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PROCEDURE FOR HYDROLOGICAL NETWORK DESIGN

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ABSTRACT

Network design enters into most aspects of hydrology. Meteorological and hydrological data characteristics of watersheds, provide the basis for all water studies and determine the major aspects of hydrological and hydraulic design of water utilisation projects. Inspite of its importance , studies for determining optimum density of hydrometric network in general and stream-gauging network in particular are not extensive in many countries-including India. Some of the important aspects of hydrological network design have been reviewed.

Recommendations and suggestions have been made for types and stages of network development. The network stations are to be so located that the data collected is useful in developing relations between the hydrological factors and the significant physical parameters. A minimum plan is to be considered as a first step, as the establishment of an optimum network is a desirable but much greater undertaking. Once the minimum network is operating, one should work towards the optimum network by establishing a relatively desne network of secondary stations.

Two basic scientific problems in network design are to determine how many data acquisition points are required and where to locate them. During recent years, most approaoches to network design have seemed to fall into one of following broad categories viz. the regionalization and system analysis. Regionalization deals with the distributed rather than point values and with treated data rather than in their original form. System analysis approach is based on the optimization of some goal, subject to constraints imposed upon the system.

Some typical network design studies have also been reviewed. The recommendations for India's network made by Rao have been plotted according to Langbein's analysis of comparative areal densities of streamga-

uging stations as a function of population densities. It is seen that while the number of stations as per existing and modified WMO norms for immediate stage fall below the reasonable objectives and minimum requirement; while the network as per WMO norms appears to be of satisfactory level for corresponding population density.

The study for design of hydrologic network in Krishna basin is a typical example of application of physical-statistical method combined with zonal characteristics approach. However, further studies with good data base would be necessary to arrive at definite conclusions for application of this approach. The review note also includes some useful information about education and training of personnel and measurement standards adopted by Indian standards Institute and International Organization for Standardization.

Though WMO norms provide useful guidelines for general network design but it does not consider the effect of man's development activities in the river basins. Benson's study indicates the likely course of action for dealing with network design problems considering the parameters such as population, per capita income, area of land and water, relief, mean annual precipitation, surface water withdrawls, average annual growth in population, irrigated area, precipitation range areally of mean annual precipitation and number of hydroelectric plants. Appropriate methodologies would have to be developed for specific regions of the country considering climatic factors, physiographic factors, population and other indices of water resources development.

1.0 INTRODUCTION

In expanding modern economy, exploitation of natural resources is of primary importance. As water is one of the main natural resource, extensive efforts are being made in every country today to harness the water potential for the benefit of the people. For economic and optimum utilization of water resources, a determination of the extent and availability of surface and ground water is the first requisite and this in turn requires adequate hydrological and hydrometeorological data. Long term hydrological and meteorological data and information about physical characteristics of watersheds provide the basis for all hydrologic studies for development and management of water resources.

Inspite of considerable effort in the pursuit of hydrologic knowledge, there still remains uncertainty in all aspects of the hydrologic cycle. Quantification of any hydrologic resource or process can be performed only with limited accuracy, and thus plans for hydrologic control and development must make provisions for this lack of information. But even the most perfect provisions can not be expected to make up for this inadequacy. In fact there is no substitute for hydrologic information.

Hydrologic information almost always is measured in a parameter-specific sense; that is information is inversely related to the error of estimation of one or more hydrologic parameters. Nevertheless, the engineer, planner or policy maker who is actually making water resources decisions is more interested in the integrated measures of information such as what impact does the lack of hydrologic knowledge have on the decision?

Some aspects of hydrology have been subject of study and investigation for a long period of time. Others have attracted considerable attention and effort during recent years. Then, there is a third group consisting of topics which, for various reasons have been largely neglected and even ignored. Design of hydrological networks comes into this last category. This neglect is rather surprising when one considers that the system employed for gathering information is such a fundamental feature in the creation of hydrological knowledge.

There is a general pattern indicating that more effort is directed to improving methods of analysis and prediction than towards advancement of the means for securing the basic information.

Hydrologic networks serve an important and fundamental role in the scientific management of water resources. Ideally, then networks should themselves be designed as scientifically as possible. The design of hydrologic networks has been examined in numerous papers and a vareity of design criteria proposed but no generally applicable design methodology has yet emerged.

In many cases, the network design has been done purely from the point of meeting a specific purpose. If such stations are continued thereafter, they become part of a national network. Studies for determining optimum density of hydrological network are not extensive in many countries including India. There is confusion regarding purpose of the hydrological network design as to whether it is determination of number of observational sites or is it the determination of their locations on the stream? There is no systematic approach that gives desired answers when a variety of requirements are to be fulfilled. Due to lack of scientific norms, many network densities were being decided on empirical and subjective considerations. In India too, a uniform procedure for determination of basic network does not seem to have evolved. The Indian Standards Institution (ISI) committee on stream gauging methods has recently drawn attention to this problem, by inquiring as to what methods or techniques could be applied to Indian catchments which will enable us to evolve norms keeping in view the WMO guidelines on network design. In a recent study of hydrological network in India, it was stated by Gole (1978) that the WMO norms relate essentially to virgin flows and pre-development flows; and as such may not be appropriate for areas where considerable development of water resources has taken place.

The ideal network design would incorporate knowledge concerning the physical and stochastic nature of the hydrologic processes into a framework that accounts for the effects that the data will have on future water resources decisions. It should be stressed that network design is an iterative process; any design should be revaluated and updated periodically. The data that are collected change the designer's perception of the hydrologic phenomena; the data user may modify his procedures for the use of the data; the information flow from an associated network may change because of changes in the network; a better technique for network design may become available.

2.0 REVIEW

2.1 Definition of Hydrological Network

The definition of a network for hydrological data acquisition is a matter of some controversy. It is clear that such a network should satisfy the demands made by the principal users of hydrological data for scientific and practical purposes. Yet the uses of data and means of collecting them are so varied that it is not always obvious how the term'network' may be applied.

Rodda (1969) has stated that a 'hydrological network' is a programme for systematically acquiring the requisite information, processing and disseminating it in a like manner. This description of a network is somewhat akin to Langebein's definition 'A network is an organised system for the collection of information of a specific kind. Its component parts must be related to one another; that is, each station, point or region of observation must fill one or more definite niches in either space or time". One way of avoiding controversy might be to employ a definition similar to that suggested for hydrological data. Following that example, 'a hydrological network is one which provides data commonly used by the hydrologist'

2.2 General Principles for Design of Hydrological Networks

Hydrological and related meteorological data are collected mainly to provide information for developing and managing the water resources of a country. They are also used for operating purposes; forecasting flood discharges or stages, low flows, monthly and, in some cases annual discharges for operation of reservoirs and hydroelectric plants etc.

besides providing data base for use in research.

The diversity of terrain and hydrologic problems throughout the world makes it impractical to derive one universally satisfactory procedure for the design of hydrological networks. Furthermore, it is commonly accepted that any theoretical approach must be supplemented with an element of judgement. This is because, first the network must attempt to provide data for purposes not yet apparent, and second, the network density and required length of records depend upon areal and time variability of hydrological and meteorological elements.

Rao, Chattopadhyay and Gole (1983) have mentioned that in many cases network design has been done purely from the point of meeting a specific purpose. If such stations are continued thereafter, they become part of a national network. Primarily, however, there is what is called a basic network or key network to satisfy the following general requirements for water resources assessment:

(a) To estimate the total water resources in a river basin with a given degree of accuracy.

