

1.0 THE NARMADA RIVER SYSTEM

1.1 The River

The Narmada river rises in the Amarkantak Plateau of Maikala range in the Shahdol district of Madhya Pradesh at an elevation of 1057 meters above mean sea level. 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. Again, 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. 1.1.

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 a 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 Dhaundhara falls, after which it flows through a narrow channel carved through the famous marble rocks.

Emerging from the marble rocks, the Narmada enters the upper fertile plains. Further west, after traversing through the middle plains, at Nandhar, 806 km from the source and at Dhardi, 47 km further downstream, the river drops over falls at 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 Sahasradhara 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 Vindhya 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 reaches 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, Hiran and Orsang which are briefly described in the following paragraphs as given in Narmada tribunal report.

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 $22^{\circ}32'$ and east longitude $81^{\circ}22'$ 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 Durg district of Madhya Pradesh near Rampur village at an elevation of 600 m at north latitude $21^{\circ}42'$ and east longitude $80^{\circ}50'$ and flows in a generally north-westerly direction for a total length of 184 km to join the Narmada from left near Mandla at 287th km of its run. The Banjar drains a total area of 3,626 sq.km.

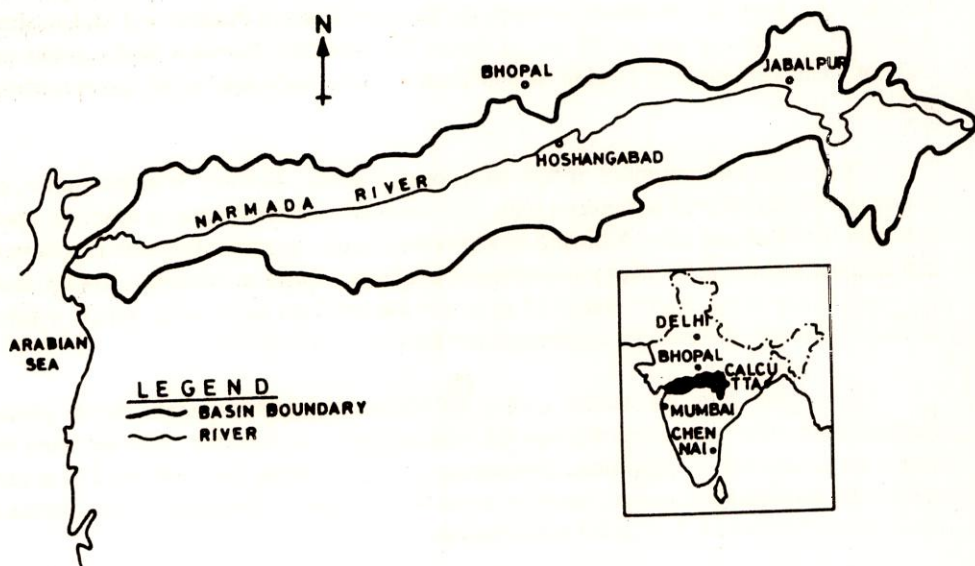
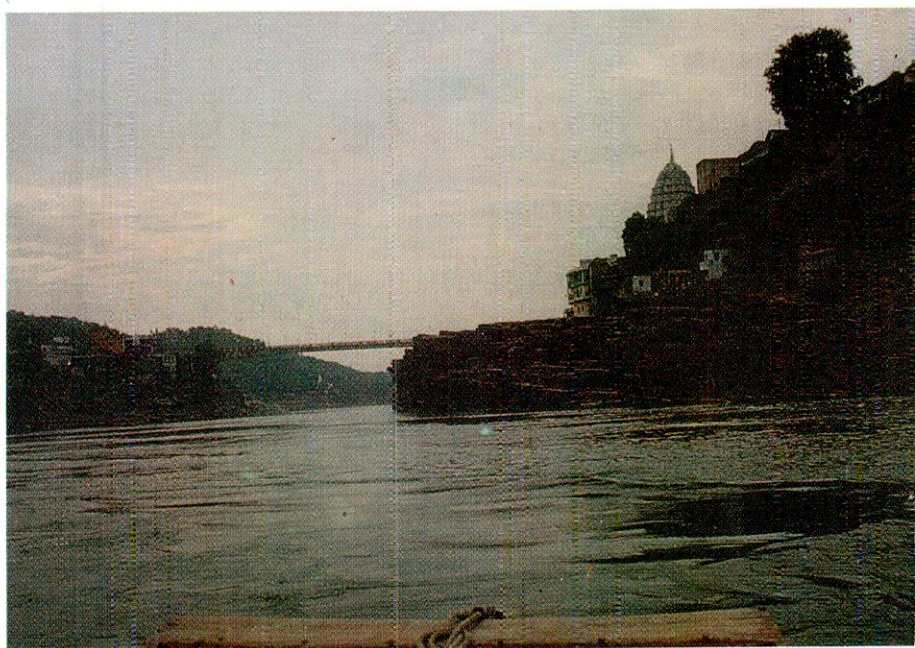


FIG.1-1: INDEX MAP OF THE NARMADA RIVER BASIN



NARAMDA AT OMKARESHWAR

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 $22^{\circ}31'$ and east longitude $79^{\circ}25'$ 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 Chhindi village, at an elevation of 600 m at north latitude $20^{\circ}23'$ and east longitude $78^{\circ}52'$ 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 Paloha. The Shakkar drains a total area of 2,292 sq.km.

The Dudhi rises in the Mahadep hills of the Satpura in the Chhindwara district of Madhya Pradesh, west of Chhindi village at an elevation of 900 m at north latitude $22^{\circ}23'$ and east longitude $78^{\circ}45'$ and flows first in a north westerly direction upto 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 $22^{\circ}13'$ 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 Chhipaner 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 or 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 sq. 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 $21^{\circ}23'$ and east longitude $73^{\circ}35'$ 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 1489 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 $23^{\circ}12'$ and east longitude $80^{\circ}27'$ and 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 Tendonri 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 $23^{\circ}22'$ and east longitude $78^{\circ}33'$ 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 $22^{\circ}55'$ and east longitude $77^{\circ}44'$ 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 1787 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 1347 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 1528 sq.km.

The Uri rises in the Vindhya range in the Jhabua district in Madhya Pradesh, near Kalmore at an elevation of 450 m at north latitude $22^{\circ}36'$ and east longitude $74^{\circ}47'$ and flows for a total length 74 km in a southerly direction to join the Narmada from the right near Nisarpur. It drains a total area of 1813 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 1943 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 $22^{\circ}30'$ and east longitude $74^{\circ}18'$ and flows for a total length of 101 km in a south-westerly direction to join the Narmada from the right, near Chandod. It drains a total area of 4079 sq km and is next size to the Hiran, among the right bank tributaries.

The major tributaries of Narmada river, their catchment area and distance of confluence of Narmada from source are given in Table 1.1.

Table 1.1 : Major Tributaries of Narmada River

Name of Tributary	Bank	Length of Tributary km	Catchment area in km ²	Distance of confluence of Narmada from source
Burhner	Left	177	4118	248
Banjar	Left	184	3626	287
Hiran	Right	188	4792	464
Sher	Left	129	2901	497
Shakkar	Left	161	2292	546
Dudhi	Left	129	1541	575
Tendoni	Right	118	1632	602
Barna	Right	105	1787	605
Tawa	Left	172	6333	676
Kolar	Right	101	1347	747
Ganjal	Left	89	1930	757
Chota Tawa	Left	169	5051	829
Kundi	Left	121	3820	943
Man	Right	89	1528	992
Uri	Right	74	1813	1029
Goi	Left	129	1891	1038
Orsang	Right	101	4079	1184
Karjan	Left	93	1489	1199

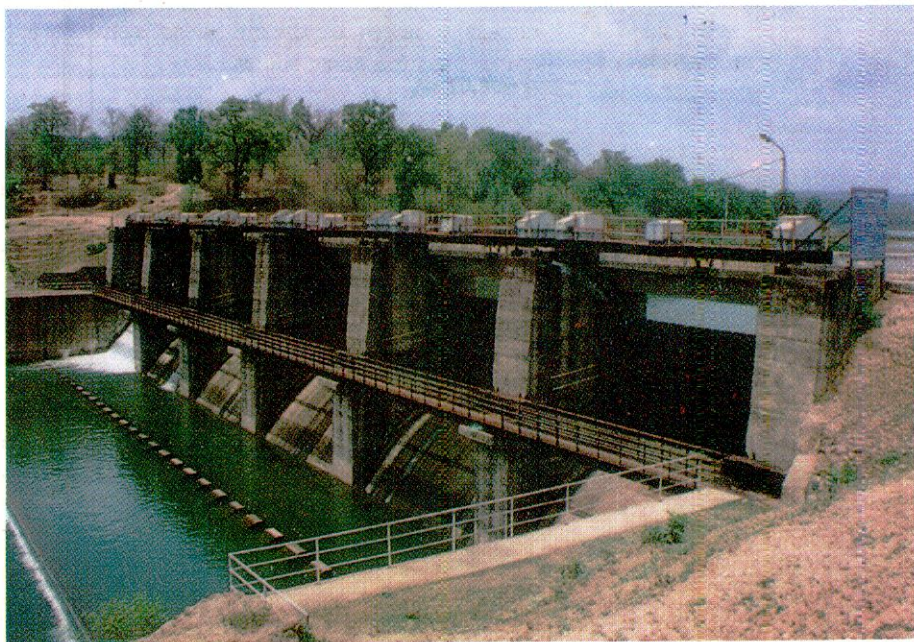
1.2 The Narmada Basin

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

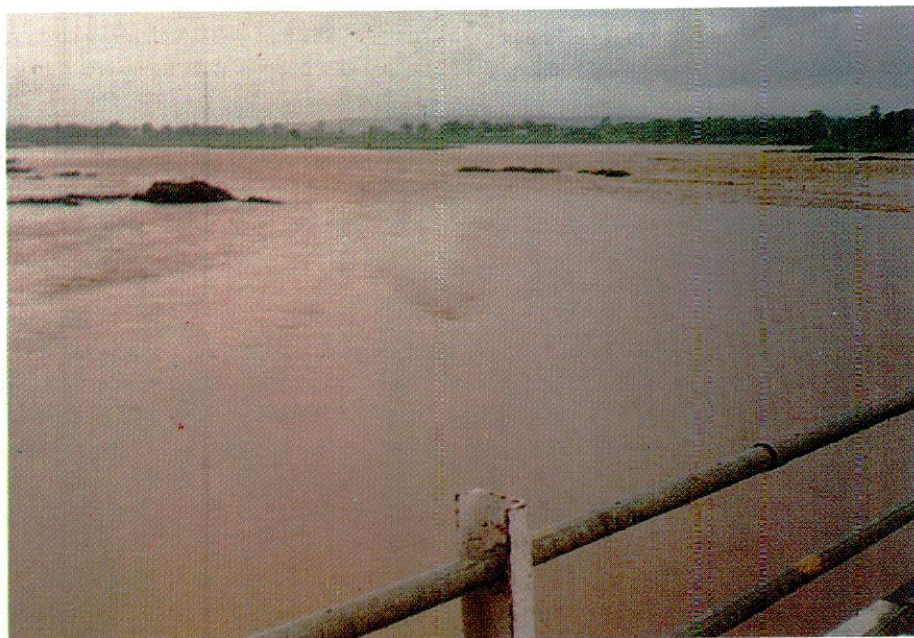
State	Drainage Area
Madhya Pradesh	85,859 sq km
Maharashtra	1,538 sq km
Gujarat	11,399 sq km

The catchment area upto Narmada Sagar proposed to be constructed near Punasa is 61,642 sq km and the area upto Sardar Sarovar under construction is 88,000 sq km.

The basin is bounded on the north by the Vindhya, 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 meters above mean sea level. A small area around Pachmarhi is at a height of more than 1000 meters above mean sea level. Brief description



MATYARI DAM - HEAD WORKS (MAJOR PROJECT)



NARMADA IN FLOODS AT MANDLA

of the climate, soils, land use, raingauge network, stream gauge network and meteorological observatories of the Narmada basin is given below.

1.2.1 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 per humid climates around higher 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.

1.2.2 Soils

The Reconnaissance soil surveys 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 covers the major portion of the basin.

1.2.3 Land Use

About 35% of the area is under forest and about 60% under arable land and remaining under grass land, waste land, etc.

1.2.4 Raingauge Network

The number of raingauge stations in the basin were 21 in 1891 which has risen to 205 stations by 1980. Of these nearly 120 raingauge stations have data for more than 40 years.

