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HYDROLOGICAL NETWORK DESIGN FOR NARMADA BASIN

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ABSTRACT

Hydrological and hydraulic design of water resources projects depend to a considerable extent on the information about hydrological processes obtained through observations at measurement sites/stations. 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, and particularly so in India. Two basic scientific problems in network design are; how many data acquisition points are required and where to locate them.

In this study, methodology and computation steps of physical-statistical method to determine representative catchment area per stream gauging station have been explained in detail. Guidelines for selection of stream-gauging sites have been highlighted. This methodology has been applied for Narmada basin using available annual flow data for five sites namely; Jamtara, Barmanghat, Mandleshwar, Rajghat and Garudeshwar. For reach Jamtara-Garudeshwar 36 years of data was available, while for Jamtara-Mandleshwar, Jamtara-Rajghat, Barmanghat-Mandleshwar, Bramanghat-Rajghat and Barmanghat-Garudeshwar reaches only 9 years data was available.

Variation of stream gauging area per station with catchment area between the various considered reaches has been studied for the available data. The effect of variation in sample length on stream gauging area per station has also been studied.

It is seen that as sample length increases from 9 to 36 years, the catchment area per station decreases from 4,183 km^2 to 2,411 km^2, following a linear pattern. In case of variability with river basin area covered by river reach, there is no systematic pattern, but there is general decrease of catchment area per station from 3,928 km^2 to 1,221 km^2 as basin area covered by the river reaches increases from 47,693 km^2 to 72,395 km^2.

On the basis of this study, with somewhat limited data a basic network density of one station per 2,411 km^2 area for developing relationships of hydrological parameters of the basin could be recommended for Narmada basin upto Garudeshwar. This does not include secondary and special purpose stations.

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 to harness the water potential for the benefit of the people. For economic and optimum utilisation, planning, design and development of water resources, determination of the extent and availability of surface and ground water is the first requisite and this in turn requires adequate hydrological and meteorological data. Long term hydrological and meteorological data; and information about physical characteristics of watersheds, provide the basis for all hydrological studies and development and management of water resources.

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 somewhat neglected in our country. 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. In general, considerably more effort is directed to improve methods of analysis and prediction than towards advancement of the means for securing the basic information.

Hydrological networks serve an important role in the scientific management of water resources. Therefore, the networks themselves should be designed as scientifically as possible. The design of hydrological networks has been examined by some authors and a variety of design criteria have been proposed in the literature, but no generally applicable design methodology has yet emerged.

The diversity of terrain and hydrologic problems throughout the world make 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.

Due to lack of scientific norms, many network densities are 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 (Rao et.al., 1983).

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. Network design is an iterative process, and design should be revaluated and updated periodically; since the data that are collected may 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.

In the present study, physical-statistical method has been applied for hydrological network design of Narmada basin to fulfil the objective of developing regional relationships of hydrological parameters of the basin. The guidelines for site selection for stream gauging have also been explained.

2.0 REVIEW

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

Rodda (1969) has termed a hydrological network as a programme for systematically acquiring the requisite information, processing and disseminating it in a like manner. This description of 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'. Different types of stream gauging stations have been defined in Appendix-I.

2.1 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. 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.

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 and 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 an 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.

2.2 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.

There are two basic 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.

2.2.1 Regionalization

Rodda (1969) has discussed the approaches tc regionalisation 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 characteristics 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 landscope, either by graphical method or by regression analysis. Measures of physiography may be derived from maps or by field work. By reversing the procedure, map of field measures may be used tc estimate the desired hydrological variable. One of the difficulties of this method is how to limit the content of the area that is being characterised, 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 study of hydrological variables that are not easily mapped, such as the mean annual flood in a catchment. The flood represents the combined effect 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 such 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 account for all the other discripencies in the network. When a network is operated on a fixed budget, then a minimum error of prediction of hydrological variables should be the aim. If a given level of accuracy is required, then the objective should be a minimum cost network.

2.2.2 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. He 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 a distributed 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 and 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. The particular use of data influences its worth, while the relative worth of information on spatial variability and long term trends have yet to be determined. Improved networks should lead to better understanding and prediction and also to financial savings. Systems 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 intrumentation be altered, and (iv) should greater use be made of the exiting 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. Hydrological 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.

Third order is restricted to data collection programmes for the design and planning of specific projects. The authors further mention that the problem of network design is difficult because of multiplicity of uses to which data may be ultimately put to. 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.

2.2.3 WMO Guidelines

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

Category (a) : Flat regions of temperate, moditerrainean 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, streamgauging stations may be classified by size of basin area, in two ways as follows:-

(i) Main-stream network gauging stations on streams draining areas larger than specified unit size 'A'.

(ii) Small-Stream or areal network gauging stations on streams whose drainage area is less than 'A'.

The value of 'A', the area of catchment which divides the main-stream from 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 = 1,000 km^2

- For regions of category (c) : A = 10,000 km^2

The minimum density norms for stream-gauging stations for the categories (a), (b) and (c) are summarized in table-1.

TABLE - 1

Minimum Density of Hydrometric Network

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) per station
(a) Flat regions of temperate, Mediterrancan and tropical zones.	1,000-2,500	3,000-10,000
(b) i) Mountainous regions of temperate, mediterranean and tropical zones	300-1,000	1,000-5,000[4]
ii) Small mountainous islands with very irregular precipitations, very dense stream network	140-300	
(c) Arid and polar zones[2]	5,000-10,000[3]	

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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.

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 author modified the norms given by WMO as follows:

(a) Flat areas: One station for $\frac{3,000 + 10,000}{2}$ or 6,500 sq.km

(b) Hilly areas: One station for $\frac{1,000+5,000}{2}$ or 3,000 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. Details of these estimates along with the number of existing stations are reproduced in Table 2.

2.3 Typical Hydrological Network Design Studies:

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

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 50,000 flat	31 8	136	94 20
2.	Ganga including Damodar	853,360	112,000 hilly 741,360 flat	38 119	130	112 296
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 200,840 flat	36 3	39 —	107 80
12.	Krishna	256,390	156,390 hilly 100,000 flat	52 15	36 —	156 40
13.	Pennar	54,700	flat	9	2	22
14.	Cauvery Extra for special regions	82,270	,,	13 30	7 —	33 —
	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

The study has been carried out in USA and includes:

A- Dependent variables -

1. N_1, Total number of gauging stations 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 withdrawls in thousands of acre-feet.
7. G, average annual percentage growth in population (Plus 1 percent) in decade 1950-1960.
8. I, irrigated acre-age 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, in 1960.

The following formulae are based on multiple-regression process and contain all the variables that were found significant. $N_1 = 22.9A^{.26}P^{.22}R^{.21}W^{.11}I^{.05}$; (standard error 28.5%)

$N = 9.37A^{.35}P^{.30}I^{.06}R^{.11}$ (standard error 31.6%).

It is assumed that the formulae contain all the important variables, computed values by the use of the formulae provide and 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 network should be. The formula for N_1, the total number of stations is probably more meaningful than that for N_2.

These 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; variability of discharge in region, in both space and time, value of station data in defining discharge at ungauged locations, accuracy required for estimates of flows, the economic value of data collection with relation to volume of waters to be used and its value to the regions.

3.0 STATEMENT OF THE PROBLEM

The task of hydrological network design includes:

a) Estimation of the optimum network density or average area per observational station,

b) Location of stations on the streams of an individual river system.

c) Determination of the priority of network development

The objective of present study is to estimate the optimum network density or to average area per stream gauging station and provide guidelines for selection and demarcation of the gauging sites for some reaches of the Narmada river basin for which data is available for varying lengths.

4.0 DESCRIPTION OF STUDY AREA:

The salient features of Narmada river and Narmada basin are described below:

4.1 Narmada River:

The Narmada river as described in Report of the Irrigation Commission, Vol. III part I (1972) rises in the Amarkanatak plateau of Maikala range in the Shahdol district of Madhya Pradesh at an elevation of 1058 m.a.s.l. The river travels a distance of 1312 km. before it falls into Gulf of Cambay in the Arabian Sea near Bharuch in Gujarat. The first 1079 km. are in Madhya Pradesh. In the next length of 35 km. the river forms the boundary between the states of Madhya Pradesh and Maharashtra. In the next length of 39 km, it forms the boundary between Maharashtra and Gujarat. The last length of 159 km. lies in Gujarat. The index map of the basin is shown in fig.1.