(b) To ensure reliable areal interpolation of runoff data at intermediate location.

(c) In general, to design a network which can estimate runoff at any required point with the same accuracy as that of measurement of streamflow data.

For this purpose, the zonal characteristics approach is adopted in which the catchment is divided into various zones based on similarity of climate, topography etc. These are then treated as homogeneous areas and network norms are derived for each of such zones.

2.3 Types of Gauging Stations

There are various types of gauging stations, which are described as follows:-

2.3.1 Primary stations(pricipal stations or base stations)

The primary stations also called principal stations, base-stations or permanent stations furnish the basis for statistical studies and thus should be observed continuously and indefinitely. In this context, it has been suggested that reliable estimates of average streamflow in areas with wet climates can be made only when observations extend for atleast 30 to 40 years. In areas of extremely variable precipitation, the minimum requirement may be 70 to 80 years. The basic network will consist of observation points on water courses with a natural regime as well as with a regime modified by management activities.

Boulton (1965) states that those stations are permanent stations which are to be operated for all time. So far as economically practicable they are "all range" stations, observations and records must be accurate and complete. These stations are located so that:

(a) they measure the flow at strategic points on major rivers and tributaries which are important in their own right, or

(b) they measure flows in rivers which are representative of those in a particular area and which are therefore suitable as permanent references with which relatively short-term records from local or secondary stations may be correlated.

McCall (1961) describes the primary stations as index stations on streams that must essentially be free from past regulation and, hopefully, free from extensive future regulation, diversion, or other development. An areal primary station is selected for representativeness and length of record; in so far as possible it is free from past and future regulation or diversion, and will be operated for an indefinite period of time to obtain a long range time sample of the hydrology of the section in which it is located. The record of index station would be used as the independent variable in making correlative estimates of long-term streamflow characteristics at other sites in the same hydrologic province.

A mainstream primary station that may be considerably affected by regulation or diversion, serves only as a record of actual flow at that point and as an index of flow at other points upstream or downstream on the same large river.

2.3.2 Secondary stations(subsidiary stations)

The secondary stations are operated for a limited number of years only. They should function just long enough to establish a good correlation between them and the base stations or with characteristics of the terrain. In studying correlations between flows at hydrometric stations, note should be made of whether the subordinate station is located on the same river as the base station or on a neighbouring stream. In the latter case, the correlations may be less significant. By moving the secondary stations after a correlation has been established, one can cover the whole country with a dense network based on the continuously operated principal stations.

Boulton(1965) has discussed important features of the secondary stations as follows:

(a) Secondary stations will normally be run for a period long enough for the record to be correlated with the record of primary station.

(b) Secondary stations will be selected in such a way as to increase the store of general hydrological knowledge, but priority may be given to streams for which abstractions or other demands are anticipated. Particular attention is also paid to geological formation boundaries when siting secondary stations.

(c) The range of a secondary station is as great as economically practicable.

(d) For Secondary stations (subject to range limitations), observations and records are as complete and as accurate as for primary stations.

McCall (1961) states that an areal secondary station would be operated where general streamflow information is wanted or will be likely be needed in the future, the length of the required record depending on the number of years necessary to define a correlation with a nearby areal primary station adequately. A mainstream, secondary station, likewise would be operated for only as many years as needed to define a correlation with a nearby mainstream primary station.

2.3.3 Special purpose stations

Special stations may be required for a specific purpose or they may be established to augment the network of base and secondary stations. The length of operation of special stations is determined by the purpose for which they were installed. In some cases, the observations may be confined to one particular aspect or to one season of the year. For example, they may be operated only during high or low flow periods or for the rainy season. Or they may consist of crest stage gauges for measuring water levels at flood peaks only. Although stations for special purposes may perform a valuable function, they do not provide all the data required for some statistical analysis.

Boulton(1965) has described some typical special purpose stations as follows:

2.3.3.1 Reservoir stations:

At these stations, daily mean rates of variation in reservoir content and supply to aqeduct are not often available and therefore, the stations cannot be used for analogy and correlation purposes, except perhaps with other stations of the same type. It is intended that as many as possible of these stations will be equipped with recorders for providing daily means.

2.3.3.2 Dry weather flow stations

These may be provided mainly for observing dry weather flows and relating them to flows at other classes of stations. They will be required more for the control of licenced/permitted abstraction and water management than the assessment of water resources They can occasionally be regarded as minor variations of the subsidiary (secondary) station network.

2.4 Planning and Classification of Hydrological networks

In planning hydrological network, WMO Guide (1974) stresses the need to keep its principal purpose always in view. For this reason, the stations should be so located that the data collected will be useful in developing relations between the hydrological factors and the significant physical parameters, such as slope, elevation, morphology, geology, landuse and soil types.

While a minimum plan should be considered as the first step, it will rapidly become insufficient as countries develop. The establishment of an optimum network is a much greater undertaking. Also, the gaps which remain even after establishment of the minimum network would still be sufficiently large to permit it to become an integral part of the optimum network with very few and only relatively minor changes. Nearly all the stations of the first network will be principal or base stations in the ultimate network.

2.4.1 Optimum network

In the developed countries, that already possess a relatively dense hydrological and climatological network with long records, WMO Guide (1974) recommends establishment of an optimum network as next step.

The aim of the optimum network is the satisfactory execution of a programme, defined by the very simple condition: that by interpolation between values at different stations, it should be possible to determine with sufficient accuracy for practical purposes the characteristics of the basic hydrological and meteorological elements anywhere in the country. By characteristics is meant all quantitative data, averages, and extremes that define the statistical distribution of the element studied. However, economic as well as technical considerations are involved in the design of an optimum network. Taking into account the economic considerations, the number of stations requiring observations over an indefinitely long period must not be excessive.

2.4.2 Minimum network

For establishing an optimum network time and experience is required. The first step should be the establishment of a minimum number of stations that experience elsewhere has indicated necessary for the economic development of the water resources of a country.

WMO Guide (1974) recommends that a minimum network is established as rapidly as possible. But once the minimum network is operating, one should work towards the optimum. For example, to establish first a provisional hydrometric station not requiring too much attendence If possible, the records of water level should be related to a permanent bench mark, and later the provisional station should be replaced by a permanent station.

Where a minimum network is established, general characteristics of rainfall or runoff may be determined at any place by interpolation among stations or by extrapolation. However, interpolation or extrapolation may be unsatisfactory for most detailed studies. Therefore, as soon as possible, it is advisable to begin to move towards the optimum network by installation of a relatively dense network of secondary stations in one or more representative areas. These stations will provide data for the study of spatial and time variability. Secondary stations may also be desirable at potential sites for hydraulic structures or at other points of special interest. A secondary station will usually be operated only long enough to provide the necessary information or untill satisfactory correlation with a nearby base station can be demonstrated.

WMO Guide (1974) stresses the need for maintaining good quality of records of all stations of a minimum network. Even if the installation of the stations is adequate, they may be of little value unless operated correctly. Continuous operation may be difficult especially over a long period as 20 years or more. It is obvious that a minimum network, of which 50 percent of the stations are abandoned or irregularly observed, has an effective density reduced by half and is no longer a suitable minimum network. For that reason, care should be taken not only in establishing but also in providing for continuing operations of the stations and checking the records.