There are about 50 self recording raingauge stations (SRRG), maintained by either India Meteorological Department or other agencies like the flood forecasting division of Central Water Commission, State Irrigation Departments, etc.

1.2.5 Meteorological Observatories

India Meteorological Department is maintaining class II or class I observatories at 18 locations in and around Narmada basin where the observations of dew point, temperature are made twice a day at 0300 GMT (0830 IST) and 1200 GMT (1730 IST). The list of observatories alongwith their date of starting is shown in Table 1.2.

Table 1.2 : List of Observatories in and around Narmada Basin

State	District	Observatory	Lat.	Long.	Elev. (meter)	Date of Starting
Madhya Pradesh	Bilaspur	Pendra Road	22°46'	81°54'	625	23.6.1903
	Balaghat	Malajikhand	22°00'	80°42'	581	01.7.1978
	Jabalpur	Jabalpur	23°12'	79°57'	393	01.1.1869
	Shahdol	Umaria	23°32'	80°53'	459	24.4.1931
	Mandla	Mandla	22°35'	80°22'	443	15.6.1950
	Seoni	Seoni	22°05'	79°33'	619	01.1.1870
	Narsimhapur	Narsimhapur	22°57'	79°11'	356	10.2.1962
	Chindwara	Chindwara	22°06'	79°00'	685	01.6.1908
	Hoshangabad	Hoshangabad	22°46'	77°46'	302	01.1.1870
	Hoshangabad	Pachmarhi	22°25'	78°26'	1075	01.5.1870
	Sehore	Bairagarh (Bhopal)	23°17'	77°21'	523	09.7.1927
	Raison	Raisen	23°19'	77°50'	440	13.6.1970
	Betul	Betul	21°52'	77°56'	653	15.9.1948
	Devas	Kannod	22°40'	76°44'	353	17.3.1969
	Nimar	Khandwa	21°50'	76°22'	318	01.1.1877
	Khargone	Khargone	21°49'	75°37'	251	27.9.1969
	Indore	Indore	22°43'	75°48'	567	25.2.1877
	Dhar	Dhar	22°36'	75°18'	583	18.2.1973
	Jhabua	Alirajpur	22°17'	74°24'	293	01.7.1955
Gujarat	Broach	Broach	21°42'	73°00'	17	25.2.1969
	Surat	Surat	21°12'	72°50'	12	29.1.1947
Maharashtra	Dhulia	Nandurbar	21°20'	74°15'	206	11.7.1949
	Jalgaon	Jalgaon	21°03'	75°34'	201	9.1936

1.2.6 Stream Gauge Network

Systematic observations of gauge and discharge were started in Narmada basin only in 1947 by the then Central Water Ways, Irrigation and Navigation Commission. The main river Narmada is now gauged at nine sites at Manot, Mandla, Jamtara, Bermanghat, Hoshangabad, Mortakka, Mandleshwar, Barwani and Garudeshwar, where daily gauge and discharge observations and hourly gauge observations during monsoon season (June-Oct.) were being made. Two sites at Sandia and Handia are also being operated which have only data of daily gauge discharge observations for the recent years. There are seventeen principal tributaries in the catchment of Narmada upto Sardar Sarovar. However, only a few of them are gauged.

2.0 DATA PROCESSING AND ANALYSIS

The hydrometeorological variables such as rainfall, temperature, humidity, wind speed, etc. are measured from the field as a time series data. Many of these hydrological variables recorded are not directly used for purpose of hydrological modeling and analysis. These data are subjected to preliminary and secondary processing in order to ensure the quality of data and also bring them in the appropriate form required for the purpose of hydrological modeling. The data which are required for hydrological modeling may be classified as: the time series data, spatial data, and location specific data. The time series data are fed on the computer and software are available for the processing of such data. During such a processing, various computations like areal estimates of data, statistical analysis including correlation and regression analysis are generally utilized. Spatial information may be stored in two or three dimensional grid systems and necessary quality control test is performed on them. For the processing of the spatial and location specific data, digitization may be achieved manually by digitizing tables or by automated or semi-automated digitizing equipment. The conversion process can be checked by computer plotting of the data into overlap and comparing with the original traces.

In the comprehensive study of Narmada river basin, the studies have been taken up to investigate the hydrological, hydrometeorological and physical characteristics of the different sub-basins. The rating curves have been developed for some of the gauging sites located in the Narmada river basin. The hydrological time series data for Manot sub-basin of river Narmada were processed using HYMOS Software Package. In order to provide the specific contents for the water year book, the hydrological data book for Narmada basin upto Bargi dam was prepared. In this data year book, the time series data of rainfall and runoff were included from 1981 to 1990 in addition to some physical features. Sometimes in hydrological analysis, it becomes necessary to disaggregate the hydrological variables from larger temporal scale to smaller scale. In order to perform such disaggregation methodologies were developed and applied for the disaggregating the monthly spatial average rainfall of a sub-basin at different raingauge stations.

2.1 Study of the Hydrometeorological Aspects of Narmada Basin

It was felt imperative to study the hydrometeorological aspects of Narmada basin including the whole gamut of design storm, behaviour of the rain storm over shorter duration and its movement in the basin.

2.1.1 *Synthetic design storm for Narmada Sagar and Sardar Sarovar*

Based on the analysis and after considering the possibilities of transposition and the different alternate synthetic combinations of storms for design purposes, the following storms were recommended for Narmada Sagar and Sardar Sarovar which were agreed upon by India Meteorological Department and Central Water Commission during a meeting on Sept. 30, 1980. The design storms recommended for Narmada Sagar and Sardar Sarovar are given at Table 2.1.

Table 2.1 : Design Storms recommended for Narmada Sagar and Sardar Sarovar

Dam Site	1st Day	2nd Day	3rd Day	4th Day	5th Day
	Depths in mm				
Narmada Sagar	33.8 (28 Aug. 1973)	100.6 (29 Aug. 1973)	99.8 (30 Aug. 1973)	90.2 (15 July 1944)	
Sardar Sarovar	28.0 (28 Aug. 1973)	63.0 (29 Aug. 1973)	80.0 (30 Aug. 1973)	61.0 (05 Sept. 1970)	72.0 (06 Sept. 1970)

The moisture maximisation factor computed by India Meteorological Department using 35 years of dew point temperature data gave a factor varying between 1.3 and 1.4, and a uniform value of 1.35 for the synthetic storms was recommended for the entire catchment.

2.1.2 Summary of the Moving Storm Studies

A summary of the inter-station lag, in other words, the time taken by a storm to move from one station to another is indicated for the four storms analyzed in the technical report (CS-3). In view of the number of stations and their network varying from storm to storm, though it may be difficult to draw any conclusions readily it could be seen that the storm of Aug. 1979, Aug. 1978 and Sept. 1970 are relatively fast moving storms as compared to the Aug. 1973 storm. The storm of Aug. 1978 was fast until it reached Bairagarh. During the recurring phase it become slow. The conclusions drawn from the study are discussed below:

- (i) The conventional methods of depth-area-duration and depth-duration analysis do not yield critical depths for design purposes in Narmada catchment. Special technique to suit the meteorological, hydrological and topographical conditions of Narmada basin had to be tailored. A four day combined storm of 1973-1944 for Narmada Sagar and five day combined storm of 1973-1970 for Sardar Sarovar are considered appropriate.
- (ii) Though doubts are expressed about the application of moisture maximisation for tropical regions, to account for the limitation of storm sample, the storms need to be maximised. In case of synthetic storms consisting of combination of the storms, different maximisation factors are to be used for the different constituent storms.
- (iii) In view of the elongated shape of the basin and the time taken by storms for moving from upstream to down stream, the time distribution for each of the sub-catchment in the Narmada basin is to be evolved separately incorporating the necessary lag from upstream to downstream while keeping a critical sequence of rainfall blocks in each of the subcatchment. Using different groups of S R rain gauges from out of 11 SRRG stations, IMD has recommended different time distributions for four main sub-catchments.

- (iv) The inter-station distance and inter-station correlation were not well related so as to indicate the expected decrease in correlation coefficient with increasing distance, due to sparse SRRG network in Narmada basin.
- (v) The analysis of small sample of four storms used in studying of the moving storms indicated a fairly consistent movement and speed of movement of storms over Narmada basin.

2.1.3 Recommendations

Though significant improvement has been achieved through sequential maximisation of storm, the methods used for moisture maximisation and time distribution fail to take into account the movement of the storm over the catchment and its effect on the flood hydrographs in each sub-catchment and on the main river. Also the data sample used for determining the time distribution is small. The moving storm studies summarised in this study are some preliminary steps in this direction. More data and further studies on modelling the movement of storms and their speeds are necessary for studying their effect of flood flows.

Though, part of the catchment is orographic, no attempt has been made to separate the orographic and non-orographic parts for design storm estimation due to non-availability of upper air meteorological data. Applying a uniform maximisation factor throughout the basin is unrealistic in view of the elongated catchment and typical orography. Storm modelling for the orographic areas needs to be studied as recommended in WMO Operational Hydrology Report No 1 and other studies in U.S.A.

For details of the study, the reader may please refer NIH Report No CS-3.

2.2 Rating Curves for Some of the Gauging Sites on Narmada river

For improving the present practice of establishing stage and discharge relations, a methodology using information about physical features is suggested and explained in the user's manual (UM-5). This methodology has been applied to the data of gauging stations in the Narmada basin. There are seven important discharge sites where measurement of discharge are carried out using current meters and some time floats. For the purpose of design flood studies in Narmada basin, discharge values at hourly intervals were needed at the gauging sites. The case study described herein relates the stage and discharge data for all the seven sites (Manot, Jamtara, Bermanghat, Houshangabad, Mortakka, Mandleshwar and Garudeshwar). At all the seven sites daily discharges are observed using current meters (or floats) and water levels are observed hourly. In order to compute hourly discharge the relationships between stage and discharge have been established.

A relationship of the form:

$$Q = a (G - e)^b$$

where G, Q are stage and discharge respectively and a, b, and e are parameters defining the relation, used alongwith atleast squares methods for estimation of parameters. This equation is compared with Manning's equation.

$$Q = \frac{1}{n} (AR)^{2/3} (S)^{1/2}$$

where, A is area, R is hydraulic radius, n is a constant and S is the bed slope. This results in the following approximation, $a = (1/n) w S^{1/2}$ where W is the width. The hydraulic radius is approximately equal to (G-e) for wide channel, where 'e' is the bottom of the channel elevation. The value of 'b' is equal to 1.6 to 1.7. The physically based estimates of a, b and e are obtained prior to using computer programme for rating, using least squares. These are used as a guide to interpret and select the parameters for rating relationship. The data availability for the study is summarized in Table 2.2. The salient features of the cross-sections of river Narmada are given in Table 2.3.

Table 2.2 : Data availability

Sl. No.	Site	Data available for the years related to		
		Cross-Section	Daily Gauge	Rating Curve
1.	Manot	1978	1977-78	1978
2.	Jamtara	1978-79	1968-80	1971-73 and 1975-79
3.	Bermanghat	1978-79	1972-77 and 1980	1972-78
4.	Hoshangabad	1973-79	1972-78	1973-78
5.	Mortakka	1978	1968-78 and 1980	1978-79
6.	Mandleshwar	1979	1971-80	1972-78
7.	Garudeshwar	1973-79	1972-78	1973-78

Table 2.3 : Salient features of the cross-sections of river Narmada

Sl. No.	Name	Zero of Gauge (m)	Width (m)	Channel slope	Area m ² at 15 m depth
1.	Manot	442	170	.00125	2592
2.	Jamtara	360	280	.00033	3715
3.	Bermanghat	306	320	.00038	3140
4.	Hoshangabad	282	700	.00023	8831
5.	Mortakka	150	670	.00053	6291
6.	Mandleshwar	138	600	.00046	10064
7.	Garudeshwar	12	500	.0001	6682

Superimposed cross-section plot of these sites revealed that there is a gradual increase in the cross-sectional area from site Manot to Bermanghat. There is a sudden increase in cross-sectional area at the site Hoshangabad, but further downstream is not that large. The cross section of all the sites are analysed and conveyance are calculated and plotted along with discharge. A simple plot of measured discharge is also made to remove obvious errors. A double log plot made for the discharge observed at all the sites exhibited a single rating curve within the channel portion for all the sites except for Mandleshwar. The analysis of data pertaining to the site Mandleshwar showed the requirement of two rating curves within the channel portion, one curve for lower discharge and other for high discharge. The Table 2.4 gives the parameters defining the rating curves for different sites:

Table 2.4 : The parameters defining rating curves for various sites

Site	Parameters			Datum (m)
	a	b	c	
Manot	99.467	1.769	0.5	86.0
Jamtara	85.046	1.795	2.3	360.0
Bermanghat	98.428	1.73	4.0	306.0
Hoshangabad	173.183	1.858	1.9	282.0
Mortakka	605.09	1.54	2.6	150.0
Mandleshwar	331.209	1.715	0.9	138.0
Garudeshwar	250.0	1.66	1.7	12.0

The plots comparing the curves supplied by field organizations and the presently established have also been prepared.