The river has a number of falls in its head reaches. At 8 km. from its source, the river drops 21 to 24 m. at Kapildhara falls; 0.4 km. further downstream, it drops by about 4.6 m at the Dudhara falls. Flowing in generally south westerly direction in a narrow and deep valley, the river takes pin head turns at places. Close to Jabalpur, 404 km from the source, the river drops nearly 15 m at the Dhuandhara falls, after which it flows through a narrow channel carved through the famous marble rocks. After passing through the marble rocks, the Narmada enters the upper fertile plains, at Nandhar, 806 km from the source and at Dhardi, 47 km further downstream,

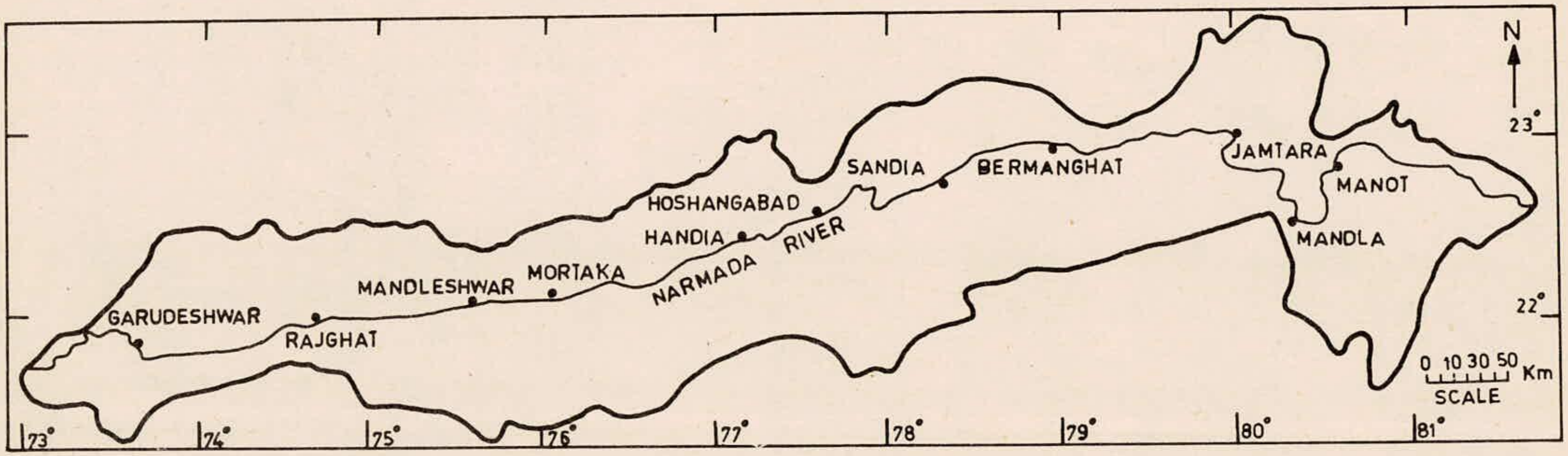

FIG.1- MAP SHOWING GAUGING SITES ON THE RIVER NARMADA

the river drops over falls of 12 m at each place. At 966 km. from source, nearly 6.4 km downstream of Maheshwar, the Narmada again drops by about 6.7 m at the Sahastradhara falls.

Flowing further west, the river enters the lower hilly regions and flows through a gorge, The 113 km. long gorge is formed by the converging of the Vindhyas from the north and the Satpuras from the South towards the river. Emerging from the gorge, the river enters the lower plains and meanders in broad curves till it falls into Gulf of Cambay in the Arabian sea near Broach.

The river has 41 tributaries of which 22 are on the left bank and 19 on the right, the important tributaries of the Narmada are the Burhner, Banjar, Sher, Tawa, Chhota Tawa, Kundi, Shakkar, Dudhi, Ganjal, Goi, Karjan, Hiran, Tendoni, Barna, Kolar, Man, Uri, Hatni and Orsang which are briefly described in the following paragraphs as given in the Report of Irrigation Commission (1972).

The Burhner rises in the Maikala range, South-east of Gwara village in Mandla district of Madhya Pradesh at an elevation of about 900 m, at north latitude $22^{o}32'$ and east longitude $81^{o}22'$ and flows in a generally westerly direction for a total length of 177 km. to join the Narmada near Manot. The Burhner drains a total area of 4,118 sq.km.

The Banjar rises in the Satpura range in the Drug district of Madhya Pradesh near Rampur village at an elevation of 600 m at north latitude $21^{o}42'$ and east longitude 80° 50' and flows in a generally north westerly direction for a total length of 184 km to join the Narmada from the left near Mandla at the 287th km. of its run. The Banjar drains a total area of 3,626 sq. km.

The Sher rises in the Satpura range near patan in the Seoni district of Madhya Pradesh at an elevation of 600 m at north latitude 22°31' and east longitude 79°25' and flows in a generally north-westerly direction for a total length of 129 km to its confluence with the Narmada from the left near Brahmand. The Sher drains a total area of 2,901 sq.km.

The Shakkar also rises in the Satpura range in the Chhindwara district of Madhya Pradesh, east of Chhindi village, at an elevation of 600 m at north latitude 20°23' and east longitude 78°52' and flows in a generally north-westerly direction for a total length of 161 km. to join the Narmada from the left, north west of Paloba. The Shakkar drains a total area of 2,292 sq. km.

The Dudhi rises in the Mahadeo hills of the Satpura in the Chindwara district of Madhya Pradesh, west of Chhindi village at an elevation of 900 m at north latitude 22°23' and east longitude 78°45' and flows first in a north-westerly direction up to Sainkheda and then in a westerly direction for a total length of 129 km to join the Narmada from the left, north-west of Nibhora. The Dudhi drains a total area of 1,541 sq.km.

The Tawa, the biggest left bank tributary, rises in the Mahadeo hills of the Satpura range in the Chhindwara district of Madhya Pradesh near Cherkathari village at an elevation of 900 m at north latitude 22°13' and east longitude

$78^{\circ}23'$ and flows in a generally north-westerly direction for a total length of 172 km to join the Narmada from the left, north-east of Hoshangabad. The Denwa is its important tributary. The Tawa drains a total area of 6,333 sq.km.

The Ganjal rises in the Satpura range in the Betul district of Madhya Pradesh north of Bhimpur village at an elevation of 800 m at north latitude $22^{\circ}0'$ and east longitude $77^{\circ}30'$ and flows for a total length of 89 km in a north-westerly direction to join the Narmada from the left near Chipaner village. The Ganjal drains a total area of 1,930 sq. km.

The Chhota Tawa rises in the Satpura range in the West Nimar district of Madhya Pradesh near Kakora village at an elevation of 600 m at north latitude $21^{\circ}30'$ and east longitude $75^{\circ}50'$ and flows for a total length of 169 km in a northerly direction to join the Narmada from the left, north of Purni village. The chhota Tawa is next in size to the Tawa among the left bank tributaries and drains a total area of 5,051 sq.km.

The Kundi rises in the Satpura range in West Nimar district of Madhya Pradesh, near Tinshemali village at an elevation of 600 m at north latitude $21^{\circ}25'$ and east longitude $75^{\circ}45'$ and flows for a total distance of 121 km in a northerly direction to join the Narmada from the left near Mandleshwar. The Kundi drains a total area of 3,820 Km.

The Goi rises in the Satpura range in West Nimar district of madhya Pradesh near village Dhavdi at an elevation of 600 m at north latitude $21^{\circ}40'$ and east longitude $75^{\circ}23'$ and flows for a total length of 129 km in a north-westerly direction to join the Narmada from the left, west of Barwani village. It drains a total area of 1,891 sq. km.

The Karjan rises in the Satpura range in Surat district of Gujarat, South of Nana village at an elevation of 300 m at north latitude 21°23' and east longitude 73°35' and flows for a total length of 93 km in a north-westerly direction to join the Narmada from the left, east of Sinor village. It drains a total area of 1,489 sq. km.

The Hiran rises in the Bhanrer range in the Jabalpur district of Madhya Pradesh near Kundar village at an elevation of 600 m at north-latitude 23°12' and east longitude 80°27' & flows in a generally south-westerly direction for a total length of 188 km to join the Narmada from the right near Sankal village. The Hiran, the biggest right bank tributary of the Narmada drains a total area of 4,792 sq. km.

The Tendoni rises in the Vindhya range in the Raisen district of madhya Pradesh, east of Sardarpur village at an elevation of 600 m at north latitude 23°22' and east longitude 78°33' and flows for a total length of 118 km in a south-westerly direction to join the Narmada from the right, near Bhatgaon village. It drains a total area of 1,632 sq.km.

The Barna rises in the Vindhya range in the Raisen district of Madhya Pradesh, east of Barkhera village at an elevation of 450 m at north latitude 22°55' and east longitude 77°44' and flows for a total length of 105 km in a south-easterly direction to join the Narmada from the right, near

Dimaria village. It drains a total area of 1,787 sq. km.

The Kolar rises in the Vindhya range in the Sehore district of Madhya Pradesh, near Bilquisganj village at an elevation of 450 m at north latitude $23^{\circ}7'$ and east longitude $77^{\circ}17'$ and flows for a total length of 101 km in a south-westerly direction to join the Narmada from the right, south of Nasrullahganj. The Kolar drains a total area of 1,347 sq.km

The Man rises in the Vindhya range in the Dhar district of Madhya Pradesh near Dhar town at an elevation of 500 m at north latitude $22^{\circ}33'$ and east longitude $75^{\circ}18'$ and flows for a total length of 89 km in a southerly direction to join the Narmada from the right north of Talwara Deb village. It drains a total area of 1,528 sq. km.

The Uri rises in the Vindhya range in the Jhabua district of Madhya Pradesh, near Kalmore at an elevation of 450 m at north latitude $22^{\circ}36'$ and east longitude $75^{\circ}18'$ and flows for a total length of 89 km in a southerly direction to join the Narmada from the right near Nisarpur. It drains a total area of 1,813 sq. km.

The Hatni rises in the Vindhya range in the Jhabua district of Madhya Pradesh, east of Kanas at an elevation of 450 m, at north latitude $22^{\circ}32'$ and east longitude $74^{\circ}40'$ and flows for a total length of 81 km in a southerly direction to join the Narmada from the right, near Kakrana. It drains a total area of 1,943 sq. km.

The Orsang rises in the Vindhya range of the Jhabua district of Madhya Pradesh, near Bhabra village at an elevation of 300 m, at north latitude 22°30' and east longitude 74°18' and flows for a total length of 101 km in a south-westerly direction to join the Narmada from the right, near Chanded. It drains a total area of 4,079 sq. km. and is next size to the Hiran, among the right bank tributaries.