2.4.2.1 Optimum use of existing stations in organising a minimum network

It is usually found that there are some stations in operation before the organisation of a minimum network is undertaken. If such stations have been operated for along period, and the records are available, the stations should be continued. if the locations of any of them are not entirely satisfactory, a new station should be started nearby, the objective being to establish a correlation between the records over a period of atleast 10 years (WMO Guide, 1974). If successful, the older station can then be abandoned. If no satisfactory correlation can be demonstrated, consideration should be given at this point to abandoning the older station, particularly if the records are known to be unrepresentative or inaccurate. However, careful weighing of all evidence and circumstances should precede any decision to abandon a long-term station at any time in the life of a network.

2.4.2.2 Factors affecting the density of observation stations for a minimum network

A measurement of flow in a river represents not only the flow from its particular catchment area, but with certain reservations, that in nearby streams as well. There is a limit of this areal representativeness, and the greater the number of stations, the more accurate the results for the region given by the network, provided the stations are properly located.

WMO Guide(1974) mentions about the difficulty in defining a uniform criterion of network density for all countries. Detailed studies worked out in several regions have shown that among the most important factors playing a part in the optimum density are (a) the geographical and hydrological conditions, particularly the areal variations in precipitation regime and in the hydrological regime, and (b) the nature of the hydrography i.e. many small streams or a few large rivers. There are other factors affecting the choice of the optimum density, such as the need for hydrological and meteorological data for design, construction and operation for hydraulic structure. The density of population and the economic activity of a region will also influence the optimum density of the hydrological network.

2.5 Approaches to network design

The study of network and their design is a subject that is common to many sciences. Hydrologists have been mostly involved in the studies of linear networks, particularly for examination of stream systems, Rodda (1969) mentions two basic scientific problems in network design. The first is to determine how many data acquisition points are required, and second is where to locate them. The second matter may present more difficulties than the first, because the optimum pattern of distributions may be affected by factors that are not always hydrological.

During recent years, most approaches to network design have seemed to fall into one of several broad categories, the regionalization and systems analysis approaches being two important approaches.

2.5.1 Regionalization

Rodda (1969) has discussed the approaches to regionalization which deal with the distributed rather than the point values and with treated data rather than in their original form. Obviously the technique for evolving region-wise characterization has to commence with analysis of point data and that point data has to be extended areally. This is achieved by relating a statistical property of the hydrological element to one or more of the pertinent surface or sub-surface features of the landscape, either by graphical method or by regression analysis. Measures of the physiography may be derived from maps or by field work. By reversing the procedure, map or field measures may be used to estimnate the desired hydrological variable. One of the difficulties of this method is how to limit the content of tne area that is being characterized, so that hydrological events that take place within it are statistically homogeneous. One homogeneity test has been derived by Langbein for regional flood frequency analysis and there are other methods for assessing uniformity within areal units, including subjective techniques.

Regionalization may be applied to the study of hydrological variables that are not easily mapped, such as the mean annual flood in a catchment. The flood represents the combined affect of basin characteristics, but such a parameter is more readily expressed by a regional relationship than by mapping the extent of flood along the river channels.

Rodda (1969) suggests that regionalization can be employed to plan a stratified sampling scheme, so that the range and interactions of the important parameters are adequately sampled, and each point of data-collection samples a unique combination of factors of the terrain. Even with the ideal distribution of data acquisition points, however, there is likely to be a residual standard error, which accounts for all the other discrepancies in the network. When a network is operated on a fixed budget, then a minimum error of prediction of the hydrological variables should be the aim. If a given level of accuracy is required, then the objective should be a minimum cost network.

2.5.2 System analysis

Rodda (1969) discussed the system analysis approach for network design which is based on the optimization of some goal, subject to constraints imposed upon the system. Objectives may range from flood forecasting to reservoir design and the constraints may be economic, those of policy and so on. For each objective, the effect of various numbers and configurations of data inputs can be examined by systems analysis, and this has made possible the development of a fresh approach to network design.

Rodda (1969) has also discussed the use of mathematical models of catchments for network design purposes. Most models try to simulate the conversion of rainfall into runoff and then deal with the problem of distributing streamflow in time. A number of assumptions have to be made about the physical processes involved in a basin, the behaviour of the model being matched against the prototype, by adjusting parameters in it to produce the best agreement between the predicted and observed outputs. The nature of input of the model, in terms of the number and arrangement of the data- acquisition points, can also be altered so as to minimise the error of prediction. Using such a model, a network could be planned that would yield the minimum error for a given cost, or would indicate points where observations should be added to produce the maximum benefit.

The concept of the information content of a record has implications for network design. It has already been applied in the primary/ secondary scheme for network design and in investigations of the choice between continuing or discontinuing stations in relation to a limited budget. The solution allows an optimal allocation of the budget between primary and secondary networks.

Information content is usually stated in terms of variability of one estimate, but the accuracy required for any given measure may depend on the use made of the information. Spectral analysis and sampling theory may help to set realistic limits to errors that can be tolerated in hydrological data collected for various needs. If a certain error criterion is set, this approach can be used to determine the density necessary for that level of accuracy, and it may allow optimization of a network, subject to constraints other than purely sampling variability.

In order to design a network within a systems analysis framework, Rodda (1969) mentions that the information content of the data must be translated into economic worth. Studies of the value of various types of hydrological data are underway. The particular use of data influences its worth, while the relative worth of information on spatial variability and on long-term trends has yet to be determined. Improved networks should lead to better understanding and prediction and also to financial savings, system analysis can help to answer the problem of (i) where should resources be invested in a network, (ii) should the network be expanded or contracted, (iii) should the instrumentation be altered and (iv) should greater use be made of the existing information?

Greis and Wood (1981) have stated that the objective of a regional network is to provide information upon which water resources planning and management decisions can be made. Hydrologic information acquired from a network can be used for several purposes. U.S. Office of Water Data Coordination has defined three major levels or orders of information. Of these three levels, levels 1 and 2 can be considered to provide regional data from which base level information suitable for national or regional planning is obtained. First order information is useful specially for policy decisions or resources inventory on national level. Second order information provides general resources information at a regional planning level. Flood insurance studies and land use planning activities could fall under first order or second order information. Third order is restricted to data collected programmes for the design and planning of specific projects. Order first and second depend directlv on the availability of an adequate methodology for obtaining regionalized estimates of flood events. Regionalization can also be of indirect importance in gaining third order information.

The authors further mention that the problem of network design is difficult because of multiplicity of uses to which the data may ultimately be put, from national base-line information to local design project. They advocate use of the probability weighted moment technique as a versatile method for hydrologic network building which will entail new relationships between the model identification processes and the data acquisition process. The network design problem is related to the problem of model building and the problem of data collection. The authors suggest that the use of the new probability weighted moment model to regionalize information would considerably change the data requirements and, hence the entire character of the network design process.

2.5.3 General W.M.O.Considerations concerning streamgauging station networks

WMO guide (1976) on hydrological practices defines three categories of the hydrological network, as follows:

Category(a) Flat regions of temperate mediterranean and tropical zones.

Category(b) Mountainous regions of temperate, mediterranean and tropical zones.

Category (c) Arid and Polar zones

Independent of these three main categories, stream gauging stations may be classified by size of basin area, in two ways as follows:-

Mainstream network gauging stations on streams draining areas larger than specified unit size A.