On the basis of this study following conclusions may be drawn:

- The following information are extracted from the analysis of the cross-section plotted and presented in the technical report (CS-6). The flow section gradually increases from the upstream site Manot upto Bermanghat. The section at Hoshangabad shows a rapid increase in the section. The river has a narrow section at Garudeshwar. It is understood that the river again widens just after this site. As the result of this typical feature, a large flow incident at or upstream of Hoshangabad will be temporarily stored and passed on to the downstream site.
- Comparison of conveyance is made approximately. The reaches containing Mandleshwar and Hoshangabad can convey large quantity of flow than other sections. They are also expected to have flatter rating curves than other sections. For this analysis a constant Manning's 'n' is assumed.
- The rating curves established at National Institute of Hydrology compare very well with curves supplied by CWC specially in the case of Mortakka, Garudeshwar, and Mandleshwar. At the site Bermanghat a depth adjustment will match the two curves well. In all other sites except at Manot, the curves agree reasonably well.

However, in view of the needed extrapolations the rating curves established through physical reasoning should be considered superior.

- (d) In the rating curve relationship, the parameter 'a' depends mostly on the width of the river section. From the Table 2.4, it can be seen that Mortakka takes a large value. Although the cross-section at Hoshangabad is wider than Mortakka and Garudeshwar the rating curve has lesser value of 'a' than even Garudeshwar. This is because of the bed slope which is the second important physical feature upon which the parameter 'a' depends. The bed slope at Hoshangabad is 0.00025 and whereas at Garudeshwar is 0.0001.

The parameter 'b' depends on the shape of the section. The Table 2.4 shows fairly a constant value. Hence the shape effect of the sections on the rating curve can be taken to be same at all sections.

The parameter 'e' is related to a datum. Its magnitude depends on the datum used.

In all the above analysis it is assumed that the cross-sections at the gauging sites do not change considerable but remains constant. Further the rating curves could be improved if the information on the variation of roughness coefficients (like the Manning's 'n') are available.

For details of the study, the reader may please refer NIH Report No. CS-6.

2.3 Hydrological Network Design for Narmada Basin

In this study, methodology and computation steps of the physical statistical method to determine representative area per stream gauging station have been explained. Guidelines for selection of stream gauging sites have been described. This methodology has been applied for Narmada basin using available annual flow data of five sites namely Jamtara, Barmanghat, Mnadleshwar, Rajghat, and Garudeshwar. 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. On the basis of the study, with somewhat limited data a basic network density of one station per 2411 square kilometers could be estimated for developing relationships of hydrological variables for the Narmada basin upto Garudeshwar.

For details of the study, the reader may please refer NIH Report No TR-58.

2.4 Hydrological Data Book for Narmada Basin (upto Bargi Dam) [1981-90]

Planning and management of various water resources projects requires vast amount of hydrological data. This hydrological data is collected and maintained by various organizations like Central Water Commission, Central Ground Water Board, India

Meteorological Department and various State Government organizations. To make the data readily available to users for various purposes, it is desirable to have all the data in a consolidated form at one place.

This hydrological data book for Narmada basin (upto Bargi Dam) contains description of the river basin, present status of water resources development and existing network of hydrological stations. A number of maps like index map showing study area in Narmada basin, administrative map, isohyetal map, map showing location of rain gauge stations, map showing location of gauge/discharge sites and subbasin maps have been included. It also includes monthly rainfall data, monthly climatological data, daily gauge/discharge data, monthly sediment load data, surface water quality data and ground water level data for the period 1981-90. Some statistical parameters like mean, maximum and minimum of data have also been provided.

The preparation of this data book is an attempt to bring all the possible information relative to study area together. Due to non-availability of some data and maps, this book might be incomplete in some aspects.

The data supplied by Central Water Commission, Narmada Valley Development Agency, Jawaharlal Nehru Krishi Vishva Vidhyalaya, State Irrigation Department, State Groundwater Survey Circles and others have been incorporated in this book.

The contents of an ideal hydrological data book have been prepared keeping in mind the objectives of the data book. Formats for different types of data are also provided.

For details of the study, the reader may please refer NIH Report No TN-114.

2.5 Spatial Disaggregation of Rainfall Data

Use of the output from global circulation models (GCMs) by regional or small scale rainfall-runoff models necessitates the disaggregation of the hydrological information available from GCMs to smaller scales. The hydrological processes of interest commonly occur at much smaller scales than those being modelled by GCMs. The present work examines the disaggregation of a really averaged monthly rainfall values of a basin or a region into point rainfall values. It uses some statistical methods based on a frequency analysis approach, a correlation approach and a disaggregation approach. A total of ten different methods have been tried and their relative performances compared based on some error criteria evaluated from observed and disaggregated point rainfall and mean areal rainfall values and their statistics. The results show the superiority of methods based on disaggregation techniques over other methods.

All the approaches used herein need point rainfall values located in and around a basin under study and mean areal rainfall values for the basin. Several methods are available in the literature to estimate the areal mean from point rainfall values but no method can provide more than an estimate of the true value. Studies done by many workers on comparisons of some of these methods indicate that for larger time intervals, i.e. monthly and yearly, the estimates by different methods are within 10% of one another.

For the present study, the Thiessen polygon method, being the most common and extensively used method for the estimation of mean areal rainfall was adopted. Various approaches used for the disaggregation of mean areal rainfall to point rainfall values are described in the technical report TR (BR)-126.

The monthly rainfall data at the recording stations at Lakhandon, Harai and Mungwani of the Sher sub-basin of Narmada basin were used. The Thiessen weights for these stations were 0.35, 0.25 and 0.40 respectively. On the basis of this study the following conclusions may be drawn.

Various techniques to disaggregate the mean areal monthly rainfall for a basin were examined. These techniques may prove a useful tool to deal with resolution incongruities associated with GCMs and local scale rainfall-runoff models, specifically when limited information about a catchment is available, and also for similar other problems. These techniques can also be used for infilling missing records. Based on the results of present study, a disaggregation technique which is a step forward as compared to other methods in terms of preservation of correlation may be preferred.

For details of study, the reader may please refer NIH Report No TR/BR-126.

2.6 Processing of Hydrological Data for Manot Sub-Basin using HYMOS

In this study, the illustration of the capabilities of the HYMOS software has been made by taking a real case study, with a view to get awareness about the type of software available in market and importance of using such a software. Various options of data storage, processing and retrieval have been demonstrated with the help of available hydrological data of this sub-basin. On the basis of the study the following conclusions may be drawn.

It is obvious that as compared to the manual handling and processing of hydrological data a computer based processing would have many advantages. In general, HYMOS is an efficient hydrological database management and processing software. It is well tailored to suit the requirements of the hydrological data processing. Some of the specific capabilities and shortcomings of HYMOS are listed below for a better understanding of this software.

- (a) As is required for a hydrological database, HYMOS is able to recognize as many number of data types and for each data type any time interval ranging from 1 minute to 1 year.
- (b) There is no need of remembering the names of the datafiles as the data can be retrieved by choosing the name from the list which is displayed in the scrolling window on the screen as and when desired. This avoids the confusion and the need to recollect the filenames which becomes extremely difficult as the size of the database increases.

- (c) Data may be edited with the help of specially designed editor which displays the time label at each data location. In absence of such labels the user is many times lost in counting the time labels. The data may be corrected whenever required and the origin of the data, viz. original or corrected is stored along with data so as to later interpret it suitably.
- (d) Data may very conveniently and fastly be validated by graphical and other statistical options.
- (e) HYMOS has adequate facility for completion and regression techniques.
- (f) Full facility is available in HYMOS for handling the flow data. Development of rating curves and their subsequent validation is very conveniently and swiftly done.
- (g) Various options are available for (Dis-) aggregation of series, series transformation and computation of areal rainfall by different procedures.
- (h) A very strong statistical analysis and time series support is rendered by the software which may be utilised in the processing of the hydrological data very conveniently.
- (i) Reporting and retrieval of data is very easily and efficiently accomplished by the help of this software. There is a very sophisticated graphics support available and may be utilised in bringing out figures in a very impressive manner.
- (j) All the operations are done with the help of menu driven selection procedure and thus avoids the difficult problem of file management and data entry and retrieval actions.
- (k) The most important thing to emphasize here is that even after making an attempt the real impression of the capabilities of such a software may be very difficult to be brought out in the form of report like this. Instead, it is very easy and convincing if the exercise of working with such software is undertaken.

For details of the study, the reader may please refer NIH Report No CS/AR-179.

2.7 Remarks

The hydrometeorological and hydrological data are subjected to preliminary and secondary processing in order to ensure the quality of data and also bring them in the appropriate form required for the purpose of hydrological modeling. The data which are required for hydrological modeling may be classified as: the time series data, spatial data, and location specific data. The time series data are fed on the computer and software are available for the processing of such data. During such a processing, various computations like areal estimates of data, statistical analysis including correlation and regression analysis are generally utilized. Spatial information may be stored in two or three dimensional grid systems and necessary quality control test is performed on them. For the processing of the spatial and location specific data, digitization may be achieved manually by digitizing tables

or by automated or semi-automated digitizing equipment. The conversion process can be checked by computer plotting of the data into overlap and comparing with the original traces.

The studies have been carried out for investigation of the hydrological, hydrometeorological and physical characteristics of the different sub-basins of the river Narmada. The rating curves have been developed for some of the gauging sites located in the Narmada River basin. Methodology and computational steps of the physical-statistical method to determine representative area per stream gauging station in the Narmada basin have been explained. Guidelines for selection of stream gauging sites have been described. The hydrological time series data for Manot sub-basin of river Narmada were processed using HYMOS Software Package. In order to provide the specific contents for the water year book, the hydrological data book for Narmada basin upto Bargi dam was prepared. In this data year book, the time series data of rainfall and runoff were included from 1981 to 1990 in addition to some physical features. Sometimes in hydrological analysis, it becomes necessary to disaggregate the hydrological variable from larger temporal scale to smaller scale. In order to perform such disaggregation methodologies were developed and applied for the disaggregating the monthly spatial average rainfall of a sub-basin at different raingauge stations.

3.0 SMALL CATCHMENT HYDROLOGICAL STUDIES

Whenever the river flow records are not available at or near the site of interest, it is difficult for hydrologists or engineers to derive reliable estimates of design flood, water availability and other hydrological variables directly. In such a situation, the regional approaches are the alternative methods which provide these estimates. Although a large number of hydrological simulation models have been developed in the past decades, yet often simplified modelling approaches are being used for predicting the hydrological behaviour of various catchments. The main problem in applying the advance hydrological modelling approaches viz. physically based or conceptual models in a developing country like India is non availability of adequate data for various catchments. Hydrologists face difficulties in calibration of complex models for different spatial and temporal scales, applying values on one scale computed from a population of parameters of another scale, adopting the limits of the applicability of physically based simulation models for different spatial scales when data uncertainty is considered. Hydrologists are concerned, how can model parameters of one scale be derived from the knowledge of the lower scale if the mathematical approach changes with scale. According to these questions the main tasks in regionalization can be characterized as: (i) developing the regional approaches for estimation of the hydrological variables for the ungauged catchments, (ii) considering spatial variability within a given scale, (iii) deriving effective or representative parameters for an aggregated area (upscaling), and (iv) disaggregating information on a larger scale (downscaling). In addition to these tasks the regional transposability is also one of the main research interests. In order to be able to apply models to ungauged catchments it is indispensable to develop tools for deriving model parameters from catchments characteristics like soil, geomorphology, geology, landuse and the climatological characteristics etc. Regionalization has been employed for solving many hydrological problems; prominent among these are regional flood frequency analysis, regional unit hydrograph derivation and regional flow duration curves. Regional studies have been carried out using the data of some of the sub-basins of the Narmada basin. These studies include the (i) regional flood frequency studies, and (ii) geomorphological instantaneous unit hydrograph studies.

3.1 Regional Flood Frequency Studies

Regional flood frequency analysis approach is widely used for estimation of frequency floods for those sites where adequate records are not available for at site frequency analysis. The main issues involved in regional flood frequency analysis and its generalized approach are: (i) regional homogeneity, (ii) degree of heterogeneity and its effects on flood frequency estimates, (iii) development of a relationship between mean annual peak flood and physiographic as well as climatologic characteristics for estimation of floods for ungauged catchments, (iv) estimation of parameters of the adopted frequency distributions by efficient parameter estimation approach, (v) identification of a robust flood frequency analysis method based on descriptive ability and predictive ability criteria.