Table 3: Major Tributaries of Narmada River

Name of Tributory	Bank	Length of Tributary (km.)	Catchment area in km²	Distance of confluence of Narmada from source (km.)
Burhner	Left	176	4070	246
Banjar	Left	182	3584	285
Hiran	Right	187	4480	461
Sher	Left	128	2867	494
Shakkar	Left	160	2266	542
Dudhi	Left	128	1523	571
Tendoni	Right	117	1613	598
Barna	Right	104	1766	602
Tawa	Left	171	6259	672
Kolar	Right	101	1331	709
Ganjal	Left	89	1907	752
Chota Tawa	Left	168	4992	824
Kundi	Left	120	3776	938
Man	Right	88	1510	992
Uri	Right	74	1792	1029
Goi	Left	128	1869	1032
Orsang	Right	80	4032	1184
Karjan	Left	93	1472	1192

4.2 Narmada Basin

The Narmada basin extends over an area of 98,796 sq.km. and lies between latitudes 21°20' N to 23°45'N and longitudes 72°32'E to 81°45' E. The statewise distribution of the drainage area is as follows:

State	Drainage Area
Madhya Pradesh	85,859 sq.km.
Gujarat	11,399 sq.km.
Maharashtra	1,538 sq.km.

The basin is bounded on the North by the Vidhyas, on the east by the Maikala range on the south by the Satpuras and on the west by the Arabian sea. Most of the basin is at an elevation of less than 500 m.a.s.l. A small area around Pachmarhi is at a height of more than 1000 m.a.s.l.

4.2.1 Climate:

The climate of the basin is humid tropical ranging from sub-humid in the east to semi arid in the west with pockets of humid or sub-humid climates around hill reaches. The normal annual rainfall for the basin works out to 1,178 mm. South West monsoon is the principal rainy season accounting for nearly 90% of the annual rainfall. About 60% of the annual rainfall is received during July and August months.

4.2.2 Soils:

The reconnaisance soil survey made by Central Water and Power Commission in connection with the Bargi, Punasa, Barna and Tawa projects indicated that the Narmada basin consists mainly of black soils. The different varieties are deep black soil, medium black soil and shallow black soil. In addition mixed red and black soil, red and yellow soil and skeletal soil are also observed in pockets; of these deep black soil coveres and major portion of the basin.

4.2.3 Land use

- About 32% of the area of the basin is under forest and about 60% under arable land and remaining under grassland, waste land etc.

4.3 Existing Stream Gauging Network in Narmada Basin

Systematic observations of gauge and discharge were started in Narmada basin in 1947 by the then central Waterway, Irrigation and Navigation Commission. The river Narmada is gauged at various sites by Central Water Commission and State Irrigation Departments of Madhya Pradesh and Gujarat. As per information available in the report entitled 'Annual Water Account of Narmada Basin upto Sardar Sarovar Dam Site-Water Year 1985-86' by Narmada Control Authority there exist 33 stream-gauging sites in Narmada basin. The main river Narmada is gauged at 11 sites while there exist 22 sites on its various tributaries. The list of existing stream-gauging station in Narmada basin is given below:-

S.No.	Name of river/tributary	Name of site	Agency by which maintained
Upper Zone			
1.	Narmada Main	Manot	CWC
2.	Burhner	Mohegaon	CWC
3.	Banjar	Hridayanagar	CWC
4.	Narmada Main	Mandla	State
5.	Narmada Main	Jamtara	CWC
Middle Zone			
6.	Hiran	Patan	CWC
7.	Sher	Belkheri	CWC
8.	Narmada Main	Barman	CWC
9.	Shakkar	Shakkar	State
10.	Shakkar	Gadarwara	CWC
11.	Narmada Main	Sandia	CWC
12.	Barna	Sultanpur	State
13.	Bagra Tawa	Bagra Tawa	CWC
14.	Narmada Main	Hoshangabad	CWC
15.	Kolar	Kolar Dam Site	State
16.	Ganjal	Chidgaon	CWC
17.	Narmada Main	Handia	CWC
18.	Jamner	Sandalpur +	CWC(New)
19.	Barna	Bareilly *	CWC(New)

S.No.	Name of river/tributary	Name of site	Agency by which maintained
20.	Tendoni	Maheshwar*	CWC(New)
Lower Zone			
21.	Chhota Tawa	Ginnore	CWC
22.	Narmada Main	Mortakka	State
23.	Choral	Choral	State
24.	Upper Beda	Upper Beda	State
25.	Kundi	Kogaon	CWC
26.	Narmada Main	Mandleshwar	CWC
27.	Karam	Karam	State
28.	Man	Ajandiman*	CWC(New)
29.	Narmada Main	Rajghat	CWC
30.	Uri	Rampura	State
31.	Goi River	Silawad	State
32.	Hatni River	Tikola	CWC
33.	Narmada Main	Garudeshwar	CWC

Note: 1. * New CWC Gauging stations (GDS) installed during the year 1984-85.

2. * Sandalpur GDS station installed by CWC in January 1987 only.

5.0 METHODOLOGY

As discussed in the previous report on 'Procedure for Hydrological Network Design (NIH, 1986-87), Physical-Statistical Method combined with zonal characteristics approach suggested by Karasseff (1972) and applied for Network design of streamgauges for water resources assessment of Krishna basin by Rao et al. (1983) has been applied for available data of some of the gauging stations of Narmada basin. For determination of stream gauge network 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.

Following three types 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 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 runoff.

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

This method, while determining the basic required network, stipulates the levels of errors and variabilities for which the network is valid. The procedure for application of physical statistical method of stream gauge network design involves the following procedure, when annual series of flow is available at two gauging sites on the river with area of basin upto the concerned site and the distance between the two sites. The areal distribution of runoff Q, may be taken to be made up of two components, one is the normal runoff and other is the deviation from normal, which can be expressed as:

$$Q_{i,j} = \bar{Q}_i + Z_{i,j} \qquad \ldots(1)$$

where $\bar{Q}_i$ is long term average runoff of N years at i^{th} observational point, and $Z_{i,j}$ is the deviation from the normal runoff in j^{th} year and at i^{th} observation point. The principle of hydrological regionalisation is applied to bring the stream flow field to homogeneous conditions. For such hydrological region, values of long term average runoff $\bar{Q}_i$, at i^{th} observational points, coefficient of variation of runoff, C_v are required to be computed. The dispersion of annual stream flow is given by:

$$\sigma_i^2 = \frac{1}{N} \sum_{j=1}^{N} (Q_{i,j} - \bar{Q}_i)^2$$

$$= (C_v \bar{Q}_i)^2 \approx \text{constant} \qquad \ldots(2)$$

where C_v is the coefficient of variation of runoff. Considering the term $\bar{Q}_i$, which gives normal runoff. The average of annual mean flows at two sites distance S apart is computed as:

$$\bar{m} = 0.5\,(\bar{Q}_i + \bar{Q}_{i+s}) \qquad \ldots(3)$$

The variation of normal runoff over the whole area characterised by the streamflow gradient:

$$\text{Grad}(\bar{Q}) = \frac{\bar{Q}_{i+s} - \bar{Q}_i}{S} \qquad \ldots(4)$$

The relative gradient can be computed as Grado $(\bar{Q}) = \frac{\text{Grad}(\bar{Q})}{m}$

...(5)

Now considering the term $Z_{i,j}$ of the equation (1) the correlation coefficient can be written as:

$$r = \frac{\sum_{j=1}^{N} Z_{i,j} \cdot Z_{i+s,j}}{N\, \sigma_i \cdot \sigma_{i+s}} \qquad \ldots(6)$$

where i and i+s are standard deviations at two stream gauging stations separated by distance S.

$$r = \frac{C_q}{\sigma_i \quad \sigma_{i+s}}$$

, where C_q is the co-variance term

$$r = \frac{C_q}{(C_v \cdot \bar{Q}_i)^2}$$

in view of assumption i=i+s

r can be expressed as

$$r = 1 - a.s$$

where, $a = 1/S_o$, S_o is the radius of correlation at which correlation function has the zero value. From values of r and S, the value of S_o is determined as:

$$r = 1 - as = 1 - \frac{S}{S_o}$$

or

$$S_o = \frac{S}{1-r} \qquad \ldots(7)$$

For the reliability of stream flow data, two conditions are given corresponding to two terms of equation(1)

(i) The criterion with regard to spatial variation of normal streamflow.

ii) The criterion on interpolation of stream flow data at intermediate points for an individual year.

The above two conditions represent the two terms on the RHS of equation (i), thus satisfying it.

Gradient Criterion

The first criterion corresponds to the determination of confidence interval for the estimation of normal streamflow at the mid point of the distance between the centres of the two regions.

The error for the estimation of normal stream flow at the mid point is given by:

$$\sigma^2_{mean} = \frac{1}{N} \sum_{j=1}^{N} \left(\frac{Q_{i+s,j} + Q_{i,j}}{2}\right) - \left(\frac{\bar{Q}_{i+j} + \bar{Q}_i}{2}\right)^2$$

$$= \tfrac{1}{4}(\sigma^2_i + \sigma^2_{i+s} + 2\sigma_i \cdot \sigma_{i+s} \cdot r_s)$$

$$= \frac{\sigma^2_i}{2}(1+r_s) \qquad ...(8)$$

In view of assumption in equation (2). Confidence interval at P = 0.95 assuming normal distribution is

$$= 1.96 \frac{\sigma_i}{\sqrt{2}} \frac{\sqrt{1+rs}}{\sqrt{N}}$$

$$= \frac{1.96}{\sqrt{2}} \frac{C_v}{\sqrt{N}} \sqrt{1+r_s} \; Q_i$$

$$= \frac{1.96}{\sqrt{2}} \sigma_o \bar{Q} \qquad ...(9)$$

where, σ_o is the relative error and N is the number of years of record.

The condition of sufficiency of streamflow-gradient between two observational points is given by:

$$S_{gr} \geqslant \frac{2.82 \; \bar{m}}{grad(\bar{Q})} \qquad ...(10)$$

This criterion expresses the minimum distance S to determine the stream flow variation caused by zonal characteristics.