Small stream or areal network-gauging stations on streams whose drainage area is less than specified unit size.

The value of 'A', the area of catchment which divides the mainstream from the small-stream network, is defined as follows:-

- for regions of category (a): A=3,000 to 5,000 km^2
- for regions of category (b) : A=1000 km^2
- for regions of category(c) : A=10, 000 km^2

To ensure adequate sampling the Guide also recommends that there must be atleast as many gauging stations on the small streams as on the main streams. Whenever possible, the base stations should be located on streams with natural regimes where this is impractable, it may be necessary to establish additional stations on canals or reservoirs in order to obtain the necessary data to reconstruct the natural flows at the base stations. Computed flows past hydro-electric plants or control dams may be useful for this purpose, but provision will have to be made for calibration of the control structures and turbines and the checking of such calibrations periodically during the life of the plants.

The minimum density norms for stream gauging for the categories defined above, specified in WMO Guide (1976) as follows:

Category (a)

Flat regions of temperate, mediterranean and tropical zones:-

4-10 stations for 5,000 km^2 - 1 station for 1,000 -2,500 km^2

But for such countries where it is difficult to achieve, lack of development of communication facilities, or for other economic reasons, the density of the stream-gauging network may be reduced to:

1 station for 3,000 - 10,000 km^2

Category(b) Mountainous regions of temperate, mediterranean and tropical zone:

In mountainous regions, it is desirable to have stations distributed in altitude zones of approximately 500 m per zone with minimum density of 10-30 stations for 10,000 km^2 - 1 station for 300-1000 km^2.

For countries where it is not feasible to achieve for the time being, the required density because of sparse population, inadequate communications facilities, or other economic reasons, the density of stream-gauging network may be reduced to:

1 station for 1,000-5,000 km^2. Under very difficult conditions this may be extended to some 10,000 km^2.

On the other hand, for small mountainous islands less than 20,000 km^2 with very irregular regimes and very dense stream network, the minimum density is:-

1 station for 140-300 km^2.

Category (c) Arid and polar zones:-

0.5 - 2 stations for 10,000 km^2 - 1 station for 5,000-20,000 km^2, depending on feasibility. Such norms are not applicable to great deserts with no defined stream networks (such as Saharan, Gobi, Arabian and Korakorum deserts and great ice fields(Antarctic, Greenland, Arctic islands).

Whenever the density is less than 1 station for 4,000 km^2 for categories (a) and (b) a region of the order of 3,000 km^2 should be instrumented o the more stringent standards of these categories in order to obtain information on the variability of runoff.

The stations should be equally divided into two categories: large river stations and stations on small streams except for certain countries which have only small rivers.

Norms for the above mentioned regions are given in the tabular form in table 1.

In general, a sufficient number of stream flow stations should be located along the main stream of large streams (those with catchments area greater than A) to permit interpolation of discharge between the stations. The specific location of these stations will be governed by topographic and climatic considerations.

Table -1

Minimum density of hydrometric networks

Type of region	Range of norms for minimum network Area(km^2) per station	Range of provisional norms tolerated in difficult conditions Area(km^2) perstation
(a) Flat regions of temperate, mediterranean and tropical zones.	1,000-2,500	3,000-10,000
(b) Mountainous regions of temperate, mediterranean and tropical zones.	300-1,000	1,000-5,000[4]
Small mountainous islands with very irregular precipitation, very dense	140-300	
(c) Arid and polar zones[2]	5,000-20,000[3]	

1. Last figure of the range should be tolerated only for exceptionally difficult conditions.
2. Great deserts are not included.
3. Depending on feasibility.
4. Under very difficult conditions this may be extended to 10,000 km^2.

2.6 General Considerations

2.6.1 Location of stream-gauging stations

For the installation WMO Guide (1974) suggests the following:-

(i) Stations are 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 the borders.

(ii) Stations are also located where rivers issue from mountains and above the points of withdrawal for irrigation water.

(iii) Subsequent hydrometric stations are sited at such points as: where the discharge varies to a considerable extent; below the points of entry of the major tributaries; and at the outlet from lakes at those locations where large structures are likely to be built.

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 not justified. In this context, it must also be stressed that the discharge of a small tributory cannot be determined accurately by subtracting the flows at two main-stream gauging stations which bracket the mouth of the tributory. Inherent errors in the measurements at the mainstream stations may represent a very significant proportion of the total discharge of the tributory. Where the tributory flow is of special interest in such a case, a station on the tributory will be required. It will usually take its place as an areal station in the minimum network.

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 would be installed to gauge the runoff in different geologic and topographic environments, including lakes and dry washes.

Since vertical zonality is well expressed in the distribution of runoff in mountains, the hydrometric 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 must be taken of the varying exposures of slope, which is of great significance in rough terrain. Similarly, consideration should be given to stations in districts containing numberous lakes, whose influence can be determined only through installation of additional stations. Stations may also be located at places where there is a change in hydrological character, as, for example, where streams leave the mountains and enter an alluvial valley or a coastal plain.

2.6.2 Coordination between different network

WMO Guide (1974) mentions about lack of co-ordination despite the well known relationships between precipitation, streamflow and other hydrologic phenomena. It is quite rare that the several kinds of observations are jointly planned. That the several kinds of data are often obtained by different organizations is only part of the reasons, because even when one organization is responsible, different units or different disciplines may be involved, or perhaps different purposes are to be served. Basically, the reasons may be found rather in the fact that each network is directed to particular purposes which rarely coincide, or that each is limited by local conditions such as availability of observers. Coordination can surmount the problem.

If one considers only the precipitation and stream-gauging networks, much can be achieved through coordinated planning. Precipitation records can serve in extending records of streamflow and in interpolating between them. Because of relation between precipitation, between precipitation and runoff maps of runoff and precipitation are effectively prepared in conjunction with one another. Records of streams that drain high mountains provide useful clues to precipitation at high altitudes where these data are hard to get. Conversely, precipitation data can aid in mapping the distribution of runoff in valley areas where small streams may not be gauged.

Thus it is important to establish the various networks on an integrated basis, particularly the precipitation and streamflow networks. In some cases both networks are operated by the same office. But often, each of these networks has been managed independently. Good cooperation is then required for operating and developing both networks. For international basins, good cooperation is necessary not only between the agencies in one country but also between the agencies of the countries sharing the basin.

2.6.3 Education and training of personnel

The WMO Guide(1977) on the education and training of personnel in meteorology and operational hydrology aims to assist in the organization and implementation of training programmes with the up-to-date information in the light of recent developments. The necessary information which the developing countries want to seek about education and training of personnel has been provided in the guide and it has been stressed that no effort should be spared in maintaining the training of personnel of all grades at as high a standard as possible in all regions of the world.

The Guide defines the field of operational hydrology as follows:

(a) Measurement of basic hydrological elements from networks of meteorological and hydrological stations; collection, transmission, processing, storage, retrieval and publication of basic hydrological data;

(b) Hydrological forecasting and;

(c) Development and improvement of relevant methods, procedures and

(d) Techniques in: network design; specification of instruments; standardization of instruments and methods of observation; data transmission and processing; supply of meteorological and hydrological data for design purposes; hydrological forecasting.