3.1.1 Data used

The study area is comprised of the two hydrometeorological subzones of zone 3, namely: (i) Lower Narmada and Tapi subzone: 3(b); (ii) Upper Narmada and Tapi: subzone 3(c). The annual maximum peak flood data varying in record length from 12 to 28 years over the period 1957 to 1989 for 19 bridge sites of the subzone 3 (b) and 15 bridge sites varying from 14 to 30 years in record length for the subzone 3 (c) as well as the catchment area of these sites are used in the study. The catchment areas vary from 17 square kilometers to 1017 square kilometers for the subzone 3 (b) and from 41.8 square kilometers to 2110.85 square kilometers for the subzone 3 (c). The area of subzones, number of bridge sites for which data are available, range of catchment area of various bridge sites, range of mean annual peak flood and record length for the various subzones are summarized in Table 3.1.

Table 3.1 : Salient Features of Various Catchments of the Subzones 3 (b) and 3 (c)

Subzone	Area of subzone (km ²)	Number of bridge sites in the subzone	Range of catchment area of bridge sites (km ²)	Range of mean annual peak flood (m ³ /s)	Range of record length (Years)
(1)	(2)	(3)	(4)	(5)	(6)
3(b)	77700	19	17.22-1017.00	34.95-558.29	12-28
3(c)	86353	15	41.80-2110.85	111.95-1730.53	14-30

3.1.2 Methodology

The comparative flood frequency studies involving the use of probability weighted moment (PWM) based at-site, at-site and regional, and regional methods using Extreme Value-1 (EV-1), General Extreme Value (GEV) and Wakeby distributions and the U.S.G.S. method as well as L-moments approach have been carried out for these two subzones for this particular data set.

(A) At-site Flood Frequency Analysis

When long term annual maximum peak flood data are available for any gauging site, then at-site flood frequency analysis may be carried out for estimation of floods of various return periods. The at-site flood frequency analysis involves:

- (i) fitting various frequency distributions to the at-site annual maximum peak flood data,
- (ii) selecting the best fit distribution based on descriptive and predictive ability criteria, and
- (iii) using the best fit distribution for estimation of T-year flood.

(B) At-site and Regional Flood Frequency Analysis

When long term annual maximum peak flood data are not available for a gauging site, but the data are available for a number of sites within the same hydrometeorologically homogeneous region; then at-site and regional flood frequency analysis may be carried out for estimation of floods of various return periods. The at-site and regional flood frequency analysis involves:

- (i) testing the regional homogeneity,
- (ii) developing flood frequency relationships for the region considering various frequency distributions,
- (iii) selecting the best fit distribution based on descriptive and predictive ability criteria,
- (iv) estimation of at-site mean annual peak flood for the catchment for which flood of desired return period is to be estimated,
- (v) using the best fit regional flood frequency relationship for estimation of T-year flood.

(C) Regional Flood Frequency Analysis

When no data are available for a particular site then; regional flood frequency analysis may be carried out for estimation of floods of various return periods. Regional flood frequency analysis involves:

- (i) testing the regional homogeneity,
- (ii) developing flood frequency relationships for the region considering various frequency distributions,
- (iii) selecting the best fit distribution based on descriptive and predictive ability criteria,
- (iv) developing a regional relationship between mean annual peak flood and catchment and physiographic characteristics for the region,
- (v) estimating the mean annual peak flood using the developed relationship,
- (vi) using the best fit regional flood frequency relationship for estimation of T-year flood.

In these studies performance of the various methods has been evaluated based on the goodness of fit criteria involving descriptive ability tests viz. (i) average of relative deviations between computed and observed values of annual maximum peak floods, (ii) efficiency and, (iii) standard error; as well as the predictive ability tests viz. (i) bias, (ii) root mean square error, and (iii) coefficient of variation. The regional flood frequency

curves are developed by fitting L-moment based GEV distribution. The methodology used for development of the regional flood frequency curves as well as regional relationship for estimation of the mean annual peak flood and developing the regional flood formulae is discussed here under.

3.1.3 Development of regional flood frequency curves

In order to develop the regional flood frequency curves a sample comprised of the station-year data of standardized values of annual maximum peak floods i.e. $Z = X / \bar{X}$ values for various gauging sites of the two subzones are considered for the analysis. Flood frequency analysis is performed with the sample of $X / \bar{X}$ values.

The GEV distribution is a generalized three parameter extreme value distribution proposed by Jenkinson(1955). Its theory and practical applications are reviewed in the Flood Studies report prepared by Natural Environment Research Council (NERC, 1975). The cumulative density function $F(z)$ for GEV distribution is expressed as:

$$F(z) = e^{-\left[1-K\left(\frac{z-u}{\alpha}\right)\right]^{1/K}} \quad (3.1)$$

Here u , α and K are location, scale and shape parameters of the GEV distribution respectively. The parameters u , α , and K of the GEV distribution are estimated using the method of L-moments (Hosking, 1990; Vogel and Fennessey, 1993). The form of the regional frequency relationship is expressed as:

$$Z_T = x_T / \bar{X} = u + \alpha Y_T \quad (3.2)$$

Here, Z_T is standardized T-year period flood estimate, x_T is T-year return period flood estimate, $\bar{X}$ is the mean annual peak flood and Y_T is GEV reduced variate corresponding to T-year return period.

The GEV reduced variate (Y_T) can be expressed as a function of return period, T as:

$$Y_T = \left[1 - \left\{1 - \ln\left(1 - \frac{1}{T}\right)\right\}^K\right]^{1/K} \quad (3.3)$$

3.1.4 Estimation of T Year Flood Using At-Site Mean

Once, at-site estimate of mean annual peak flood ($\bar{X}$) is made for the gauged catchments the T year floods are estimated using the following relationship:

$$X_T = \bar{X} \cdot Z_T \quad (3.4)$$

3.1.5 Development of Relationship Between Mean Annual Peak Flood and Catchment Area

For estimation of T-year return period flood at a site, the estimate for mean annual peak flood is required. For gauged catchments, such estimates can be obtained based on the at-site mean of the annual maximum peak flood data. However, for ungauged catchments the at-site mean can not be computed in absence of the flow data. In such a situation, a relationship between the mean annual peak flood of gauged catchments in the region and their pertinent physiographic and climatic characteristics is needed for estimation of the mean annual peak flood. Since, catchment area is considered to be one of the most prominent physiographic characteristics and is readily available, a relationship of the following form is developed in terms of catchment area for estimation of mean annual peak flood for ungauged catchments.

$$\bar{X} = a A^b \quad (3.5)$$

Here, A is the catchment area and a and b are the coefficients to be estimated using the least squares approach.

3.1.6 Development of Regional Flood Formulae

Form of the developed regional flood formula is:

$$X_T = C_T A^b \quad (3.6)$$

Here, X_T is the flood estimate for T year return period flood, C_T is a coefficient for the T year return period flood to be estimated from the regional flood frequency curve and b is a coefficient for a region, evaluated from the relationship between mean annual peak flood and catchment area for the region. Dividing equation (3.5) by equation (3.4) and substituting the expression for growth factor ($X_T / \bar{X}$) from equation (3.2), the following expression is obtained for evaluating X_T :

$$X_T = (u + \alpha Y_T) a A^b \quad (3.7)$$

From equations (3.5) and (3.6), the expression for C_T is obtained as:

$$C_T = a Z_T \quad (3.8)$$

From the above equation, it is evident that the flood estimate (X_T) for return period T is a function of regional frequency curves developed using L-moment based GEV distribution, return period as well as the regional coefficients a and b . Equation (3.7) may be used to compute the floods for desired return periods for various ungauged catchments of the region.

3.1.7 Analysis and discussion of results

The form of regional flood formula developed for the two subzones based on the methodology discussed above is:

$$X_T = [\beta + \gamma \{-\ln(1 - 1/T)\}^K] A^b \quad (3.9)$$

where, X_T is flood estimate in m^3/s for T -year return period, $\beta = a(\alpha/K + u)$, $\gamma = -a\alpha/K$, A is the catchment area in km^2 , a and b are the regional coefficients obtained from the regression analysis of the mean annual peak flood ($\bar{X}$) and catchment area (A) in log domain. Values of the regional coefficients K , u , α , a , b , r (correlation coefficient for the regression relationship between $\bar{X}$ and A), standard error (SE) of the estimate of ($\bar{X}$) for the regression relationship, β , and γ for the two subzones are computed based on the available data. The values of the regional parameters of the subzones 3 (b) and 3 (c) are given in Table 3.2. The growth factors ($\frac{Q_T}{Q}$) for these subzones are given in Table 3.3.

Table 3.2 : Regional Parameters for the Subzones 3 (b) and 3 (c)

S No. (1)	Subzone (2)	K (3)	u (4)	α (5)	a (6)	b (7)	r (8)	SE (9)	β (10)	γ (11)
2.	3(b)	-0.200	0.591	0.500	24.53	0.46	0.77	0.50	-46.85	61.33
3.	3(c)	-0.109	0.665	0.481	11.82	0.67	0.87	0.42	-44.30	52.16

Table 3.3 : Growth Factors ($\frac{Q_T}{Q}$) for the subzones 3 (b) and 3 (c)

Sl. No.	Subzone	Return Period							
		2	10	20	50	100	200	500	1000
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
2.	3(b)	0.780	2.009	2.615	3.540	4.335	5.289	6.736	8.021
3.	3(c)	0.844	1.892	2.352	3.004	3.538	4.112	4.939	5.621

Substituting values of the regional parameters, mentioned in Table 3.2, the regional flood formulae for the two subzones are expressed as:

$$\text{Subzone 3 (b), } Q_T = [61.3 (-\ln(1 - \frac{1}{T}))^{-0.20} - 46.9] A^{0.46} \quad (3.10)$$

$$\text{Subzone 3 (c), } Q_T = [52.2 (-\ln(1 - \frac{1}{T}))^{-0.11} - 44.3] A^{0.67} \quad (3.11)$$

(Here, Q_T is flood in cumec for T year return period, A is the catchment area in square kilometers). The graphical representations of the above formulae are shown in Fig. 3.1 and 3.2.

From this study, the following conclusions may be drawn.

- (i) For estimation of floods of different return periods for gauged catchments, the regional flood frequency curves developed for the subzones 3 (b) and 3 (c) together with the at-site mean annual peak floods may be used. For this purpose, the growth factors ($\frac{Q_T}{Q}$) of the respective subzones may also be multiplied by the at-site mean of the gauged site.
- (ii) The conventional empirical flood formulae do not provide floods of desired return periods. However, the flood formulae developed in this study are capable of providing flood estimates for different return periods.
- (iii) The form of the developed regional flood formulae is very simple; as for estimation of flood of desired return period for an ungauged catchment, it requires only catchment area which is readily available. Hence, these formulae may be used by the field engineers for estimation of floods of desired return periods.

For details of the study, the reader may please refer NIH Report No TR/BR-133 and TR/BR-149.