Correlation Criterion

The correlation criterion for network density depends upon the maximum error of interpolation of streamflow values for individual years for a basin situated at middle of S. The interpolation is assumed to be the same as the error of stream flow estimation and is given by:

$$= \frac{1}{N} \sum_{j=1}^{N} (Q_{i,j} - Q_{i+s,j}) - (\bar{Q}_i - \bar{Q}_{i+s})^2$$

$$= \frac{1}{N} \sum_{i=1}^{N} (Q_{i,j} - \bar{Q}_i) - (Q_{i+s,j} - \bar{Q}_{i+s})^2$$

$$= \frac{1}{N} \sum_{j=1}^{N} Z^2_{i,j} + \sum_{j=1}^{N} Z^2_{i+s,j} - 2 \sum_{j=1}^{N} Z_{i,j} \; Z_{i+s,j}$$

$$= \sigma_i^2 + \sigma_{i+s}^2 - 2 \, r_s \, \sigma_i \quad \sigma_{i+s}$$

$$= 2Cv^2 \, \bar{Q}_i \; (1 - r_s)$$

$$\text{or } C_s^2 = 2Cv^2 \; (1 - r_s) \qquad \ldots(11)$$

The empirical structure function is given by:

$$C_s^2 = 2C^2v \; (1 - r_s) + 2C_o^2$$

$$= 2C_v^2 \; (a.S) + 2 \, C_o^2$$

$$C_{s12}^2 = \left(\frac{C_s}{2}\right)^2 + \frac{2C_v^2 \; (a.S) + 2C_o^2}{4}$$

$$\text{or} \quad C_{s12} = 1/2 \; (C_v^2 \; a.S. + C_o^2)^{\frac{1}{2}} \qquad \ldots(12)$$

since, C_o and σ_o are inter-related and taking S as S_c at zero correlation,

$$\text{Then, } C_v^2 \, a \, S_c + \sigma_o^2 = 0$$

This satisfies the condition:

$$S_c \leq \frac{\sigma_o^2}{aC_v^2} \qquad \ldots(13)$$

Considering F_{gr} and F_c as limiting areas of the gradient function and correlation function, we get

$$F_{gr} = 8 \left(\frac{\sigma_o}{\text{Grad}_o \, Q}\right)^2 \qquad \ldots(14)$$

$$F_c = \frac{\sigma_o^4}{a^2 \, Cv^2} = \frac{\sigma_o^4}{C_v^4} (S_o)^2 \qquad \ldots(15)$$

assuming the following relationships:

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

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

Where L is the length of river, F is the drainage area and S is the distance between two gauging stations. The optimum area for determining the stream gauge density, therefore will be minimum of F_{gr} and F_c.

5.1 Data Used

Available mean annual flow data of nine years for the period 1975-76 to 1984-85 (excluding the year 1977-78) of the five gauging sites namely, Jamtara, Barmanghat, Mandleshwar, Rajghat, and Garudeshwar have been used to find out requirement of network (catchment area in km² represented by one stream gauging site). The data of following reaches of the river Narmada considering pairs of gauging sites were analysed.

Case-1 : Barmanghat and Mandleshwar

Case-2 : Barmanghat and Rajghat

Case-3 : Barmanghat and Garudeshwar

Case-4 : Jamtara and Mandleshwar

Case-5 : Jamtara and Rajghat

Case-6 : Jamtara and Garudeshwar

For studying the effect of length of data series, available annual mean flow data of thirty six years for the period 1949-50 to 1985-86 (excluding the year 1973-74) for Jamtara and Garudeshwar sites has been used. The variation of mean annual flows with distance from origin of river Narmada of various sites considered, for the nine years period as well as thirty six years period has been shown in fig.2. Annual mean flows for thirty six years period of Jamtara and Garudeshwar gauging sites have been shown in fig. 3. Catchment area represented by one gauging station has also been determined for different lengths of the samples viz. 9 years, 25 years, 30 years and 36 years; using the 36 year period data of Jamtara and Garudeshwar gauging sites for the following cases:

Case-7 : 28 samples each sample of 9 years period

Case-8 : 12 samples each sample of 25 years period

Case-9 : 7 samples each sample of 30 years period

Case-10 : 1 sample of 36 years period

The details of specific years constituting alternative samples of various lengths for case-7 to case-10 are given in Table-4.