The curriculam for education and training of professional personnel in operational hydrology recommends coverage of following subjects:-

(A) Education in the basic sciences

(a) Mathematics

(b) Physics

(B) Education in operational hydrology and related subjects

(a) Principles of descriptive geometry and technical drawing.

(b) Theoretical mechanics and fluid mechanics,

(c) General chemistry and hydrochemistry

(d) Principles of geophysics, geology and soil science

(e) Surveying

(f) Hydraulics

(g) General meteorology and climatology

(h) Hydrological instruments and methods of observations

(i) Design of networks

(j) Collection, processing and publication of data

(k) Hydrological analysis

(l) Hydrological forecasting

(m) Applications of water management

(n) Organization of hydrological services.

For the design of networks the guide recommends:-

(i) General principles for design of networks:- General requirements; optimum network; minimum network; optimum use of existing stations in organising a minimum network; data to be considered in determining network density; quality of data to be collected

(ii) Density of observation stations for a minimum network:- Factors affecting the density; minimum density limit of climatological networks ; hydrometric network of minimum density.

(iii) Integration of bench marks stations and representative basins in the network.

2.7 Typical Hydrologic Network Design Studies

Benson (1965) presented the study based on multiple regression techniques to relate the dependent variables (number of gauging station s per state) to independent variables (demographic, economic and hydrologic factors).

The study has been carried out in U.S.A. and includes:

A. Dependent Variables

1. N_1, Total Number of gaging station in 1963;

2. N_2, Total number of gauging stations in 1963; excluding

water-management stations.

B. Independent variables

1. P, population in millions in 1963 (latest available)
2. C, per capita income in $1,000 in 1962(latest available)
3. A, area, land water combined, in 1,000 square miles.
4. R, Relief (difference between highest and lowest altitudes) in 1,000 feet.
5. Pm, mean annual precipitation in inches.
6. W, surface-water withdrawals in thousands of acre-feet.
7. G, average annual percentage growth in population (plus 1 percent) in decade 1950-1960.
8. I irrigated acreage in 1,000 acres, in 1959 (latest available).
9. Pr, precipitation range areally, of mean precipitation, in inches, based on 1931-52 period.
10. H, number of hydroelectric plants, 1960.

The following formulas are based on the multiple-regression process and contain all the variables that were found statistically significant.

$N_1 = 22.9 \ A^{.26} \ P^{.22} \ R^{.21} W^{.11} I^{.05}$; (standard error 28.5%)

$N_2 = 9.73 \ A^{.35} P^{.30} I^{.06} R^{.11}$; (Standard error 31.6%)

It is assumed that the formulas contain all the important variables, computed values by the use of the formulas provide an estimate of rationally designed system in which economical as well as physical factors have an influence. The classification of water management stations is somewhat arbitrary, so that N_2 for each state is not a good representation of what a well-designed primary or basic network for collecting general hydrologic knowledge should be. The formula for N_1, the total number of stations, is probably more meaningful than that for N_2.

The formulae can serve only as a guide to the relative number of gages in separate parts of a region or a country. They cannot provide a guide for the absolute number. The absolute number depends on several considerations as yet unevaluated. Among these are:-

1. The variability of discharge in the region, in both space and time.
2. The value of station data in defining discharge at ungaged locations.
3. The accuracy required for estimates of critical classified flow.
4. The economic value of data collection with relation to the volume of water to be used and its value to the regions.

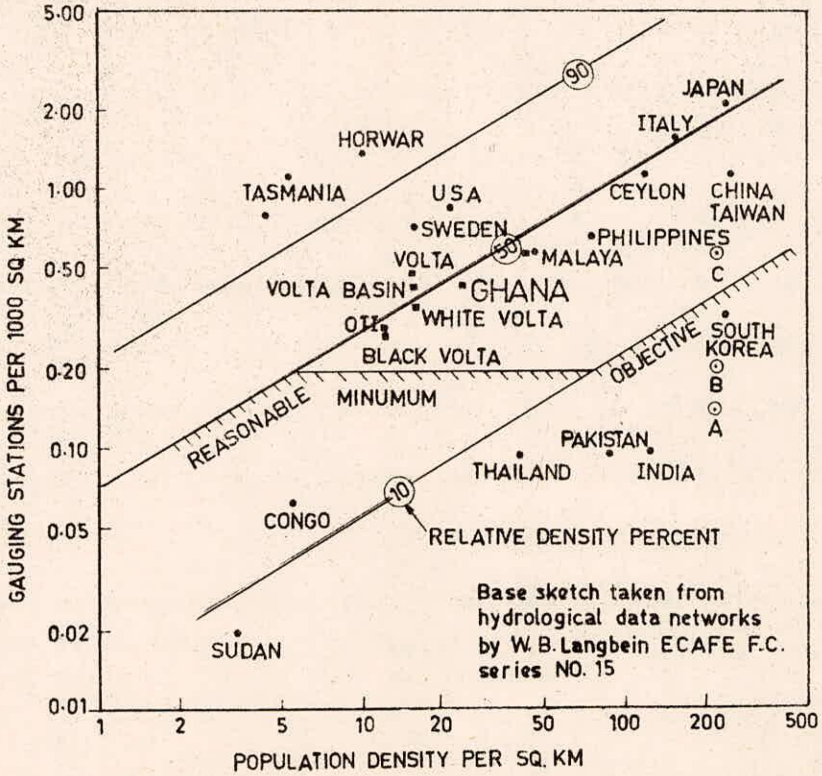
Sackeyflo and Krishnamurthy (1965) have described hydrological networks in Ghana. They have mentioned that at that time existing network in Ghana was based on immediate needs of development projects, to give reliable data on all the major rivers and tributaries, to ensure derivation of well correlated relationsips between rainfall and flow in different drainage areas, to meet the needs of hydrological forecasting etc.

Ghana's network has been compared with recommended standards:

Ghana	W.M.O.standard 1 station for	Actual in Ghana 1 station for
(Flat region of (tropical zone)	1000-2500 sq.km.	2380 sq.km.

Ghana's netowrk has also been found to be well plotted according to Langbein's analysis of comparative areal densities of stream flow gauging stations. In Ghana it works out to be a density of 0.41 gauging stations per 1,000 sq.km.against a population density of 24 sq.km. The areal density is almost of 50%adequacy which is well above the reasonable objectives and the requirements for minimum network.In relation to comparative areal densities of stream flow gauging stations Ghana's network which plots very well has been shown in Fig.1 (original sketch taken from Mr.Langbein's paper, as produced in the F.C.series Journal No.15).

It has been proposed to increase the hydrological network by an addition of 5-10 stations per year and realise a dense network of about 150-200 stations within the next few years. In the fig-1 population density per square kilometers has been plotted against gauging stations per square kilometer and the lines of relative areal



Base sketch taken from hydrological data networks by W. B. Langbein ECAFE F.C. series NO. 15

Fig.1 Comparative areal densities of streamflow gauging stations densities of 10%, 50% and 90% adequacy have been drawn.

India's stream-gauging network of the existing stations, network as per modified WMO norms for immediate stage and the ultimate stage stations as per WMO norms as mentioned by Rao (1979) have also been plotted in the fig-1 and represented by the points A,B, and C respectively as given in the table-2. India's population density has been taken as 235.77 for the population of 683 million as per 1981 census and basin area of 2,896,881 sq.kms.