3.2 Geomorphological Instantaneous Unit Hydrograph (GIUH) Studies

Regional unit hydrograph studies are carried out for estimation of the unit hydrographs for ungauged catchments. A large number of regional relationships are developed by many investigators relating either the parameters of instantaneous unit

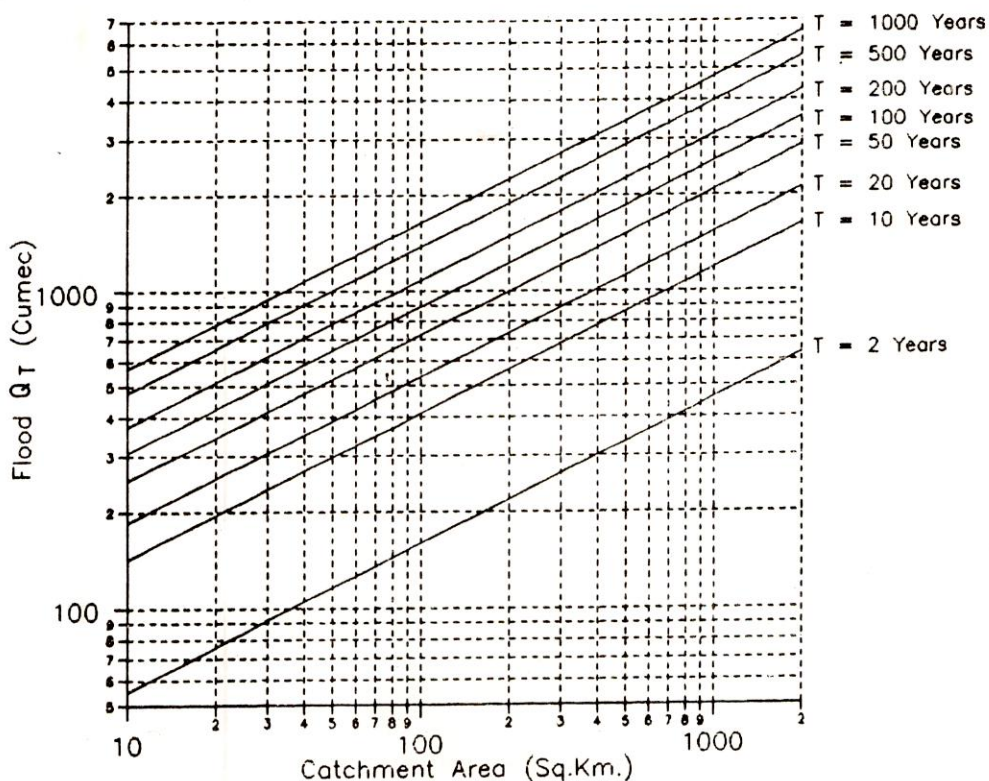


Fig.3-1: Variation of flood frequency estimates with catchment area for subzone 3(b)

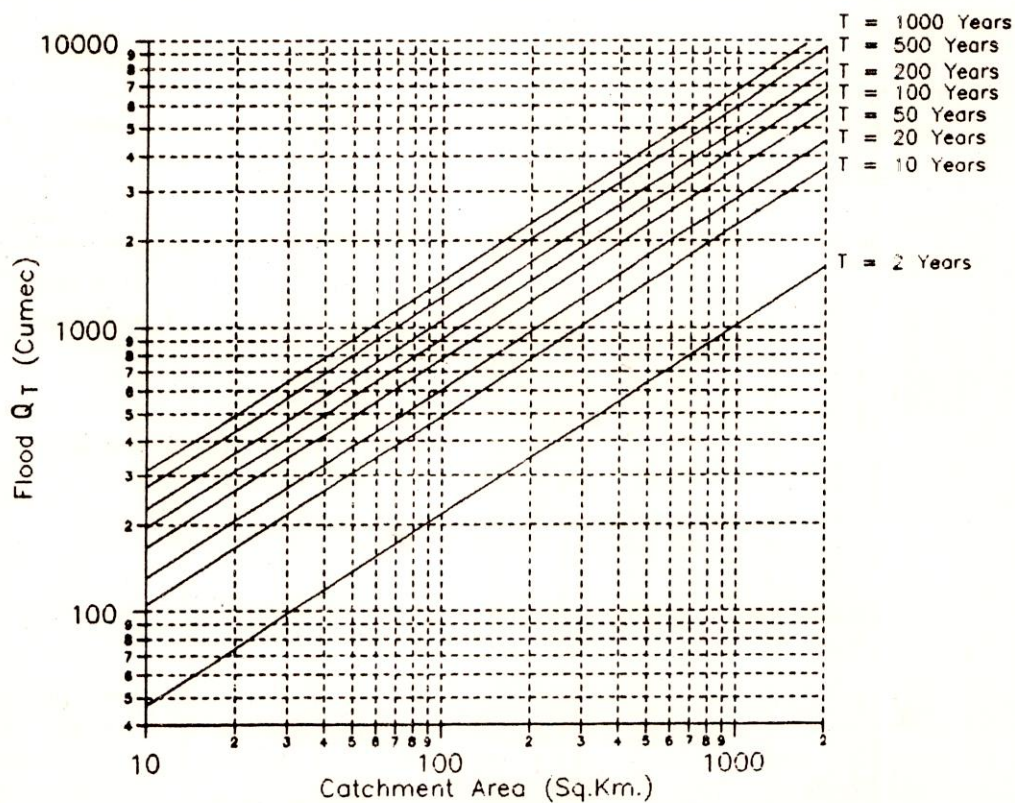


Fig.3.2: Variation of flood frequency estimates with catchment area for subzone 3(c)

hydrograph IUH models or UH characteristics with physiographic and climatologic characteristics. GIUH approach is being popularised because of its direct application to the ungauged catchments without going for the tedious method of regionalisation of UH wherein the data of storm events for all the gauged catchments of a region are required to be analyzed. In the application of GIUH approach, some of the important geomorphological parameters are required to be derived from the available toposheets. It is extremely difficult for the user to derive the geomorphological parameters from the maps manually. Thus, it discourages the users to adopt GIUH approach. Now, GIS softwares like ILWIS, Arc/Info, ERDAS and GRASS etc. are available for the derivation of these characteristics in a simplified manner. But the number of users who have access of such software is limited.

The unit hydrograph for gauged catchments can be derived by analysing the available rainfall-runoff data of the historical storms. However, for many small catchments the stream flow data are limited and for ungauged catchments these are not at all available. Therefore, the unit hydrograph for such catchments can only be derived using their physical and storm characteristics. This necessitates the development of suitable regional relationship for unit hydrograph derivation. The procedure for this purpose involves derivation of the parameters, for the gauged catchments in the region, that describe the unit hydrograph for ungauged catchments and then the development of the regional relationships between the unit hydrograph parameters with pertinent physiographic and storm characteristics of the gauged catchments. Thus, for modelling the ungauged or poorly gauged catchments the regionalisation process is adopted in which the relationships between the model parameters and physically measurable watershed characteristics are established with the help of nearby gauged catchments. These relationships are then assumed to hold good for ungauged watersheds having similar hydrologic characteristics. In India, such relationships are published for different regions by the CWC.

The limitations of the regional unit hydrograph approaches are: (i) the catchments of which data are used in a regional study have to be similar in hydrological and meteorological characteristics; however, it is usually difficult to locate catchments strictly satisfying these requirements; (ii) while establishing such relations, the inherent limitations of the unit hydrograph theory are also being carried with it. As a result, the prevailing method of predicting the design flood hydrograph for a design storm using the average unit hydrograph will not be appropriate, since the average unit hydrograph does not necessarily reproduce the actual response due to such inherent limitations; (iii) the relationship evolved are based upon the gauged observations in number of catchments in the region. It is practically very difficult to always have gauged catchments available in adequate numbers in a region to enable the development of such relationships; (iv) generally, the data for intense and short duration storms are not available for the derivation of average unit hydrograph for gauged catchments; hence, the average unit hydrograph derived from minor flood events is considered for the regionalisation. It may result in the under estimation of design flood for ungauged catchments.

In the light of above limitations of unit hydrograph regionalization procedure, use of geomorphological characteristics of the drainage basin for deriving the unit impulse response function as proposed by Rodriguez-Iturbe and Valdes seems to have very good

potential. In this approach, a unifying synthesis of the hydrological response of a catchment to surface runoff is attempted by linking the instantaneous unit hydrograph (IUH) with the geomorphological parameters of a basin. Equations of general character are derived which express the IUH as a function of Horton's numbers i.e. area ratio (R_a), bifurcation ratio (R_b) and length ratio (R_l); an internal scale parameter L_n denoting the length of highest order stream; and the peak velocity of streamflow V expected during the storm. The IUH is time varying in character for different storms. This variability is accounted for by the variability in the mean streamflow velocity. Rodriguez-Iturbe and Valdes have derived the basic equations for the GIUH of a third-order basin. But equations for higher-order can be derived with exactly the same framework. But the derivation is complicated and tedious. However, for basins of any order the peak q_{pg} and the time to peak t_{pg} , which are the most important characteristics of the GIUH, are worked out from the derived functional relationship of the GIUH. For the dynamic parameter velocity (V), Rodriguez et al. in their studies assumed that the flow velocity at any given moment during the storm can be taken as constant throughout the basin. The characteristic velocity for the basin as a whole changes throughout as the storm progresses. For the derivation of GIUH, this can be taken as the velocity at the peak discharge time for a given rainfall-runoff event in a basin. However, for ungauged catchments the peak discharge is not known and so this criterion for estimation of velocity cannot be applied. In such a situation the velocity may be estimated using the relationship developed between the velocity and the excess rainfall intensity.

These peak characteristics do not give the complete shape of the GIUH. For obtaining the complete shape one has to resort to the tedious procedure, as mentioned above. To overcome this difficulty an attempt has been made to couple the above equations with the parameters of the Clark rainfall-runoff model. The Clark model concept suggests that the IUH can be derived by routing the unit rainfall excess in the form of time-area diagram through a single linear reservoir. In addition to time-area diagram, two more parameters: (i) the time of concentration (T_c) in hours, which is the base length of the time-area diagram, and (ii) the storage coefficient (R), in hours, of the linear reservoir are required for the derivation of the Clark model IUH.

A new approach has been developed at the National Institute of Hydrology for the estimation of the parameters of the Clark model through use of geomorphological characteristics. The step by step explanation of the procedure for derivation of unit hydrograph for a specific duration using this approach is given here-under:

- (i) Excess rainfall hyetograph is computed either by uniform loss rate procedure or by SCS curve number method or by any other suitable method.
- (ii) For a given storm, the estimate of the peak velocity V using the highest rainfall excess is made by using the relationship between velocity and intensity of rainfall excess.
- (iii) Compute the time of concentration (T_c) using the equation:

$$T_c = 0.2778 \ L/V \quad (3.12)$$

where, L = length of the main channel, V = the peak velocity in m/sec.

- (iv) Compute the peak discharge (Q_{pg}) and of IUH given by following equation:

$$Q_{pg} = 1.31 R_L^{0.43} \left(\frac{V}{L_\Omega} \right) \quad (3.13)$$

where, L_Ω = length in kilometers of the highest-order stream, V = expected peak velocity in m/sec, and R_L = length area ratio by the Horton's provedure.

- (v) Assume two trial values of the storage coefficient of GIUH based Clark model as R_1 and R_2 . Compute the ordinates of two instantaneous unit hydrographs by Clark model using time concentration T_c as obtained in step (iii) and two storage coefficients R_1 and R_1 respectively with the help of following equation:

$$u_i = C I_i + (1-C) u_{i-1} \quad (3.14)$$

where, u_i = ordinate of the IUH at time t , I_i = the i^{th} ordinate of the time-area diagram, C = the routing coefficient = $\Delta t / (R + 0.5\Delta t)$, Δt = the computational interval in hours

- (vi) Find out the peak discharges Q_{pc1} and Q_{pc2} of the instantaneous unit hydrographs obtained for Clark model for the storage coefficients R_1 and R_2 respectively at step (v).
- (vii) Find out the value of objective function using the relation:

$$FCN1 = (Q_{pg} - Q_{pc1})^2, \quad FCN2 = (Q_{pg} - Q_{pc2})^2 \quad (3.15)$$

- (viii) Compute the first numerical derivative FPN of the objective function FCN with respect to parameter R as:

$$FPN = \frac{FCN1 - FCN2}{R_1 - R_2} \quad (3.16)$$

- (ix) Compute the next trial value of R using the following governing equations of Newton-Raphson's method:

$$\Delta R = \frac{FCN1}{FPN} \quad (3.17)$$

and $R_{NEW} = R_1 + \Delta R$

- (x) For the next trial consider $R_1 = R_2$ and $R_2 = \text{RNEW}$ and repeat steps (v) and (ix) till one of the following criteria of convergence is achieved.

(a) $\text{FNC2} = 0.000001$, (b) No. of trials exceeds 200, (c) $\text{ABS}(\Delta R)/R_1 = 0.001$

- (xi) The final value of storage coefficient (R_2) obtained as above is the required value of the parameter R corresponding to the value of time of concentration (T_c) for the Clark model.
- (xii) Compute the instantaneous unit hydrograph (IUH) using the GIUH based Clark model with the help of final values of storage coefficient (R), time of concentration (T) as obtained in the step (xi) and time area diagram.
- (xiii) Compute the D-hour unit hydrograph (UH) using the relationship between IUH and UH of D-hour as given by following equation:

$$U_i = \frac{1}{n} [0.5 u_{i-n} + u_{i-n} + u_{i-n+1} + \dots + u_{i-1} + 0.5 u_i] \quad (3.18)$$

U_i = ith ordinate of unit hydrograph of duration D-hour and at computational interval Δt hours, n = number of computational intervals in duration D-hours.

3.2.1 Derivation of GIUH for small catchments of upper Narmada and Tapi subzone 3 (c)

The mathematical model developed at the National Institute of Hydrology which enables evaluation of the Clark model parameters using the geomorphological characteristics of the basin has been applied for deriving the instantaneous unit hydrograph and thereby for simulation of flood events of the three bridge catchments viz. Bridge Nos. 249, 930 and 253 of upper Narmada and Tapi subzone 3 (c).