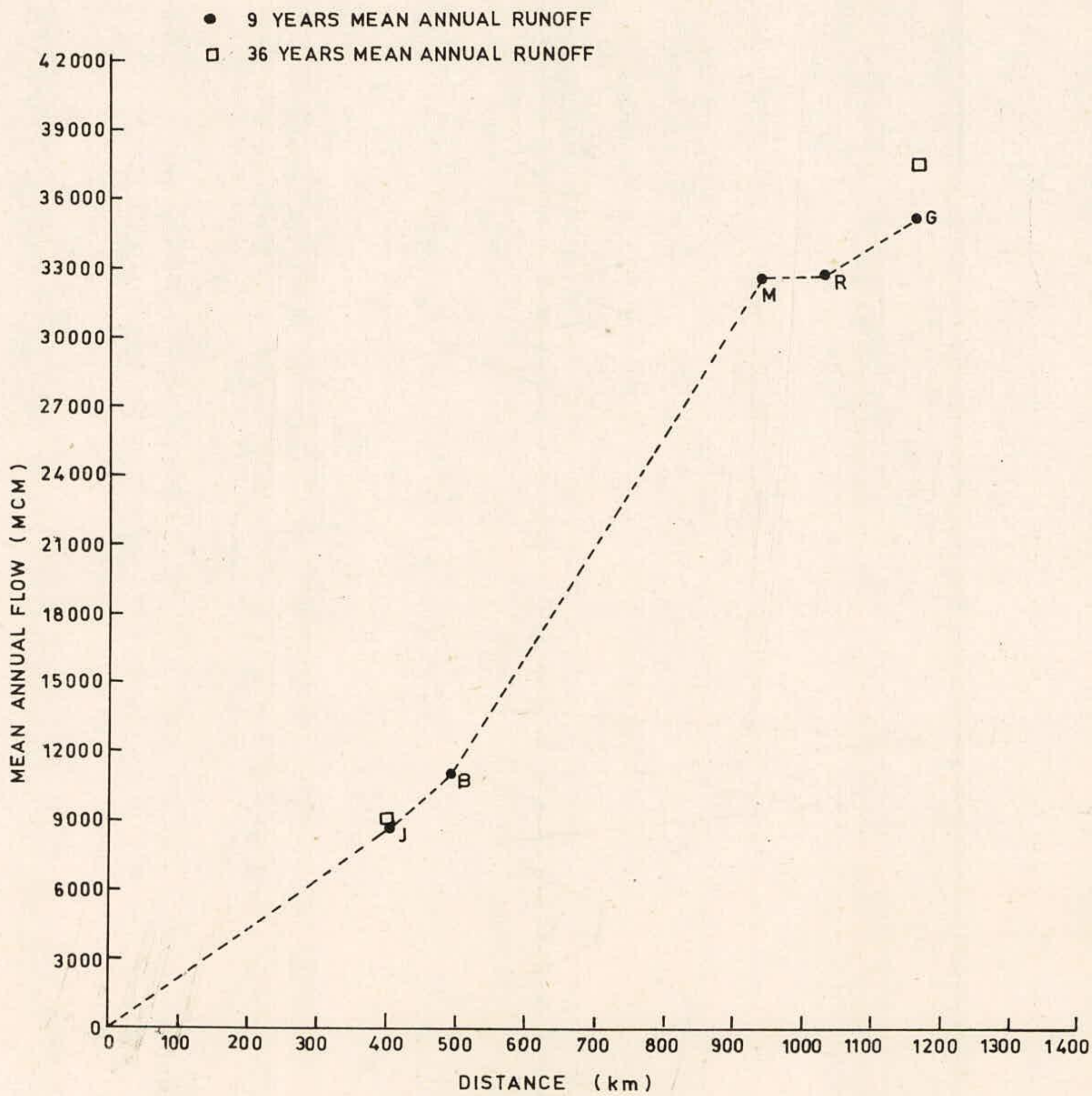

FIG. 2. VARIATION OF MEAN ANNUAL FLOW WITH DISTANCE FROM ORIGIN OF NARMADA

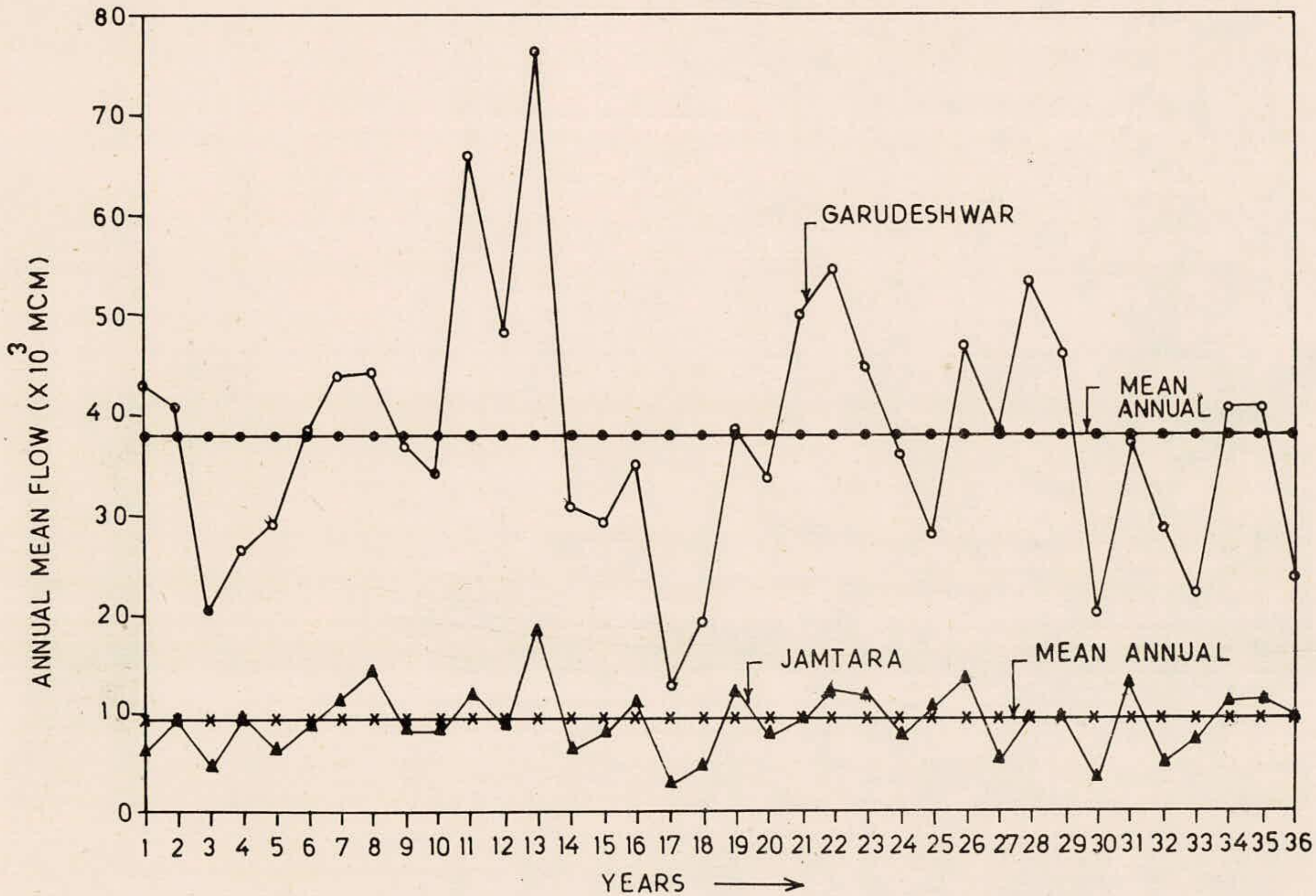

FIG. 3. ANNUAL MEAN FLOWS AT JAMTARA AND GARUDESHWAR (36 YEARS DATA)

TABLE 4 : PERIOD OF VARIOUS SAMPLES FORMED OUT OF 36 YEARS DATA

S.No.	Case No.	Length of samples	Number of samples	Period of samples
1.	7	9	28	(1). 1949-50 to 1957-58, (2). 1950-51 to 1958-59, (3). 1951-52 to 1959-60, (4). 1952-53 to 1960-61, (5). 1953-54 to 1961-62 (6). 1954-55 to 1962-63, (7). 1955-56 to 1963-64, (8). 1956-57 to 1964-65, (9). 1957-58 to 1965-66, (10). 1957 --58 to 1966-67, (11). 1958-59 to 1967-68 (12). 1959-60 to 1968-69, (13). 1960-61 to 1969-70, (14). 1961-62 to 1970-71, (15). 1962-63 to 1971-1972, (16). 1963-64 to 1972-73, (17). 1964-65 to 1974-75, (18). 1965-66 to 1975-76, (19). 1966-67 to 1976-77, (20). 1967-68 to 1977-78 (21) 1968-69 to 1978-79, (22). 1969-70 to 1979-80, (23). 1970-71 to 1980-81, (24). 1971-72 to 1981-82, (25) 1972-73 to 1982-83, (26). 1974-75 to 1983-84, (27). 1975-76 to 1984-85, (28). 1976-77 to 1985-86.
2.	8	25	12	(1). 1949-50 to 1974-75, (2). 1950-51 to 1975-76, (3). 1951-52 to 1976-77, (4) 1952-53 to 1977-78, (5). 1953-54 to 1978-79, (6). 1954-55 to 1979-80, (7). 1955-56 to 1980-81, (8). 1956-57 to 1981-82, (9). 1957-58 to 1982-83, (10). 1958-59 to 1983-84, (11). 1959-60 to 1984-85, (12). 1960-61 to 1985-86
3.	9	30	7	(1). 1949-50 to 1979-80, (2) 1950-51 to 1980-81, (3). 1951-52 to 1981-82, (4). 1952-53 to 1982-83 (5). 1953-54 to 1983-84, (6). 1954-55 to 1984-85 (7). 1955-56 to 1985-86.
4.	10	36	1	1948-49 to 1985-86

5.2 Location of Stream-Gauging Stations

Selection of site for location of stream gauge stations is no less important then determining the density of the stream-gauging network. For the location of stream gauging stations 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 (usuallly 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 hydromatric 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.

Some of the points which need special consideration and are highlighted by Hiranandani and Chitale (1964) for selecting a gauge site are summarised below:

(i) The river bank and bed should be reasonably straight and stable both upstream and downstream of the gauge site for a distance of atleast 4 times the normal width of the river at high flood or 0.8 km whichever is less. The river in this reach should be free from continuous aggradation or degradation.

(ii) The reach both upstream and downstream of the gauge site should be free from sudden changes in water surface and bed slopes.

(iii) The water level in the reach should not preferably be affected by backwater effect from any structure.

(iv) Water level at the gauge site should not be affected on account of a falling curve obtained over a weir or barrage crest or immediately below a constricted bridge. It is recommended that when the gauge is located downstream of a structure, a minimum distance between the gauge and structure should be kept 4 times the width of the section at high flood level in case of small streams. In case of big rivers length of 0.8 km. below a weir or bridge may be considered adequate.

(v) When situated near a confluence, its minimum distance upstream from the confluence point on either of streams should be such that the backwater or disturbances due to floods in the other stream would not affect the gauge, even in low flow conditions.

(vi) Gauges at railway bridges should be located at points where highest water level will be obtained.

(vii) Sites at which there is tendency for the formation of vortices, return flow or local disturbances should be avoided

(viii) The site should not be unduely exposed to wind.

(ix) The chosen site should be easily accessible and should have clear and dependable approach during all times of the year.

(x) The site should be such that water flows in a single channel and does not overflow banks. If over bank spills are unavoidable these should be limited to minimum. Where single channel is not available, two or more channels satisfying these conditions should be used.

(xi) Availability of easy and cheap facilities for transport of construction materials, equipment and personnel should not be lost in choosing a stream gauging site.

6.0 ANALYSIS AND RESULTS

The optimal catchment area per gauging station in Narmada basin considering the different reaches between pairs of stations for the ten cases as discussed earlier, have been computed. The details of computations carried out for determining the optimal area for gauging station, for the reach between Jamtara and Garudeshwar using 36 years mean annual stream flow data (case-10) are as follows:

6.1 Computation for Determination of Optimal Gauging Area

For determination of representative catchment area per stream gauging station for reach between Jamtara and Garudeshwar (Case-10) following steps are involved:

Step-1 Compute mean annual flow at Jamtara as:

$$Q_J = 9003.334 \text{ million cubic meter(mcm)}$$

Step-2 Compute mean annual flow at Garudeshwar as:

$$Q_G = 37438.992 \text{ mcm}$$

Step-3 Compute average of mean annual flow at Jamtara and Garudeshwar as:
(Eqn. 3)

$$\bar{m} = 0.5\ (9003.334 + 37438+37438.992) \text{ mcm}$$

$$= 23221.163 \text{ mcm}$$

Step-4 Compute streamflow gradient as(Eqn.4) $Grad(\bar{Q}) = \frac{\bar{Q}_G - \bar{Q}_J}{S}$

S = 772 km, is the length of the river between Jamtara and Garudeshwar

$$Grad(\bar{Q}) = \frac{37438.992 - 9003.334}{772} \text{ mcm/km}$$

$$= 36.833754 \text{ mcm/km}$$

Step-5 Compute the relative streamflow gradient as (Eqn. 5)

$$\text{Grad}_o(\bar{Q}) = \frac{\text{Grad}(\bar{Q})}{\bar{m}}$$

$$= \frac{36.833754}{23221.163}$$

$$= 1.58624 \times 10^{-3} \text{ mcm/km}$$

Step-6 Compute the correlation coefficient between annual flows at Jamtara and Garudeshwar as (Eqn. 6)

$$r = 0.719$$

Step-7 Compute the radius of correlation function as(Eqn.7)

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

$$= \frac{772}{1 - 0.719} \text{ km}$$

$$= 2747.331 \text{ km.}$$

Step-8 Compute area of gradient function as (Eqn. 14)

$$F_{gr} = 8 \left(\frac{\sigma_o}{\text{Grad}_o \bar{Q}}\right)^2$$

For a relative error of 5%, $\sigma_o = 0.05$

$$F_{gr} = 8 \left(\frac{0.05}{1.58624 \times 10^{-3}}\right)^2 \text{sq.km.}$$

$$= 7948.88 \text{ sq.km.}$$

Step-9 Compute coefficient of variation of annual mean flows at Jamtara and Garudeshwar as

$$C_{vJ} = 0.374$$

$$C_{vG} = 0.350$$

Step-10 Compute area of correlation function for coefficient of variation of annual mean flow = 0.374 at Jamtara as (Eqn. 15):

$$F_{c(J)} = \frac{\sigma_o^4}{C_v^4}(S_o)^2 = \frac{(0.05)^4}{(0.374)^4}(2747.331)^2$$

$$= 2411.10 \text{ km}^2$$

Step-11 Compute area of correlation function for coefficient of variation of annual flow = 0.35 at Garudeshwar as (Eqn. 15)

$$F_{c(G)} = \frac{\sigma_o^4}{C_v^4}(S_o)^2$$

$$= \frac{(0.05)^4}{(0.35)^4}(2747.331)^2 \text{ km}^2$$

$$= 3143.62 \text{ km}^2$$

Step-12 Minimum value out of area of gradient function, F_{gr} = 7948.88 sq.km, area of correlation function $F_{c(J)}$ = 2411.10 and $F_{c(G)}$ = 3143.62 km^2, which is = 2411.10 sq.km. is the optimal catchment area per stream gauging station considering the reach between Jamtara and Garudeshwar (Case-10).