Table - 2

Table 2 Existing, immediate and ultimate stage stream gauge networks

S.No.	Point in Fig.1	Streamgauge networks	No.of stream gauge stations	No. of stream gauges stn. per 1000 sq.km
1	A	Present Existing stations	423	0.146
2	B	As per modified WMO norms for immediate stage	600	0.027
3	C	Ultimate stage station	1700	0.586

It is observed India's network of the presently existing stations and of the stations as per modified WMO norms for immediate stage plots below the reasonable objectives and the minimum requirement and its areal density is of less than 10% adequacy. While the ultimate stage network as per WMO norms plots somewhat above the reasonable objectives and minimum requirement according to the analysis of comparative areal densites of stream-flow gauging stations, and its areal adequacy is above 10% and below 50%.

Rao (1979) mentions about existence of very few gauge and discharge sites in India prior to 1947. It was only during the second half of the century that observation sites were set up on large scale. For immediate implementation of network, the norms given by the WMO have been modified as below:

(a) Flat areas: One station for $\frac{3,000 + 10,000}{2}$ or 6500 sq.km. instead of 2,500 sq.km.

(b) Hilly areas: One station for $\frac{1,000+5,000}{2}$ or 3000 sq.km instead of 1,000 sq.km.

(c) Arid Zones: One station for 30,000 sq.km.instead of 20,000 sq.km.

Using these modified norms and WMO norms, Rao (1979) worked out the number of gauge and discharge stations to be set up under the immediate and ultimate stages for major, medium and minor river basins of India. All these stations along with the existing stations have been reproduced in the table-3.

Studies for determining optimum density of hydrometric network in general and stream-gauging network in particular are not extensive in many countries including India. Rao, Chattopadhyay and Gole (1981) have presented a study for network design of stream-gauges for water resources assessment of Krishna basin. In this study physical-statistical method combined with the zonal characteristics approach is applied to Krishna basin and the network in Krishna basin is arrived at by considering the criterion of reliability of interpolation of streamflow data at intermediate locations and the stream-gauge network has been evolved for different sets of conditions of variability and relative errors. Relevant extract of this study has been given in the Appendix-I.

2.8 Indian and International Standards for Fluid Flow Measurements

Various Indian Standards and International Standards are adopted

TABLE — 3

*Number of gauge and discharge stations at present and to be set up under the intermediate and **ultimate stages***

S. No.	*River basin*	*Basin area in sq. km. (accessive)*	*Type of region*	*Network as per norms for intermediate stage*	*Existing key stations*	*Ultimate stage stations*
1	*2*	*3*	*4*	*5*	*6*	*7*
	Major basins					
1.	Indus Basin	143,750	93,750 hilly	31	136	94
			50,000 flat	8		20
2.	Ganga including Damodar	853,360	112,000 hilly	38	130	112
			741,360 flat	119		296
3.	Brahmaputra (including Barak) (Brahmaputra in India)	238,137	hilly	84	12	238
4.	Sabarmati	20,770	flat	3	1	8
5.	Mahi	34,120	"	5	2	141
6.	Narmada	98.670	"	15	6	40
7.	Tapi	63,630	"	10	3	26
8.	Subarnarekha	19.296	"	3	3	8
9.	Brahmani	39.008	"	6	3	16
10.	Mahanadi	139,710	"	20	25	56
11.	Godavari	307,840	107,000 hilly	36	39	107
			200,840 flat	3	—	80
12.	Krishna	256,390	156,390 hilly	52	36	156
			100,000 flat	15	—	40
13.	Pennar	54,700	flat	9	2	22
14.	Cauvery	82,270	"	13	7	33
	Extra for special regions			30	—	—
	Total	2,351,651		500	405 or say 400	1,493 or say 1,500
	Medium River Basins					
1.	West flowing 6 rivers	35,435	flat	7	4	14
	13 rivers	45,774	hilly	17	5	46
2.	East flowing 21 rivers	133,682	flat	26	5	50
3.	Flowing into other countries	25,636	hilly	8	1	25
	Total 44	240,527	—	58	15	135
	Minor River Basins	205,271	Mostly flat	31	Nil	87
	Desert rivers	99,432	—	7	3	7
	Grand total	2,896,881		about 600	423	about 1,700

for measurements of fluid flows. Guidelines for selecting the appropriate methods to suit the various conditions have also been provided by I.S.I., since no one method would be suitable for all conditions of flow. As the choice of the method of discharge measurement is guided by the limiting conditions and factors like size of the river, place of gauging like hilly terrain or estuary, availability of equipment and trained personnel. Some of the relevant standards have been listed in the appendices as mentioned below:-

(i) Appendix II- Indian Standards

(ii) Appendix III- International Standards

(iii) Appendix IV- Guidelines for selecting the appropriate method for flow measurement.

3.0 REMARKS

Design of hydrological network is that aspect of hydrology which has been somewhat neglected, though the optimum utilization of water resources is based upon the determination of the extent and availability of surface and ground waters. This in turn requires adequate hydrological and meteorological data. The design of hydrological network has been examined by a number of workers and a variety of design criteria have been proposed, but no generally applicable design methodology has yet emerged. In many cases, the network design has been done purely from the point of meeting a specific purpose, if such stations are continued thereafter, they become part of a national network.

The Indian Standards Institution committee on stream-gauging methods has recently drawn attention to this problem in the context of Indian catchments keeping in view the WMO guidelines on network design. However, as rightly stated by Gole (1978) the WMO norms relate essentially to virgin flows, and as such may not be appropriate for the areas where considerable development of water resources has taken place. As indicated by the studies of Langbein(F.C.series Journal No.15) and Benson (1965) stage of development in the changing environment, influence of man's development activities, population density, various physiographic factors and other parameters of water resources development should be taken into account for determining the density of network. There is, thus a need for development of appropriate methodologies for specific areas to determine the optimum hydrological network considering all the relevant factors. The network design is an iterative process and has to be revaluated and updated periodically to account for changing hydrological environment. It is also important to establish and

and operate the various networks on an integrated basis, particularly the precipitation and streamflow networks for the river basins as a unit.

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APPENDIX - I

In this approach, the catchment has been divided into various zones based on similarity of climate, topography etc. which are regarded as homogeneous areas, and network norms are derived for each of such zones. For determination of stream gauge network in Krishna basin the criterion of reliability of interpolation of stream flow data at intermediate location and examination of its adequacy for long term and short term requirements in respect of water resources assessment has been followed.

It has been mentioned that the following three type of errors are possible in the estimate of average flow at a point on a stream:

(1) Interpolation errors.

(2) Sampling errors

(3) Measurement errors

In this study the first two aspects mentioned above have been considered and the general principles adopted are as given below:

(a) Determination of minimum area which is not subject to further interpolation.

(b) Consideration of linear gradient in mean annual run-off.

(c) Correlation of annual flows per unit distance between centres of drainage areas.

Quantitative limits can be ascribed to the above factors depending upon the accuracy desired. After this is done, an optimum size of the gauging area per station is computed which will lie in between the gradient and correlation functions.

This method while determining the basic required network, stipulates the level of errors and variabilities for which the network is valid. The regional approach, in which the catchment could be divided into zones of similar climatic characteristics peculiar to the basin, is used for delineating those areas. The Koppen's classification limits are applied to the Krishna basin, which is the study presented here.

