 168)

4.1 Stream flow stations

The main objective of the stream-gauging network is to obtain information on the availability of surface-water resources, their geographical distribution and their variability in time. Magnitude and frequency of floods and droughts are of particular importance in this regard. In general, a sufficient number of stream flow stations should be established 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 main stream-gauging stations that 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.

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 locations, 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 where large structures are likely to be built.

Hydrometric stations are often established at major cities to meet a number of societal needs. To ensure adequate sampling, there should be at least as many gauging stations on small streams as on the main streams. However, a sampling procedure for small streams 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 km^2.

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, and to land cover, which may vary with exposure and other factors. Similarly, consideration should be given to stations in districts containing numerous lakes, the influence of which can be determined only through the installation of additional stations.

4.2 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:

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

5. 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 in e.g. 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 with what are river/reservoir stages and flows to be measured.

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

- Individual areal estimates,
- long term mean values.

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

$h_{1,1}$	$h_{1,2}$	$h_{1,3}$ ………$h_{1,N}$	year 1	Data $h_{1,1}$ to $h_{1,N}$ spatially correlated
$h_{2,1}$	$h_{2,2}$	$h_{2,3}$ ………$h_{2,N}$	year 2	
$h_{3,1}$	$h_{3,2}$	$h_{3,3}$ ………$h_{3,N}$	year 3	Data $h_{1,j}$ to $h_{n,j}$ serially not correlated
$h_{n,1}$	$h_{n,2}$	$h_{n,3}$ ………$h_{n,N}$	year n	

Figure - 2: Data matrix n x N of n years of data at N stations

For most hydrological purposes the objective of the rainfall network should be to provide reliable estimates of individual events of areal rainfall of a particular duration, like a duration of an hour, day, month or season. It implies that the uncertainty in each element of the areal rainfall series, estimated from point rainfall data, should not exceed a certain value.

This is particularly so for the network in use for the Hydrological Information System, where various users have to be served with different objectives. A measure for the quality of the areal rainfall data is the mean square error of the estimate. Hence, the root mean square error in estimating the areal rainfall of a particular duration, expressed as a percentage of the average rainfall in an area is an appropriate measure for the effectiveness of the network.

6. Summary

A hydrological data network is a group of data collection activities that is designed and operated to address a single objective or a set of compatible objectives. These objectives are generally associated with a particular use that is anticipated for the data being collected in the network such as water resources assessment, development plan, or project design. WMO guidelines are discussed for designing of the hydrometric network. A measure of effectiveness level which is based on the variables to be measures (what), location of measurement (where) frequencies of measurement (when) and accuracy of measurement (technique/equipment) is discussed. As these quantities also determine the cost of establishing and running of the network, the network design should also be based on the maximization of the economic worth of the data that are to be collected.

Annexure - I

Partial List of WMO Publications Related to Precipitation and Surface Water

World Meteorological Organization, 1988: *Technical Regulations.* Volume I, General meteorological standards and recommended practices, WMO–No. 49, Geneva.

World Meteorological Organization, 1983: *Guide to Meteorological Instruments and Methods of Observation.* Fifth edition, WMO–No. 8, Geneva.

World Meteorological Organization, 1966: *International Meteorological Tables* (S. Letestu). WMO–No.188, Geneva.

World Meteorological Organization, 1988: *Technical Regulations.* Volume III, Hydrology, WMO–No. 49, Geneva.

World Meteorological Organization, 1983: *Guide to Climatological Practices.* Second edition, WMO–No. 100, Geneva.

World Meteorological Organization, 1980: *Manual on Stream Gauging.* Volumes I and II, Operational Hydrology Report No. 13, WMO–No. 519, Geneva. 9. World Meteorological Organization, 1988: *Manual on Codes.* Volumes I and II, WMO–No. 306, Geneva.

World Meteorological Organization, 1983: *Guide to Meteorological Instruments and Methods of Observation.* Fifth edition, Chapter 7, WMO–No. 8, Geneva.

World Meteorological Organization, 1982: *Methods of Correction for Systematic Error in Point Precipitation Measurement for Operational Use* (B. Sevruk). Operational Hydrology Report No. 21, WMO–No. 589, Geneva.

World Meteorological Organization, 1985: *Use of Radar in Meteorology* (G. A. Clift). Technical Note No. 181, WMO–No. 625, Geneva, pp. 80-86.

World Meteorological Organization, 1980: *Manual on Stream Gauging.* Volumes I and II, Operational Hydrology Report No. 13. WMO-No. 519, Geneva.

World Meteorological Organization, 1986: *Level and Discharge Measurements under Difficult Conditions* (Ø. A. Tilrem). Operational Hydrology Report No. 24, WMO-No. 650, Geneva.

World Meteorological Organization, 1986: *Methods of Measurement and Estimation of Discharges at Hydraulic Structures.* Operational Hydrological Report No. 26, WMO–No. 658, Geneva.

World Meteorological Organization, 1971: *Use of Weirs and Flumes in Stream gauging.* Technical Note No. 117, WMO–No. 280, Geneva.

World Meteorological Organization, 1994: Guide to hydrological practices WMO–No. 168, Fifth edition, Geneva.