Variation of values of F_{gr} and F_c with coefficient of variation and relative error for this case is given in Table-5. Following the above mentioned steps the values of F_{gr} and F_c have been computed for the six cases of available 9 years data (Case-1 to Case-6) for relative error of 5% and coefficient of variation of annual mean flows at the respective sites of the six cases. The values of F_{gr} and lower value of F_c with respect to coefficient of variation at either of the sites for these cases are given in Table-6.

6.2 Analysis of Multiple Samples

Cases of multiple samples consisting of sample lengths 9, 25, 30 and 36 years formed out of 36 years mean annual flow data of Jamtara and Garudeshwar have been considered to determine catchment area per stream gauging station. Table-7 shows the annual mean values, coefficients of variation and correlation coefficients of the flows at Jamtara and Garudeshwar for 28 samples of 9 years period. Fig. 4 shows the coefficients of variation of mean annual flows and correlation coefficient for 28 samples of 9 years sample length. Table-8 and Table-9 show the annual mean flows, coefficients of vriation and correlation for samples of 25 and 30 years lengths respectively.

To reduce the computational work, F_{gr} and F_c values for determining the gauging area per stream gauging station, computations have been carried out for the samples having median value of annual mean flow at Jamtara and corresponding sample at Garudeshwar and the samples having median value of annual mean flow at Garudeshwar and corresponding sample at Jamtara. Similarly for the samples of annual mean flows having highest and lowest mean values, at one site and the corresponding samples at the other site. The sample considered for computing F_{gr} and F_c values out of various possible samples have been shown by (*) in Table-7 through Table-9.

6.3 Variability of Estimates of Area per Station

The variability of catchment area per station with river basin area covered by the concerned reach was examined as shown in fig. 5. There is considerable scatter, but somewhat decreasing trend is indicated i.e. as the basin area for the river reach increases catchment area per station decreases.

Variability of catchment area per stream gauging station with length of sample has also been studied for sample lengths of 9,25,30 and 36 years (case-7 to case-10) and the results have been given in Table-10. Table 11 summarises the average values of F_{gr} and F_c for different sample lengths. It is seen that representative catchment area per station varies with sample length in an inverse manner. The plot between these two variables given in fig.6, clearly shows a systematic linear pattern.

TABLE 5

Variation of Values of F_{gr} and F_c for reach between Jamtara & Garudeshwar with Coefficient of variation and relative error (Case-10)

S.No.	C_v	σ_o	F_{gr} (km)²	F_c (km)²
1.	.20	.03	2861.59	3821.00
		.04	5087.28	12076.52
		.05	7948.88	29483.70
		.10	31795.55	471739.21
2.	.25	.03	2861.59	1565.11
		.04	5087.28	4946.54
		.05	7948.88	12076.52
		.10	31795.55	193224.38
3.	.30	.03	2861.597	754.78
		.04	5087.284	2385.48
		.05	7948.881	5823.94
		.10	31795.552	93183.05
4.	.35	.03	2861.59	407.41
		.04	5087.28	1287.62
		.05	7948.88	3143.61
		.10	31795.55	50297.89
5.	.40	.03	2861.59	238.81
		.04	5087.28	754.78
		.05	7948.88	1842.73
		.10	31795.55	29483.70
6.	.45	.03	2861.59	149.09
		.04	5087.28	471.20
		.05	7948.88	1150.40
		.10	31795.55	18406.52

TABLE 6: CATCHMENT AREA REPRSENTED BY ONE STREAM GAUGING STATION FOR VARIOUS REACHES

S.No.	Case No.	Reach between stream gauging stations	River reach (km)	Basin area of reach (km^2)	F_{gr} (km^2)	F_c (km^2)	Optimal gauging area per station (minimum of F_{gr} & F_C) (km^2)
1.	1	Barmanghat-Mandleshwar	437	47693	3928.42	9126.88	3928.42
2.	2	Barmanghat-Rajghat	524	57859	4011.17	5169.83	4011.17
3.	3	Barmanghat-Garudeshwar	667	62933	8265.60	3274.99	3274.99
4.	4	Jamtara-Mandleshwar	542	57155	4358.89	4269.74	4269.74
5.	5	Jamtara-Rajghat	629	67321	5823.61	3839.59	3839.59
6.	6	Jamtara-Garudeshwar	772	72395	8115.76	1221.06	1221.06

TABLE 7: ANNUAL MEAN FLOWS, COEFFICIENTS OF VARIATION AND CORRELATION FOR VARIOUS SAMPLES OF 9 YEARS LENGTH (CASE-7)

Sample No.	Annual Mean Flows(mcm)		Coefficients of variation		Correlation coefficient	Remarks (Mean annual flow)
	Jamtara	Garudeshwar	Jamtara	Garudeshwar		
1.	2.	3.	4.	5.	6.	7.
1.	8661.64	35703.13	0.345	0.240	0.592	
2*	8877.23	34697.01	0.320	0.235	0.774	A:Median-1(Jamtara)
3*	9161.77	37508.95	0.328	0.353	0.709	B:Median-1(Garudeshwar)
4.	9574.85	40617.05	0.263	0.292	0.526	
5*	10530.38	46132.63	.368	.335	.824	
6*	10505.03	46307.65	.372	.329	.821	C:Highest(Jamtara)
7.	10433.49	45270.43	.380	.356	.824	D:Highest(Garudeshwar)
8.	10406.22	44284.46	.380	.373	.795	
9.	9112.71	40794.94	.482	.481	.901	
10.	8733.62	38844.94	.531	.539	.912	
11.	9203.71	39332.98	.517	.530	.881	
12.	8748.65	35728.62	.535	.513	.911	
13.	8829.11	35898.15	.529	.514	.918	
14*	8121.08	33497.52	.410	.396	.829	
15.	8770.58	35054.04	.388	.390	.850	
16.	8747.14	35832.65	.390	.376	.842	
17.	8675.18	35044.99	.388	.393	.805	
18.	9878.20	38831.93	.288	.290	.695	
19.	9927.84	40948.75	.277	.207	.413	
20.	9583.69	42573.52	.273	.217	.405	
21.	9716.18	43923.34	.261	.197	.330	
22*	9050.91	40585.76	.374	.283	.657	F:Median-2(Jamtara)
23*	9160.43	38592.25	.383	.266	.516	G:Median(Garudeshwar)

1.	2.	3.	4.	5.	6.	7.
24.	8396.21	36773.54	.433	.287	.296	
25.	8338.70	35194.09	.438	.332	.542	
26.	8407.72	36587.02	.440	.312	.631	
27.	8148.96	35895.84	.413	.304	.582	
28.	3690.24	34259.12	.368	.340	.545	

* Sample selected for further analysis.

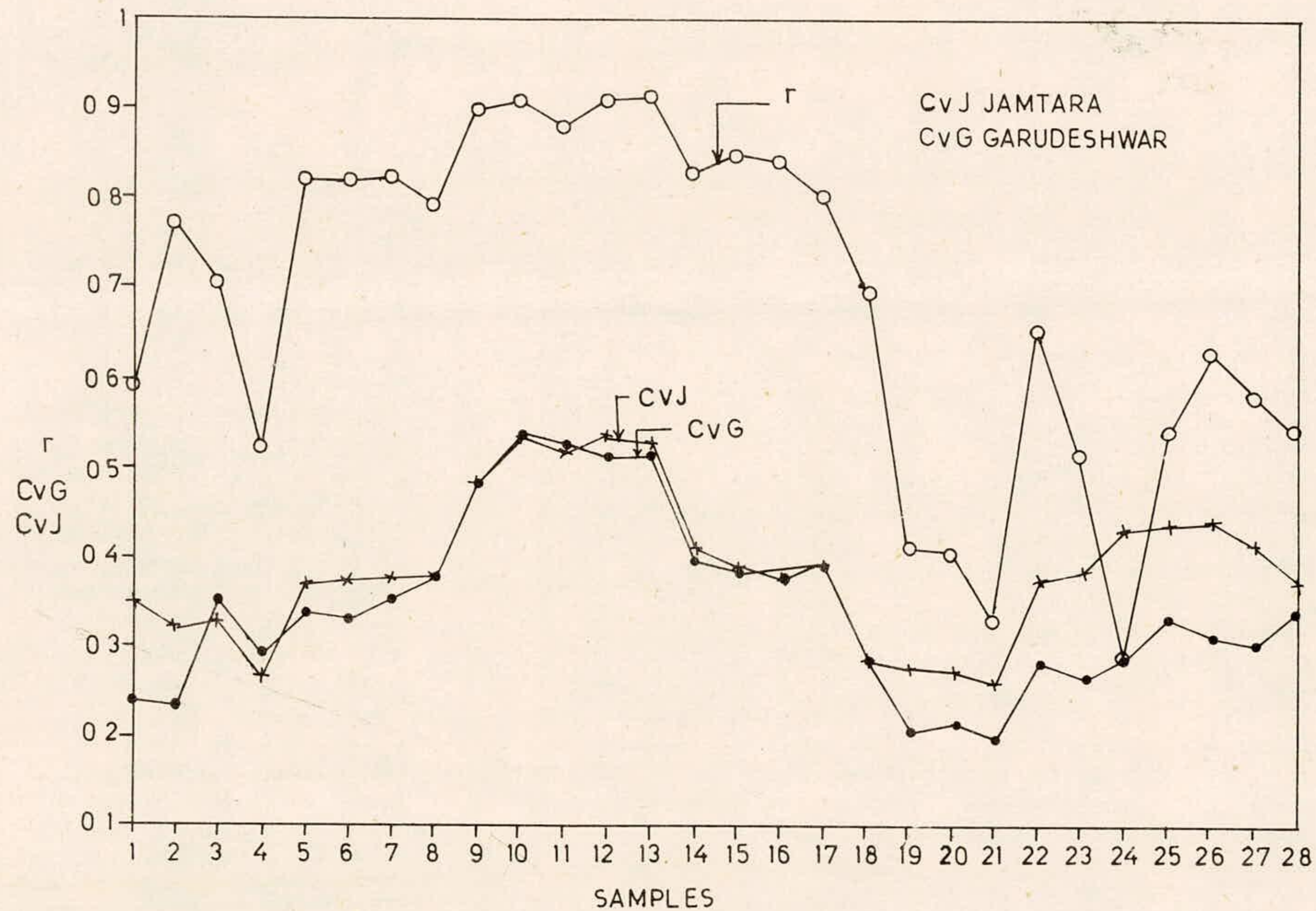

FIG. 4 COEFFICIENTS OF VARIATION AND CORRELATION FOR SAMPLES OF 9 YEARS DATA OF JAMTARA AND GARUDESHWAR FORMED FROM 36 YEARSDATA