To describe the climate a place based on temperature and rainfall Kappen's classification has been used. The Krishna basin has a total area of 2,59,000 sq.km. The length of the stream is 1093 km and at that time it had a density of 38 stream gauging stations. The average rainfall of the basin is 868 mm. The streamflows pertaining to a period from 1960-1970 and in some cases upto 1973 have been used. The annual runoff totals at different gauge sites are used for the computation.

The parameters used for dividing the catchment into similar climatic zones, are computed as per Koppen's classification. From these limiting values it was shown that the Krishna basin falls broadly into two climatic zones. They are :(a) Tropical rainy with dry season (AW), (b) Warm temperature rainy (CW).

The authors have recommended three variables which can be used to supplement the above classification, for determining homogeneity:

(i) Uniformity of spatial variation of rainfall in the area.

(ii) The distribution of coefficient of variation of rainfall.

(iii) The gradient of streamflow along the river.

Krishna basin is not prone to very large year to year fluctuations of rainfall. The stream gauge network design appears to be quite sensitive to the value of the stream gauge flow gradient chosen. The actual variation of streamflow with distance in Krishna catchment was studied and the area with uniform gradient of flow with Karad to Marukonda, was chosen as part of this study.

The procedure for application of physical-statistical method of stream gauge network to Krishna basin includes the following steps when annual series of flow is available at two gauging sites on the river alongwith the area of the basin upto the concerned site and the distance between the two sites.

Step 1: Compute the means $\bar{Q}_1$ and $\bar{Q}_2$ and standard deviations σ_1 and σ_2 of annual flow series and correlation coefficient r between annual flows at two gauging sites.

Step 2: Compute S_o, the radius of correlation of which correlation function is zero by substituting the value of correlation coefficient r in the following expression.

$$So = \frac{S}{1 - r}$$

Where, S is the distance between two sites on the river.

Step 3: Compute relative gradient Grado $(\bar{Q}) = \frac{Q'e}{\bar{m}} = \frac{Grad\ (\bar{Q})}{\bar{m}}$

Where $\bar{Q}$ is long term average runoff of N years

Q_e is obtained by dividing the difference of mean annual flows at two sites by the distance between two sites.

Thus $Q'_e = (\bar{Q}_1 - \bar{Q}_2)/S$, $\bar{m}$ is average of flow at the two gauging sites, i.e. $(\bar{Q}_1 + \bar{Q}_2)/2$.

Step 4: Compute the condition of sufficiency of streamflow gradient Sgr as:

$$Sgr \geqslant \frac{2.82\ \sigma o}{Grado(\bar{Q})}$$

where, σo is the relative error. This can be estimated by the following expression

$$\sigma o^2 = \frac{1}{N} \sum_{j=1}^{N} \left(\frac{Q_{1_j} + Q_{2_j}}{2} - \frac{\bar{Q}_1 + \bar{Q}_2}{2}\right)^2$$

$$= \frac{\sigma_1^2}{2}(1+r) \approx \frac{\sigma_2^2}{2}(1+r)$$

Assuming $\sigma_1 \approx \sigma_2$.

Step 5: Compute S_c; taking as Sc at zero correlation i.e. distance between two sites as:

$$S_c \leqslant \frac{\sigma^2}{aC_v^2}$$

where C_v is the coefficient of variation of annual flows at concerned site and $a \overset{v}{=} (1/S_o)$.

Step 6: Compute Fgr, the limiting area of the gradient function as:

$$Fgr \geqslant 8 \quad \left(\frac{\sigma_o}{\text{grado}(\bar{Q})}\right)^2$$

Step 7: Compute F_c, the limiting area of the correlation function as:

$$F_c \leqslant \frac{\sigma_o^4}{a^2 C_v^4}$$

This is based on assumption of the following relationships:

$$L \approx 2F^{0.5}$$

$$S \approx F^{0.5}$$

where, L is the length of the river and F is the drainage area.

Step 8: Compute the number of gauging stations N as:

$$N = \frac{F}{\text{Minimum of } F_{gr} \text{ or } F_c} = \frac{F}{F_{min}}$$

where, F is area of the basin.

As an example, optimum number of gauging stations of Krishna basin between Marukonda have been computed as follows:

The catchment area between Karad and Marukonda F=205038 Sq.km.

The distance between Karad and Marukonda S = 552.47 km.

Step 1: The correlation coefficient r, between annual flows at Karad and Maraukonda is calculated

$$r = 0.7359$$

Step 2: So the radius of correlation for which correlation function is zero is computed as

$$So = \frac{S}{1-r}$$

$$= \frac{552.47}{1-0.7359}$$

$$= 2091.9 \text{ km.}$$

Step 3: Compute Grado ($\bar{Q}$)

$$\text{Grado } (\bar{Q}) = \frac{Q'e}{\overline{m}}$$

The mean annual flow at Karad = 170.45 TMC (thousand million cubic)

or 4826.6 MCM (million cubic meters)

The mean flow at Maruakonda = 1353.31 TMC

or 37811.71 MCM

$$\therefore Q'_e = \frac{1335.31 - 170.45}{552.47}$$

$$= 2.1084 \text{ TMC/km}$$

or 59.7048 MCM/Km

$$\text{Grado } (\bar{Q}) = \frac{59.7059}{21319.15}$$

$$= 0.0028005 \text{ MCM/Km}$$

Step 4: Compute Sgr the condition of sufficiency of stream flow gradient as:

$$\text{Sgr} \ngtr \frac{2.820\sigma_0}{\text{Grado } (Q)}$$

$$\text{Sgr} \ngtr \frac{2.82 \times 0.05}{0.0028005}$$

$$\ngtr 50.35 \text{ km}$$

Where $\sigma_0 = 5\%$

Step 5: Compute S_c as

$$S_c \leqq \frac{\sigma_o^2}{aC_v^2}$$

$$S_c \leqq 2091.9 \left(\frac{0.05}{0.30}\right)^2$$

$$\leqslant 58.13 \text{ Km}$$

Step 6: Compute Fgr the limiting area of the gradient function as:

$$\text{Fgr} \geqslant 8 \left(\frac{\sigma 0}{\text{grado } (\bar{Q})}\right)^2$$

$$\geqslant 8 \left(\frac{0.05}{0.0028005}\right)^2$$

$$\geqslant 2534.93 \text{ sq.km.}$$

Step 7: Compute F_c the limiting area of correlation of function

$$F_c \leqslant \frac{\sigma_o^4}{a^2 C_V^4}$$

$$\leqslant \left(\frac{.05}{.30}\right)^4 \times (2091.90)^2$$

$$\leqslant 3379.28 \text{ sq.km.}$$

Step 8: Compute the number of gauging stations N as:

$$N = \frac{205038}{2534.93}$$

Since Fgr $\leqslant F_c$; for this particular case.