The straight line base flow separation techniques has been used to compute the direct surface runoff ordinates from the total runoff ordinates. The raw data had been analyzed by the Central Water Commission for deriving the regional unit hydrograph for the subzone. The same analyzed data have been used in this study for all the events of the three bridge catchments.

(a) Development of relationship between velocity and intensity of the excess rainfall

Since the Manning's roughness coefficient prevailing at the time of occurrence of events can not be ascertained. It is not possible to employ approach-I explained in the technical report (TR(BR)-132). For all the three bridge sites the discharges and the corresponding velocities for different range of depth of flow is available. Therefore the approach-II given in the above report, is utilized for the development of the relationship between the equilibrium velocity and the corresponding excess rainfall intensity. The plot

between the peak velocity and the corresponding excess rainfall intensity for the three bridge catchments are given in Fig. 3.3 (a) to (c) respectively.

The relationship obtained for the three bridge catchment sites are as given below:

$$V = 1.072 * i^{0.6129} \quad \{\text{For Br. No. 249}\} \quad \dots (3.19)$$

$$V = 0.928 * i^{0.4429} \quad \{\text{For Br. No. 930}\} \quad \dots (3.20)$$

$$V = 1.072 * i^{0.5100} \quad \{\text{For Br. No. 253}\} \quad \dots (3.21)$$

(b) Estimation of geomorphological characteristics

The topographical maps prepared for the three bridge catchments, number of streams, average lengths and average areas for each stream order is found out from the topographic maps. These are then plotted against the order of the stream. Bifurcation, length and area ratios are calculated as the slope of the best fit lines through these plotted points given by the Horton's laws of stream numbers, lengths and areas respectively. The summary of this evaluation of geomorphological characteristics for all the three catchments is given in Table 3.4.

Table 3.4 : Geomorphological characteristics for all the three catchments

Catchment	Order	No. of Streams	Average Length (km)	Average Area (km ²)	Constants
TEMUR (Br. No. 249) L=56.51 km	1	1432	0.282	0.084	$R_b = 4.17$ $R_l = 3.89$ $R_a = 5.81$
	2	291	0.982	0.501	
	3	61	2.224	2.884	
	4	12	6.250	16.596	
	5	4	9.187	95.499	
	6	1	24.750	518.67	
UMAR (Br. No. 930) L=33.60 km	1	363	0.618	0.347	$R_b = 4.04$ $R_l = 2.56$ $R_a = 4.76$
	2	94	0.527	1.013	
	3	24	2.050	4.572	
	4	7	6.050	16.960	
	5	1	30.00	226.270	
TYRIA (Br. No. 253) L=35.42 km	1	265	0.448	0.139	$R_b = 4.08$ $R_l = 2.75$ $R_a = 4.58$
	2	59	0.867	1.151	
	3	13	1.977	5.475	
	4	2	6.900	47.490	
	5	1	4.000	114.22	

From this study the following conclusions are drawn:

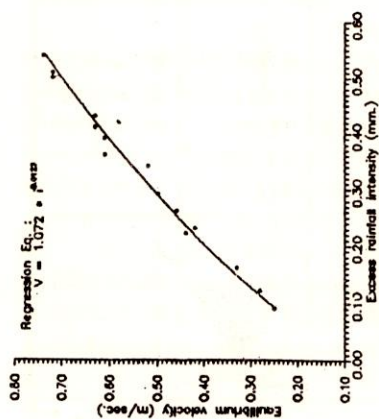


Fig. 3.3 (c) : PLOT OF EQUILIBRIUM VELOCITY WITH THE VELOCITY
 FOR BR. NO. 748.

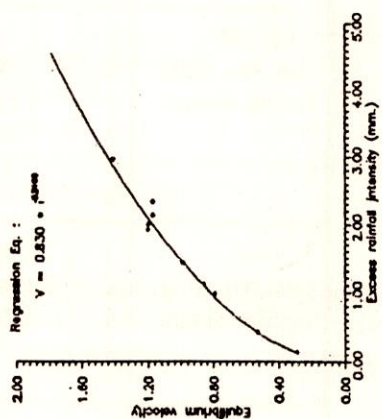


Fig. 3.3 (e) : PLOT OF EQUILIBRIUM VELOCITY WITH THE INTENSITY
 FOR BR. NO. 753.

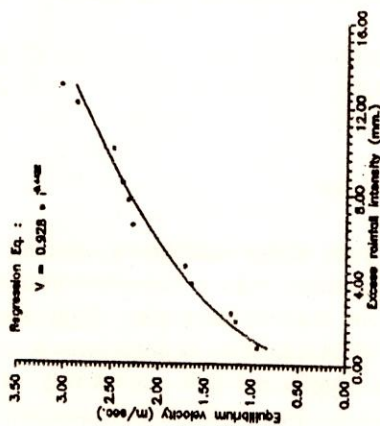


Fig. 3.3 (b) : PLOT OF EQUILIBRIUM VELOCITY WITH THE INTENSITY
 FOR BR. NO. 930.

- (1) The parameters of the proposed GIUH based Clark model could be estimated satisfactorily by using geomorphological characteristics instead of using the observed runoff data, which are not available for the ungauged catchments.
- (2) The ratio between storage coefficient (R) and the sum of storage coefficient and the time of concentration (T_c), i.e. $R/(T_c + R)$, has a unique value for a particular catchment. Thus, the value of this ratio may be ascertained for a catchment which may then be used for employing simple Clark model also.
- (3) This methodology provides a different unit hydrograph for each event. This shows that the proposed methodology is capable of simulating the non-linear response to different storm events. However, this capability is limited in the sense that only the highest rainfall intensity block is made the criteria for getting the peak velocity.
- (4) Generally, the ϕ -index method of computing the excess rainfall under estimates the infiltration in the beginning and over estimates in it in the later portion of the storm. This shifts the entire hydrograph to the left side of the observed hydrograph. A better a priori estimate may be made using methods like SCS curve number for which different catchment characteristics like soil type, land use, treatment class, hydrologic conditions and antecedent moisture conditions would be needed as input.
- (5) For the estimation of the velocity, a relationship is established between the velocity and intensity of excess rainfall for the three bridge catchments on the basis of the observed discharge and corresponding velocities at the gauging sites. It must not be argued that this type of information would be available for the gauged catchments only. For this, only at few points along the depth of the section, the discharge and simultaneous velocity measurements are needed which may be observed with a little effort and cost. However, in case the value of the Manning's roughness coefficient can be assumed with sufficient accuracy then the above requirement of the discharges and velocities may be avoided.
- (6) Further study may be carried out to examine the effects of using the velocity-excess rainfall intensity relationships of the nearby catchments over the simulation results of various events of different small catchments. Possibility of using a regional velocity-excess rainfall relationship may also be examined.
- (7) The most important factor in this methodology is the estimation of the peak velocity. This peak has been estimated corresponding to the highest rainfall block. Though this criteria has worked satisfactorily but it would be improved further. This improvement may be done in the light of the fact that it is not only the highest rainfall intensity block but the whole pattern of rainfall distribution over the event which would govern the peak velocity. The incorporation of an improved criteria may further improve the reproduction of the runoff hydrographs.

In another study, a methodology to derive the gamma pdf parameters is proposed using dimensionless Horton numbers, and characteristic stream flow velocity which in turn is estimated from basin lag calculated from basin area. The applicability of the proposed

method has been tested by simulation runs using data for four sub-basins of river Narmada namely Narmada at Manot, Burhner at Mohegaon, Banjar at Hridenagar and Sher at Belkheri. The results of simulation are in reasonable agreement with observed records.

For details of the study, the reader may please refer NIH Report No TR/BR-132 and TR/BR-113.

3.3 Relationship between Frequency of Rainfall and Frequency of Flood for a Catchment of Upper Narmada and Tapi Subzone 3(c)

Relationship between Frequency of Rainfall and Frequency of Flood for a Catchment of Upper Narmada and Tapi Subzone 3 (c) has also been studied. In this study, floods of various return periods have been estimated for the catchment defined by Bridge No. 253 of the Upper Narmada and Tapi Subzone 3(c) using various methods involving frequency analysis of rainfall and frequency analysis of annual maximum peak floods computed from the annual maximum excess rainfall of the design storm duration. The floods of various return periods have also been computed using the regional flood frequency analysis approach based on the observed annual maximum peak flood record for 13 gauging sites of the Subzone 3(c). Sensitivity analysis has also been conducted by increasing and decreasing the peak of the unit hydrograph, which has been used to convert the excess rainfall hyetographs into direct surface runoff hydrographs for identifying the peak values of floods.

The analysis carried out based on rainfall data shows that the floods are under estimated by 4.3% to 5.7% for the return periods of 2 to 200 years, by frequency analysis of floods as compared to the frequency analysis of rainfall.

The regional flood frequency methods used in the study, viz. SREV1, SRGEV and SRWAKE are based on 'at site and regional data'; whereas, RGEV method is based on 'regional data' alone. Flood estimates obtained by these methods show a deviation of -5.4% for SREV1, 0.4% for SRGEV, -1.4% for SRWAKE and 7.5% for RGEV methods for the return period of 50 years. The deviation varies from -3.1% to 13.5% for the return period of 100 years. For the return period of 200 years the deviation is -1.4% for SREV1, 11.3% for SRGEV, 2.8% for SRWAKE and 19.1% for RGEV method. Percentage deviations for flood estimates by the SRWAKE method, for the return periods of 50, 100 and 200 years are -1.4%, 1.2% and 2.8% respectively; which show that the flood frequency estimates obtained by SRWAKE method are very close to the flood frequency estimates obtained by the method based on frequency of rainfall [RAIN(CS)]. The rainfall data used in the study is of the limited record length of 19 years of one raingauge station only; hence the results of the study may be considered as indicative only, and detailed studies with long term data for a large number of catchments should be carried out for drawing more realistic conclusions.

For details of the study, the reader may please refer NIH Report No CS/AR-206.

3.4 Remarks

Based on the comparative flood frequency studies involving at-site, at-site and regional and regional methods using Extreme Value-1 (EV-1), General Extreme Value (GEV) and Wakeby distributions as well as the USGS method carried out for the Upper Narmada and Tapi subzone 3(c) and Lower Narmada and Tapi subzone 3(b) at site and regional GEV method is found to be robust. The conventional empirical flood formulae do not provide floods of desired return periods. However, the flood formulae developed in this study are capable of providing flood estimates for different return periods. Regional flood frequency relationships and flood formulae have been developed using the L-moment based GEV distribution.

The methodology developed at the Institute enables estimation of the Clark model parameters, which in turn may be used for obtaining the complete shape of the IUH. This proposed approach has been called as **"GIUH based Clark model"**. It may be noticed here that by employing this new approach the requirement of runoff data for the calibration of Clark model parameters is altogether eliminated. Thus, in situations where the data availability is a problem, this approach can be advantageously applied using geomorphological characteristics of the basin. These geomorphological characteristics for a basin may easily be evaluated from the topomaps. In general, the reproduction of observed flood events using this approach is good for all the events considered in the studies. Further investigations and are needed to improve upon the present form of the model structure by incorporating the latest developments in the area of fluvial geomorphology.

Regional transposability of flow parameters is one of the most important problems which concerns the hydrologists. Various issues which are still unresolved and being investigated by many researchers in the area of regionalisation of flow parameters include the homogeneous regions versus non-homogeneous regions, appropriate methodology to develop regional relationships for flow parameters and various physiographic and climatological characteristics. The flow parameters require regionalization include flood frequency, unit hydrograph, low flow and flow duration curves, etc. Often the carried out regional studies have limited scope as the adequate amount of data are not available for these studies. However, the methodology suggested above in the Section 3.0 for regionalisation the hydrological variables viz. regional flood frequency analysis, regional unit hydrograph derivation as well as geomorphological instantaneous unit hydrograph may be used for development of quite reliable regional relationships for different regions of India provided adequate data are made available.

4.0 HYDROLOGICAL MODELING

Development and application of computer based mathematical models for solving the various hydrological problems have increased significantly during last two decades. A mathematical model provides a quantitative mathematical description of the processes through a collection of mathematical equations, logical statements, boundary conditions and initial conditions expressing relationships between inputs, variables and parameters.