TABLE 8: ANNUAL MEAN FLOWS, COEFFICIENTS OF VARIATION AND CORRELATION FOR SAMPLES OF 25 YEARS LENGTH (CASE-8)

Sample No.	Annual Mean Flows (mcm)		Coefficients of Variation		Correlation coefficients	Remarks (Mean annual flow)
	Jamtara	Garudeshwar	Jamtara	Garudeshwar		
1*	9092.036	38196.098	0.374	0.367	0.783	A:Lowest(Garudeshwar)
2.	9390.724	38344.363	0.367	0.368	0.811	
3*	9224.558	38238.051	0.385	0.369	0.789	B:Median-1(Jamtara)
4.	9405.781	39547.363	0.384	0.351	0.753	
5*	9369.640	40315.125	0.305	0.338	0.768	C:Highest(Garudeshwar)
6.	9248.012	39942.742	0.388	0.358	0.785	
7*	9430.671	39873.840	0.389	0.353	0.757	D:Highest(Jamtara)
8*	9170.155	39250.926	0.409	0.363	0.764	E:Median-2(Jamtara)
9*	8880.455	38361.918	0.407	0.382	0.777	F:Lowest(Jamtara)
10.	9000.625	38514.297	0.404	0.380	0.774	
11*	9128.545	38775.934	0.401	0.377	0.770	G:Median-1(Garudeshwar)
12*	9054.807	37068.105	0.400	0.372	0.751	H:Median-2(Garudeshwar)

* Samples selected for further analysis.

TABLE 9: ANNUAL MEAN FLOWS, COEFFICIENTS OF VARIATION AND CORRELATION FOR SAMPLES OF 30 YEARS LENGTH (CASE-9)

Sample No.	Annual Mean Jamtara	Flows(mcm) Garudeshwar	Coefficients of Jamtara	Variation Garudeshwar	Correlation Coefficients	Remarks (Mean Annual flow)
1*	8899.207	38585.398	0.389	0.354	.764	A:Lowest (Jamtara)
2*	9131.803	38372.891	0.383	0.355	.761	B:Median (Garudeshwar)
3*	8984.27	37956.336	0.399	0.362	.765	C:Lowest (Garudeshwar)
4.	9067.470	38008.918	0.387	0.360	.752	
5*	9109.268	38469.840	0.387	0.351	.767	D:Median (Jamtara)
6*	9279.270	38852.793	0.377	0.345	.760	E:Highest (Garudeshwar)
7*	9329.580	38351.918	0.375	0.357	.736	F:Highest (Jamtara)

* Samples selected for further analysis

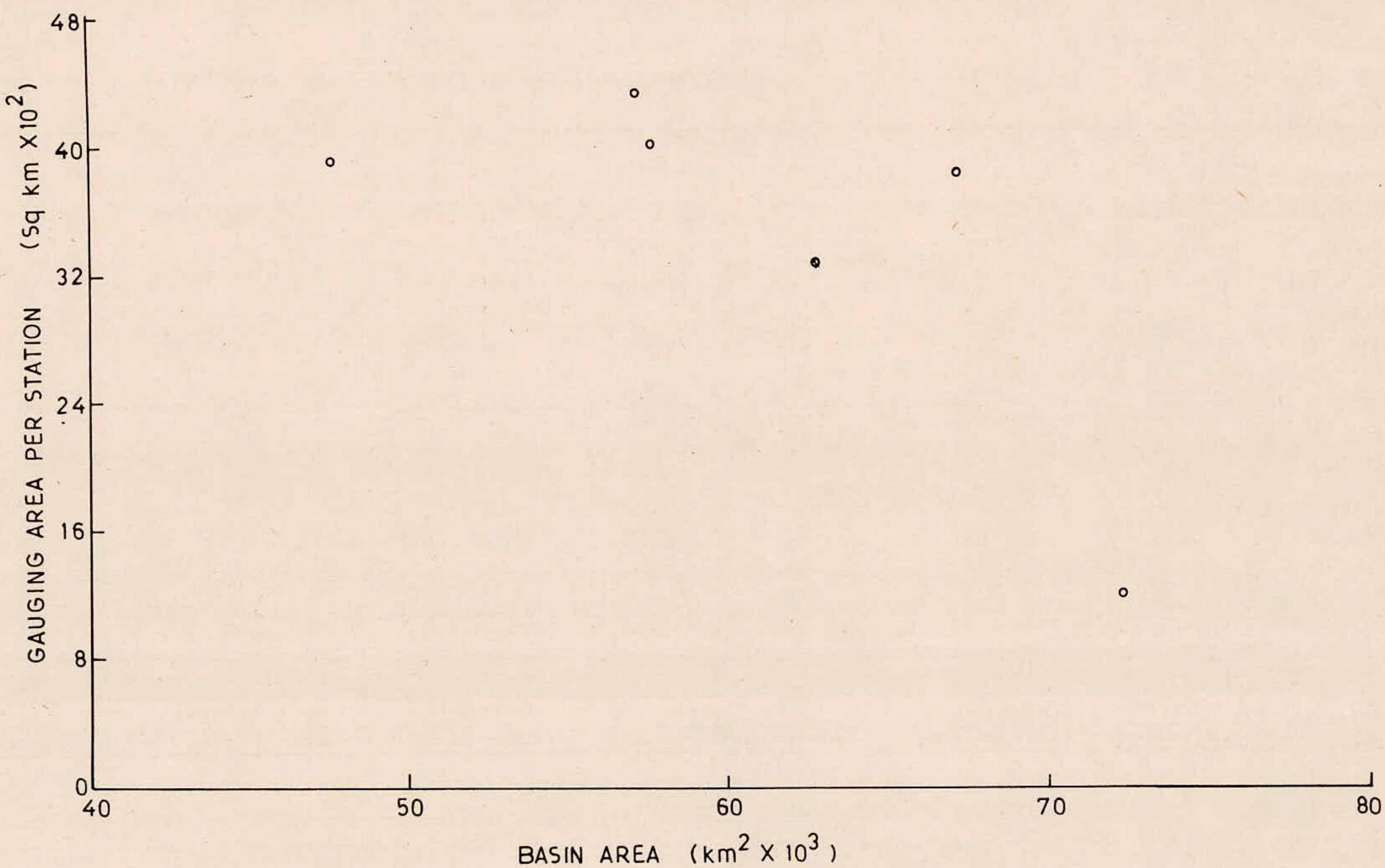

FIG 5 PATTERN OF VARIATION OF CATCHMENT AREA PER STREAM GAUGING STATION WITH BASIN AREA COVERED BY RIVER REACH.

TABLE 10: VALUES OF F_{gr} AND F_c FOR SELECTED SAMPLES OF DIFFERENT LENGTHS (IN km²)

S.No.	Sample name	Sample length 36 years (Case-10)		Sample length 30 years (Case-9)***		Sample length 25 yrs. (Case-8)**		Sample length 9 yrs (Case-7)*	
		F_{gr}	F_c	F_{gr}	F_c	F_{gr}	F_C	F_{gr}	F_C
1.	A	7948.88	2411.10	7624.33	2920.74	7866.87	4043.05	8487.09	6955.01
2.	B	-	-	7864.85	3030.57	7974.58	3808.09	7857.56	2832.89
3.	C	-	-	7822.45	2661.27	7681.68	3899.13	7548.30	6558.89
4.	D	-	-	7825.43	3058.86	7816.24	2920.74	7503.53	6070.67
5.	E	-	-	7893.46	3201.30	7721.39	2389.99	8008.34	4509.19
6.	F	-	-	8043.39	2702.60	7651.92	2896.86	7382.92	1618.23
7.	G	-	-	-	-	7780.00	2723.21	7844.51	738.97
8.	H	-	-	-	-	8078.11	2346.80	-	-
Average value		7948.88	2411.10	7845.65	2929.22	7821.36	3126.73	7804.61	4182.84

* As per Table-7

** As per Table-8

*** As per Table-9

Table 11: CATCHMENT AREA REPRESENTED BY ONE GAUGING STATION FOR VARIOUS SAMPLE LENGTHS

S.No.	Case No.	Length of sample (in yrs.)	No. of samples	F_{gr} (km²)	F_c (km²)	Optimal area per gauging station (minimum of F_{gr} & F_c) (km²)
1.	7	9	28	7804.61	4182.84	4182.84
2.	8	25	12	7821.36	3129.73	3129.73
3.	9	30	7	7845.65	2929.22	2929.22
4.	10	36	1	7948.88	2411.10	2411.10

6.4 Recommendations for Basic Network

As discussed in section 6.1, using 36 years data for Jamtara and Garudeshwar sites, optimal network density of 2411.10 sq.km. per station is obtained. The analysis of multiple samples as discussed in section 6.2 clearly shows effect of short sample length on network computations. With the data available for present study no clear pattern for variability of network density estimates with catchment area could be established. It is, therefore, recommended that primary network in Narmada basin could be designed assuming an optimal network density of 2411.10 sq.km. per station. This compares with WMO guidelines for flat regions i.e. 1000 to 2500 km² per station (see section 2.2.3).