Rao et al (1983) have assumned different values of C_V viz.0.20, 0.25, 0.30 and 0.35 and for each value of C_V, relative error has been taken as 0.03,0.04, 0.05, 0.10, 0.15 for reach between Karad and Maruakonda. The estimated number of gauging stations for Krishna basin (catchment area = 205038 km^2) have been given in tabular form. An extract of the same is given as follows:

TABLE 2

S.N.	C.V.	σ_o	F_{min}	N	Remarks Critical criteria
1	0.20	0.03	912.57	225	Gradient
2		0.04	1622.36	126	Gradient
3.		0.05	2534.93	81	Gradient
4		0.10	10139.74	20	Gradient
5		0.15	22814.41	9	Gradient
6	0.25	0.03	907.42	226	Correlation
7		0.04	1622.36	126	Gradient
8		0.05	2534.93	81	Gradient
9.		0.10	10139.74	20	Gradient
10.		0.15	22814.41	9	Gradient
11	0.30	0.03	437.60	469	Correlation
12		0.04	1318.66	114	Correlation
13		0.05	2534.93	81	Gradient
14		0.10	10139.74	20	Gradient
15		0.15	22814.14	9	Gradient
16	0.35	0.03	236.16	869	Correlation
17		0.04	786.65	274	Correlation
18		0.05	1822.74	212	Correlation
19		0.10	10139.74	20	Gradient
20		0.15	22814.41	9	Gradient

It is seen that for most of the cases the limiting area of the gradient function is the critical criteria and the limiting area of the correlation function is the critical criteria only for a few cases.

It is also seen that for a constant value of coefficient of variation as the relative error increases the number of gauging stations decreases. The number of gauging stations varies from as high as 869 for coefficient of variation 35% and relative error of 30% to as low as 9 for coefficient of variation 20%, 25%, 30% and 35% and relative error of 15%. For different values of coefficient of variation and relative error of 10% the number of gauging stations comes out to be 20, while for coefficient of variation 20%, 25% and 30% and relative error of 30% the number of gauging stations comes out to be 81.

APPENDIX-II

Indian Standards:

The various Indian standards for measurements of fluid flows have been listed below. Any further information about these can be obtained from Indian Standards Institution, Manak Bhawan, 9, Bahadur Shah Zafar Marg, New Delhi-110002.

IS:1191-1971 Glossary of terms and symbols used in connection with the measurement of fluid flow with a free surface (first revision).

IS:1192-1981 Velocity area methods for measurement of flow of water in open channels (first revision).

IS:2912-1964 Recommendation for liquid flow measurement in open channels by slope-area method (approximate method).

IS 2913-1964 Recommendation for determination of flow in tidal channels.

IS:2914-1964 Instructions for collection of data for the determination of error in measurement of flow by velocity area methods.

IS:2915-1964 Instructions for collection of data for the determination of error in measurement of flow by velocity area methods.

IS:6059-1971 Recommendation for liquid flow measurement in open channels by weirs and flumes-weirs of finite crest width for free discharge.

IS:6062-1971 Method of measurement of flow of water in open channels using standing-wave flume fall.

IS:6063-1971 Method of measurement of flow of water in open channels using standing wave-flumes.

IS:6330-1971 Recommendation for liquid flow measurement in open channels by weirs and flumes-end depth method for estimation of flow in rectangular channels with a free overfall (approximate method).

IS:9108-1979 Liquid flow measurement in open channels using thin plate weirs.

IS: 9117-1979 Recommendation on liquid flow measurement in open channels by weirs and flumes-end depth method for estimation of flow in non-rectangular channels with a free overfall (approx.method).

IS:9163(Part I)-1979 Dilution method for measurement of steady flow: Part I constant injection method.

IS:9922-1981 Guide for selection of method of measuring flow in open channels.

APPENDIX -III

International Standards:

The various international standards adopted for liquid flow measurement in open channels have been listed here:

ISO 555/1 Liquid flow measurement in open channels-Dilution methods for measurement of steady flow-part 1:Constant rate injection method.

ISO 555/2, Liquid flow measurement in open channels-Dilution methods for measurement of steady flow-Part 2: Integration (Sudden injection) method.

ISO 748, Liquid flow measurement in open channels-velocity area methods.

ISO 772, Liquid flow measurement in open channels-volcabulary and symbols.

ISO 1000, SI Units and recommendations for the use of their multiples and of certain other units.

ISO 1070, Liquid flow measurement in open channels-slope area method.

ISO 1088, Liquid flow measurement in open channels-velocity area methods-Collection of data for determination of errors in measurement.

SIO 1100/1, Liquid flow measurement in open channels- Establishment and operation of a gauging station.

ISO 1100/2, Liquid flow measurement in open channels-
Part 2: Determination of stage discharge relation.

ISO 1438/1, Water flow measurement in open channel using weirs and venturi flumes-Part 1: thin plate weirs.

ISO 2425, Measurement of flow in tidal channels.

ISO 2537, Liquid flow measurement in open channels-cup-type and propeller-type current meters.

ISO 3454, Liquid flow measurement in open channels-sounding and suspension equipment.

ISO 3455, Liquid flow measurement in open channels-Calibration of routing element current meters in straight open tanks.

ISO 3716, Liquid flow measurement in open channels- Functional requirements and characteristics of suspended load samplers.

ISO 3846, Liquid flow measurement in open channels by weirs and flumes-Free overfall weirs of finite crest width (rectangular broad-crested weirs).

ISO 3847, Liquid flow measurement in open channels by weirs and flumes-End-depth method for estimation of flow in rectangular channels with a free overfall.

ISO 4359, Liquid flow measurement in open channels using flumes.

ISO 4360, Liquid flow measurement in open channels by weirs and flumes-Triangular profile weirs.

ISO 4463, Liquid flow measurement in open channels-methods of measurement of suspended sediment.

ISO 4364, Liquid flow measurement in open channels- Bed material sampling.

ISO 4366, Echo sounders for water depth measurements.

ISO 4369, Measurement of liquid flow in open channels- Moving-boat method.

ISO 4373, Measurement of liquid flow in open channels- Water level measuring devices.

ISO 4375-Measurement of liquid flow in open channels-Gableway systems for stream gauging.

ISO 4377, Measurement of liquid flow in open channels-Flat-V weirs.

ISO 5168, Measurement of fluid flow-Estimation of uncertainty of a flow-rate measurement.

ISO/TR7178, Measurement of liquid flow in open channels- Investigation of the total error in measurement of flow by velocity area methods.

APPENDIX-IV

Guidelines for selecting the appropriate method of discharge measurement

IS:9922-1981 gives the guidelines for selecting the appropriate methods to suit various conditions of flow. Table 1 given in IS 9922-1981 can serve as useful guideline for making the choice of the method of discharge measurement. This table gives the guidelines for the following methods of liquid flow measurement in open channels:

1. Velocity area method by wading.
2. Velocity area method from bridge.
3. Velocity area method using cableway.
4. Velocity area method using static boat.
5. Velocity area method using moving boat.
6. Velocity area method using float.
7. Slope area method.
8. Ultra sonic method.
9. Dilution method with chemical tracer-sudden injection.
10. Dilution method with chemical tracer-continuous injection.
11. Dilution method with radio active tracer-sudden injection.
12. Dilution with radio active tracer-continuous injection.
13. Cubature method.
14. Weirs-Sharp crested V-Notch
15. Weirs-sharp crest rectangular with suppressed side contractions.
16. Weirs-sharpest rectangular with side contractions.
17. Weirs-broad crested with sharp upstream edge.
18. Weirs-broad crested with rounded upstream edge.
19. Weirs-triangular crest crupm.
20. Weirs triangular crest flat V.
21. Flumes rectangular throated.

22. Flumes trapezoidal throated.

23. Flumes U shaped throat.

24. Flumes V shaped throat

25. Flume falls rectangular throated.

26. Venturi flumes.

27. Free overfalls.