A large number of hydrological models exist. However, many of the models function in basically the same way. A model represents the physical/ chemical/biological characteristics of the catchment and simulates the natural hydrological processes. It is not an end in itself but is a tool in a larger process which is usually a decision problem. A model aids in making decisions, particularly where data or information are scarce or there are large numbers of options to choose from. It is not a replacement for field observations. Its value lies in its ability, when correctly chosen and adjusted, to extract the maximum amount of information from the available data, so as to aid in decision making process.

The hydrological modeling is required not only for estimating the water yield and design parameters but also for understanding and evaluating the effects of developmental and other activities on hydrological regime of a river basin. The challenging task of preparing developmental plans for managing the limited resources of river basins for their optimal use necessitates application of multi-disciplinary approach system engineering for comprehensive planning of water resources projects. The use of physically based distributed modeling approach can provide such information and could also incorporate scenarios of proposed/likely land use changes in the river basin for use in planning/operation of water resources projects.

In the area of hydrological modeling significant amount of studies were carried out by the Institute to deal with calibration, validation and simulation of lumped conceptual models (event based as well as continuous) and physically based models for some of the sub-basins of Narmada river basin. Flood hydrograph simulation study was carried out in Kolar sub-basin using event based model. Watershed Hydrology Simulation Model (WAHS) was also applied to simulate the flood event of the Kolar sub-basin. Excess rainfall and direct surface runoff modeling was carried out for some of the sub-basins using the geomorphological characteristics. Simple linear modeling of river flow was carried out in one of the case studies. BATS model was used to carry out the sensitivity analysis of the various hydrological parameters on the hydrological response using the data of few sub-basins of Narmada River basin. Impact assessment studies were also carried out for some of the sub-basins. SCS method was used for modeling the runoff.

The hydrological modelling efforts of the Institute using Narmada basin data are summarised below:

4.1 Application of Event Based Models

4.1.1 Development of event based distributed rainfall-runoff model

An event based distributed rainfall-runoff model has been developed for the simulation of flood hydrograph and estimation of design flood hydrograph. The model has very simple structure. It involves the representations of the catchment into various zones obtained by dividing it into a number of isochronal areas. The direct surface runoff generated from each of these zones are suitably lagged in time according to the time of travels for individual areas. These generated direct surface runoff hydrographs are superimposed in order to obtain the translated direct surface runoff. This hydrograph is then routed through a single linear reservoir. Thus, the model consists of two parameters viz. time of concentration (T_c) and the storage coefficient (R). Rosenbrock optimization technique is used to calibrate these parameters alongwith trial and error method. The schematic representation of the distributed model is shown in Fig. 4.1. During the calibration, the model is run for various trial values of time of concentration and corresponding storage coefficient is determined using Rosenbrock optimization technique. Then the set of those parameter values is chosen which provides the better reproduction of the observed hydrograph.

The developed model has been applied to simulate the six historical storm events of Kolar river basin. The hourly rainfall-runoff data for four storm events are used for the calibration of the model. However, the data for the remaining two storm events are utilized for the validation of the model. Performance of this model for the simulation of flood events is found to be good. This model can be applied for design flood estimation, filling of short term runoff records, reservoir inflow computation and extension of runoff records and real time flow forecasting.

For details of the study, the reader may please refer NIH Report No CS/AR-130.

4.1.2 Application of WAHS model to Kolar basin

A quasi-conceptual event-based model that simulates individual rainfall-runoff events in a river basin using its geomorphological parameters called Watershed Hydrology Simulation Model (WAHS), was applied to simulate flood events of Kolar basin in central India. It is two parameters model and assumes that the transformation of effective rainfall to direct runoff is linear and time invariant. The model computes the Instantaneous Unit Hydrograph (IUH) of the basin using a geomorphological approach and the direct surface runoff (DSRO) is calculated by convoluting the derived IUH with effective rainfall hyetograph. The results of study suggest that the model can predict peak and general shape of the flood hydrograph reasonably well.

For details of the study, the reader may please refer NIH Report No CS/AR-136.

$TRH_1, TRH_2, \dots, TRH_n$ — Average rainfall over different isochronous zones (mm)
 $A_1, A_2, \dots, A_n$ — Area of different isochronous zones (Km²)
 $ERH_1, ERH_2, \dots, ERH_n$ — Excess rainfall volume hyetograph contributed from different isochronous zones (m³)
 Δt — Sampling interval (hrs)
 DRH — Direct surface runoff hydrograph (m³/s)
 $BASE$ — Base flow hydrograph (m³/s)
 DIS — Discharge hydrograph (m³/m)

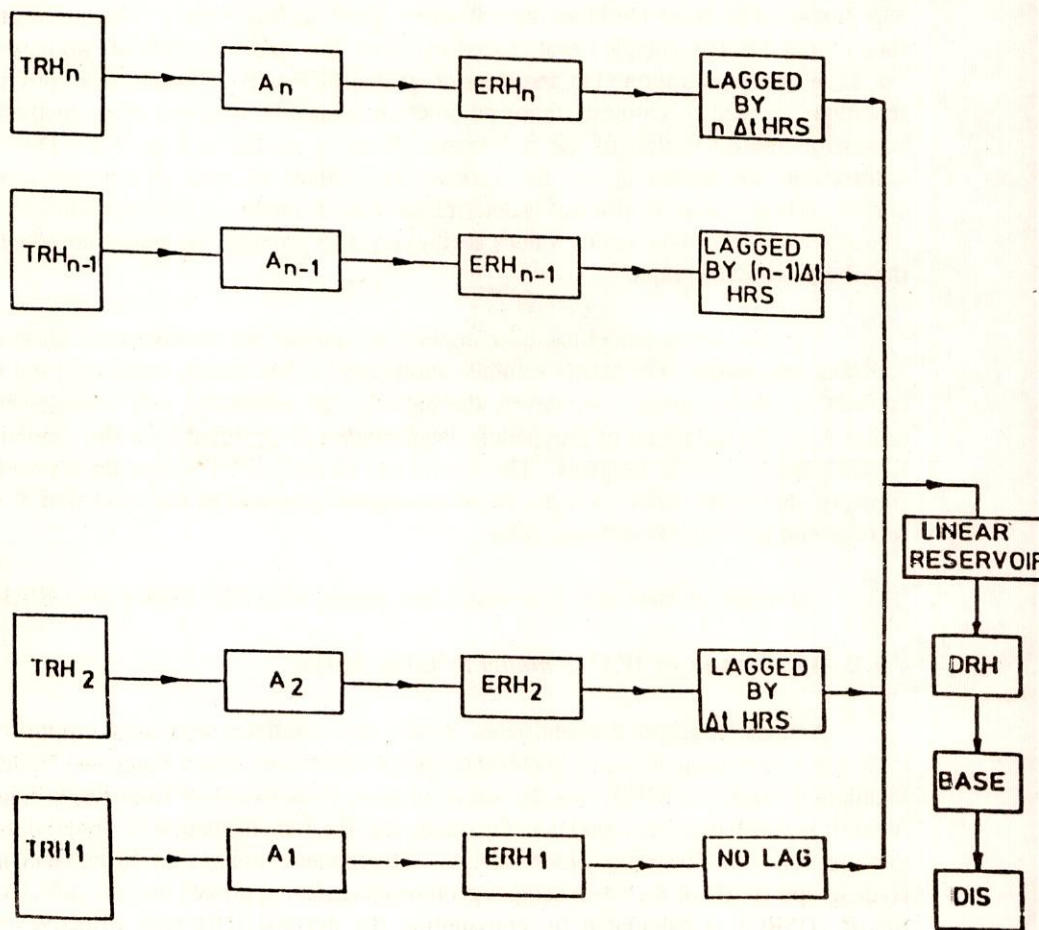


FIG. 4-1 - SCHEMATIC REPRESENTATION OF DISTRIBUTED MODEL

4.2 Application of Continuous Models

4.2.1 Application of SHE model to six sub-basins of Narmada basin

The entire land phase of the hydrological cycle has been modelled for the six sub-basins of the Narmada basin using the SHE model. These sub-basins include Kolar, Barna, Sher, Ganjal, Hiran and Narmada upto Manot. The Systeme Hydrologique Europeen - European Hydrological System (SHE) is an advanced, physically based, distributed catchment modelling system. It has been developed jointly by the Danish Hydraulic Institute, the British Institute of Hydrology, U.K. and SOGREAH (France) with the financial support of the Commission of the European Communities. Currently British responsibility for the SHE lies with the Natural Environment Research Council's Water Resource System Research Unit at the University of Newcastle upon Tyne (UON). In France the responsibility has been transferred from SOGREAH to Laboratoire d'Hydraulique de France (LHE).

The SHE was developed from the perception that conventional rainfall/runoff models are inappropriate to many hydrological problems, specially those related to the impact of man's activities of land use change and water quality. These problems can be solved only through the use of models which have a physical basis and allow for spatial variations within a catchment. The SHE is a physically based model in the sense that the hydrological process of water movement are modelled either by finite difference representations of the partial differential equations of mass, momentum and energy conservation or by empirical equations derived from independent experimental research. Spatial distribution of catchment parameters, rainfall input and hydrological response is achieved in the horizontal by an orthogonal grid network and in the vertical by a column of horizontal layers at each grid square. River channels are superimposed on the grid element boundaries. Parameters must be evaluated as appropriate for each grid element, river link and subsurface layer. Basic processes of the land phase of the hydrological cycle are modelled in separate components viz. interception by the Rutter accounting procedure; evapotranspiration, by the Penman-Monteith equation or by an approach developed by Kristensen and Jensen (1975); overland and channel flow by simplifications of St. Venant equations; unsaturated zone flow, by one dimensional Richard's equation; saturated zone flow by the two dimensional Boussinesq equation and snowmelt, by an energy budget method. The schematic representation of the SHE model is shown in Fig. 4.2.

(a) Data used

The various rainfall, runoff, topographical, soil, landuse, ground water data of the six sub-basins were used. These data were collected from the various organizations. Field investigations were carried out for the Kolar basin for obtaining the various soil and vegetation data of this sub-basin, which were used for simulating the hydrological response of this sub-basin as well as conducting the sensitivity analysis studies. The details of the data collected during the field investigation are given in Section 11.1 under field and laboratory investigations.

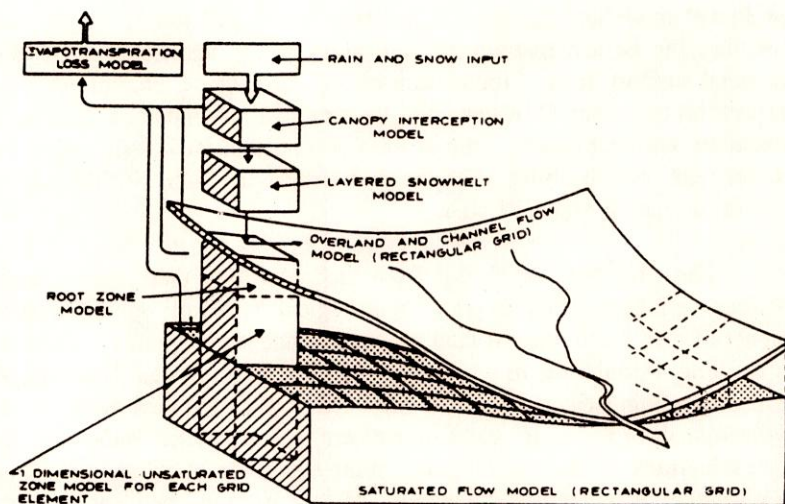
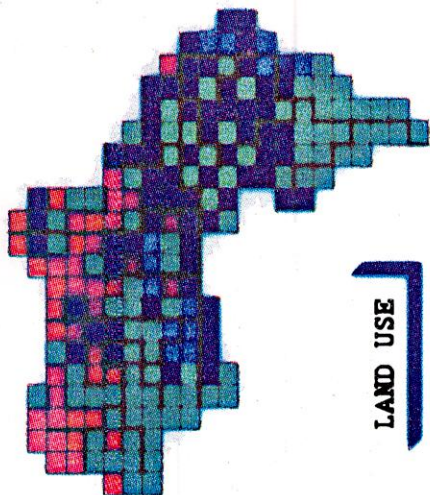
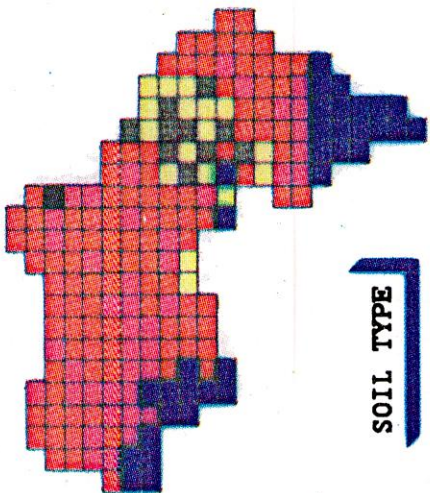


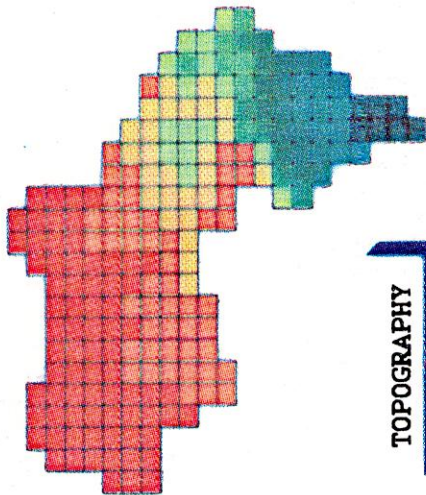
Fig.4-2 Schematic representation of the SHE.