The number of stream gauging stations for basin area covered between different reaches of river Narmada are computed

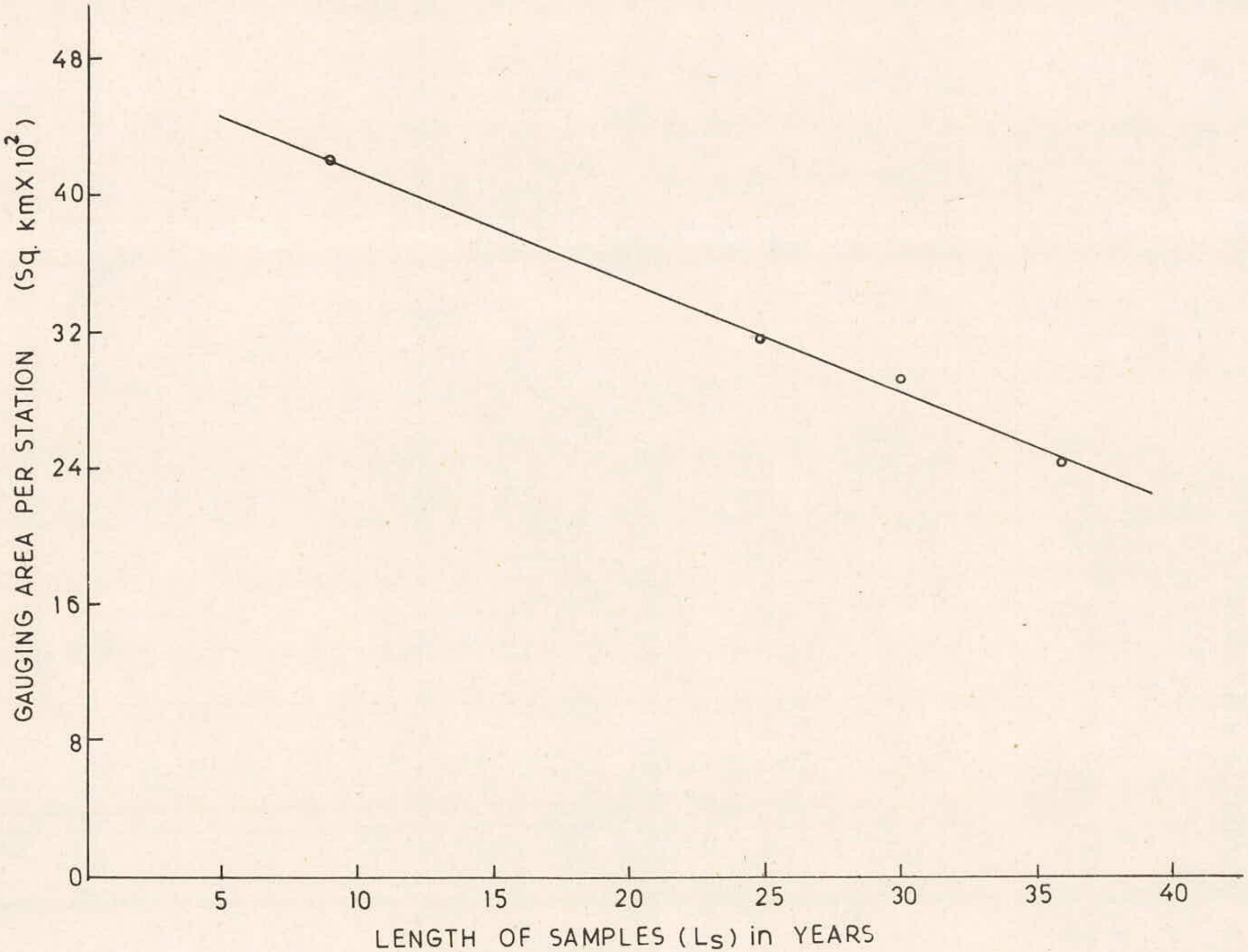

FIG. 6 VARIATION OF CATCHMENT AREA PER STATION WITH LENGTH OF SAMPLES

using the network density of 2411.10 km^2 per station and are given Table-12 and shown in Fig. 7. This does not include secondary and special purpose stations. Existing stations of CWC, MP and Gujarat States in Narmada basin upto Garudeshwar are 3 3 in number (see section 4.3).

TABLE 12: NUMBER OF STREAM GAUGING STATIONS FOR BASIN AREA COVERED BETWEEN VARIOUS RIVER REACHES

S.No.	River reach	Area(km^2)	Number of stream gauging stations
1.	Origin of Narmada to Jamtara	17157	7
2.	Jamtara to Barmanghat	9462	4
3.	Barmanghat to Mand-leshwar	47693	20
4.	Mandleshwar to Rajghat	10166	4
5.	Rajghat to Garudeshwar	5074	2
	Total	89552	37

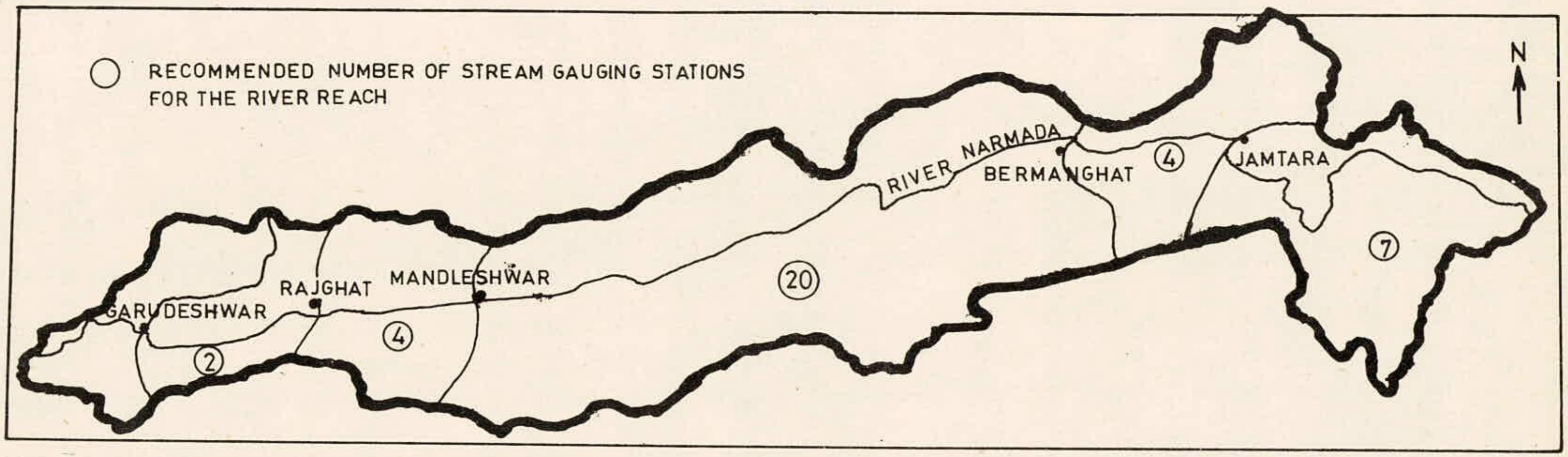

FIG. 7. RECOMMENDED NUMBER OF STREAM GAUGING STATIONS IN DIFFERENT REACHES OF NARMADA RIVER

7.0 CONCLUSIONS AND REMARKS

In the study presented here, the physical statistical method has been applied for determination of basic network of stream gauging stations for general water resources assessment of Narmada basin. The conclusions and recommendations of the study are given below:

(1) The physical-statistical method satisfies the conditions with regard to spatial variation of normal stream flows and interpolation of stream flow data at intermediate points for a individual year. It considers the coefficient of variation of annual mean flows at the respective sites, correlation coefficient between them, stream length between two gauging sites and permissible relative error.

(2) On the basis of this study with somewhat limited data a basic stream-gauging network density of one station per 2,411.10 sq. km. basin area could be recommended for Narmada basin upto Garudeshwar, excluding secondary and special purpose stations as obtained from 36 years data of Jamtara and Garudeshwar stations. Thus, on the basis of catchment area (89,552 sq.km.) upto Garudeshwar the basic network will comprise of around 37 stream-gauging stations on the main river and its tributaries. The specific locations of the stream gauging stations in various river reaches may be determined, keeping in view guidelines in para 5.2. As mentioned earlier (para 4.3)

the existing network in Narmada basin consists of a total number of 33 stream gauging sites out of which 5 sites are in its upper zone, 15 in middle zone and 13 in lower zone.

(3) It is observed that with variation of river basin area covered by the river reach, there is no systematic pattern of catchment area per stream-gauging station but there is general decrease from 3,928 km^2 to 1,221 km^2 as basin area between the reaches changes from 47,693 km^2 to 72,395 km^2.

(4) It is seen that as the sample length increases viz 9, 25, 30 and 36 years the catchment area per stream gaging station decreases viz 4,183;3,130; 2,929 and 2,411 sq.km. respectively.

(5) The statistical parameters obtained from short samples are not robust and sample length of about 30 years should be used.

(6) It is desirable to consider long term flow data of a number of river reaches between various stream-gauging stations in any study for network design.

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Types of Stream Gauging Stations

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

1.0 Primary stations (principal 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 accrate 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 measre 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.

2.0 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 enogh for a 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 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.

3.0 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 dring 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:

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 prposes, 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.

3.2 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 variation of the subsidiary (secondary) station network.