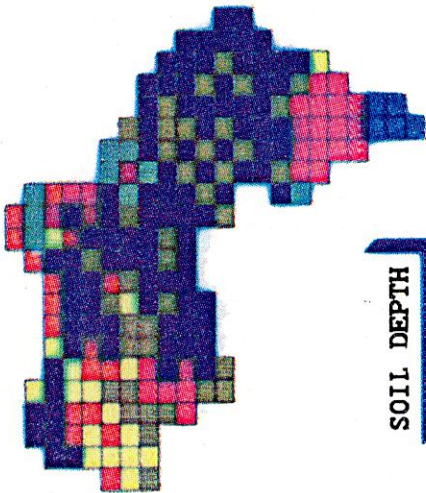
LAND USE



SOIL TYPE



TOPOGRAPHY



SOIL DEPTH

LAND USE, SOIL TYPE, TOPOGRAPHY AND SOIL DEPTH FOR
KOLAR SUB-BASIN FOR 2 km. x 2 km. GRID SIZE

(b) Discussion of Results

The hydrological response of the six sub-basin was simulated using the SHE model. The observed and simulated hydrographs at the outlets of the study areas were compared. The variation of ground water table, variation of soil moisture as well as comparison of the observed pan evaporation and simulated evapotranspiration was carried out. The study of impact of soil and land use changes on hydrological regime using SHE model as well as change of the grid scale were also studied. The SHE model was also applied to study the hydrological problems for irrigation command area using the data in the Barna command area in the Narmada river basin. The values of the final parameters adopted for calibration for one of the sub-basins viz. Kolar sub-basin are given in Table 4.1. A typical plot showing variation of moisture content, observed potential evaporation, simulated actual evapotranspiration and soil moisture deficit for a grid under dense forest of the Ganjal sub-basin of River Narmada given at Fig.4.3.

Table 4.1 : Final Parameters for Kolar Basin

	Black Soil		Yellow Soil		Red Soil	
WASTE LAND						
1. Proposed Soil Depth (m)	.3		%		.3	
2. Calibrated depth (m)	.2				.2	
3. Ks {UZ} (mm/hr)	2				20	
4. Kstr {OC} (m 1/3/s)	7				7	
5. No. of Grids (-)	1				17	
OPEN FOREST						
1. Proposed Soil Depth (m)	.3	.5	.3	.5	.3	.5
2. Calibrated depth (m)					.5	.7
3. Ks {UZ} (mm/hr)	%	%	%	%	50	50
4. Kstr {OC} (m 1/3/s)					5	5
5. No. of Grids (-)					22	2
MEDIUM DENSE FOREST						
1. Proposed Soil Depth (m)	.3	.5	.3	.5	.3	.5
2. Calibrated depth (m)			.5		.5	.7
3. Ks {UZ} (mm/hr)	%	%	40	%	50	50
4. Kstr {OC} (m 1/3/s)			3		3	3
5. No. of Grids (-)			17		43	6
DENSE FOREST						
1. Proposed Soil Depth (m)	.3	.5	.3	.5	.3	.5
2. Calibrated depth (m)					.5	
3. Ks {UZ} (mm/hr)	%	%	%	%	50	%
4. Kstr {OC} (m 1/3/s)					4	
5. No. of Grids (-)					13	

AGRICULTURE			
1. Proposed Soil Depth (m)	8.0	8.0	8.0
2. Calibrated depth (m)	8.0		
3. Ks {UZ} (mm/hr)	4	%	%
4. Kstr {OC} (m 1/3/s)	7		
5. No. of Grids (-)	5		
AGRICULTURE			
1. Proposed Soil Depth (m)	1.7	1.7	1.7
2. Calibrated depth (m)	4.0		4.0
3. Ks {UZ} (mm/hr)	4	%	40
4. Kstr {OC} (m 1/3/s)	7		7
5. No. of Grids (-)	13		13
AGRICULTURE			
1. Proposed Soil Depth (m)	1.0	1.0	1.0
2. Calibrated depth (m)	2.5		2.5
3. Ks {UZ} (mm/hr)	4	%	40
4. Kstr {OC} (m 1/3/s)	7		7
5. No. of Grids (-)	3		13
AGRICULTURE			
1. Proposed Soil Depth (m)	.5	.5	.5
2. Calibrated depth (m)	1.0	1.0	1.0
3. Ks {UZ} (mm/hr)	4	20	40
4. Kstr {OC} (m 1/3/s)	7	7	7
5. No. of Grids (-)	8	10	22

In one of the studies carried out for the Kolar subcatchment, the SHE was setup for a single column (Fig. 4.4) representing an arbitrary chosen point in the catchment, and the runoff from the plot was simulated, using different parameter values of soil depth, soil type and vegetation type. The simulations were carried out during the period 1986-1988.

(i) Impact of soil depth

The soil depth determines, in combination with soil properties in the profile, the storage capacity of the soil. Shallow soils are filled earlier than deep soil may, therefore, generate surface runoff soon after the monsoon has started. Fig. 4.5 show the influence of soil depth on the monsoon runoff for four depths of a 'black' soil and three depths of a 'red' soil. The figure clearly illustrates that the runoff volume is inversely proportional to the depth. This is the most pronounced in moderately wet years (1987 and 1988). The effect seems more significant for the 'black' soil than for the 'red' soil, indicating that shape of the soil moisture retention curve influences the capillary rise, and thereby the evapotranspiration rate.

(ii) Impact of soil type

The impact of soil type on runoff generation is shown in Fig. 4.6 which illustrates that the soil type plays an important role when the soil is deeper than 2.5 meters. Since a

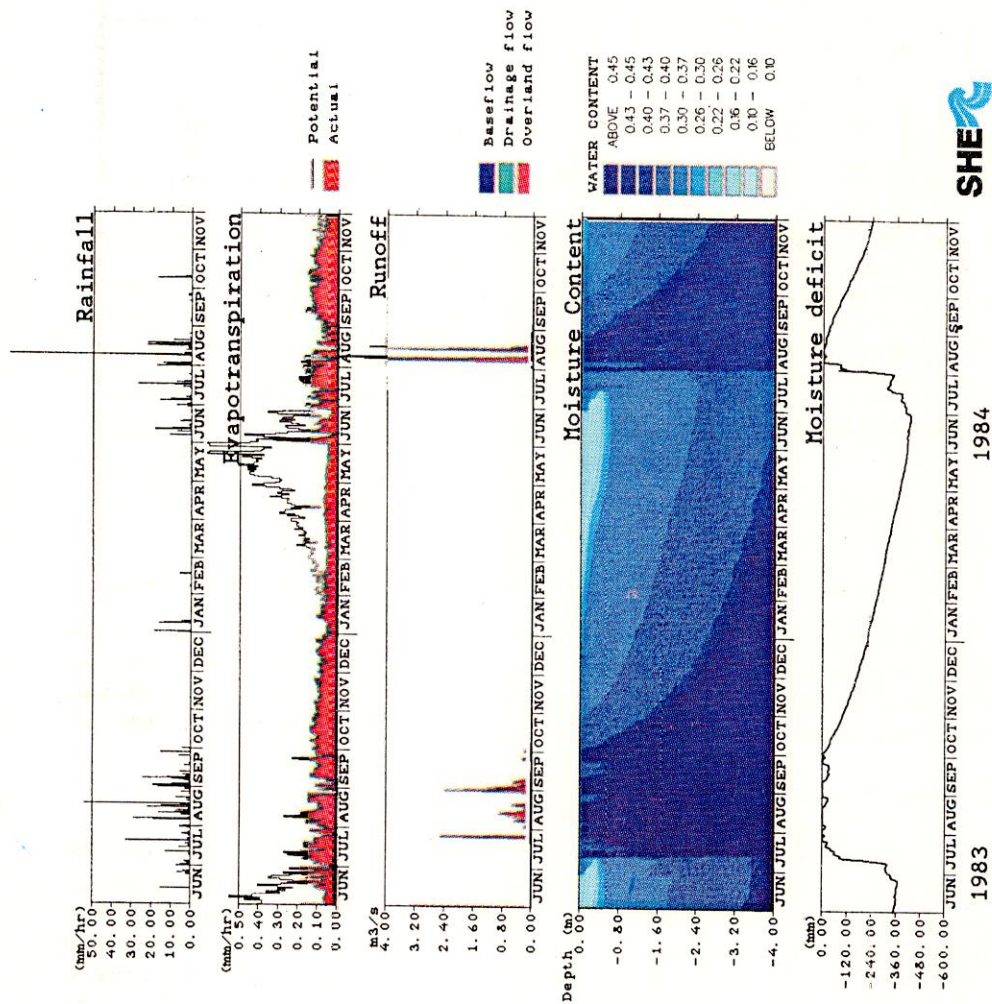


Fig. 4.3 : Variation of moisture content, observed potential evaporation, simulated actual evapotranspiration and soil moisture deficit for a grid under dense forest in Ganjal sub-basin.

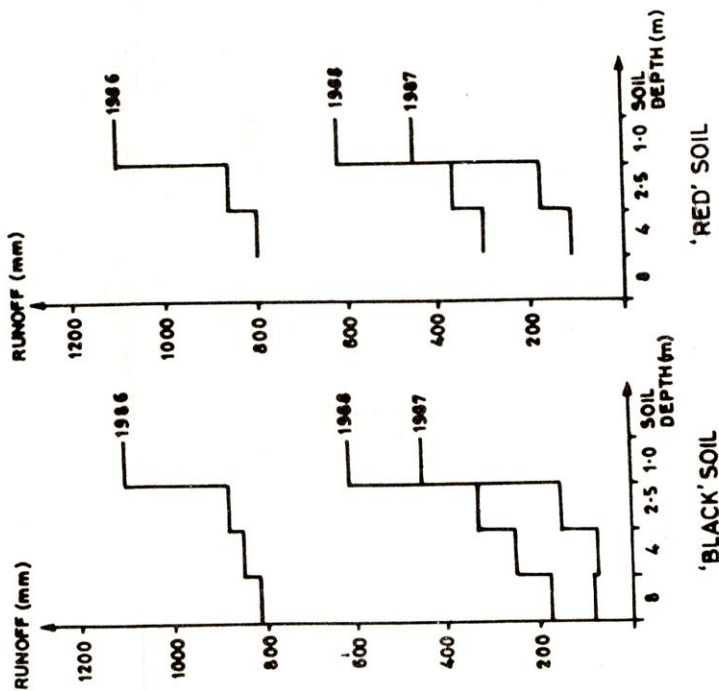


FIG.4.5: SURFACE RUNOFF AS A FUNCTION OF SOIL DEPTH FOR A 'BLACK' AND 'RED' SOIL.

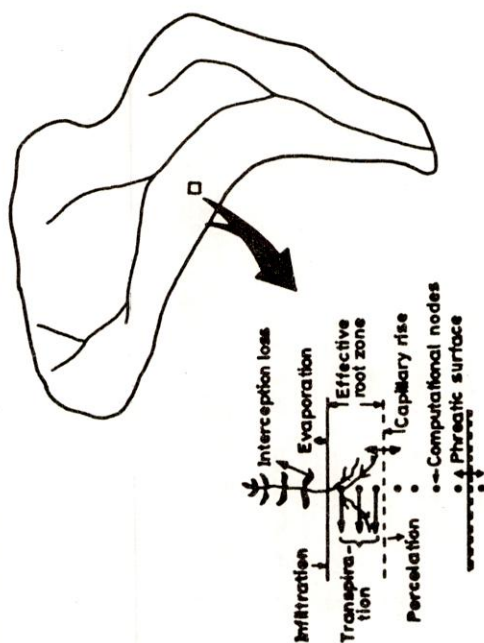


FIG.4.4: SOIL COLUMN REPRESENTATION IN THE SHE

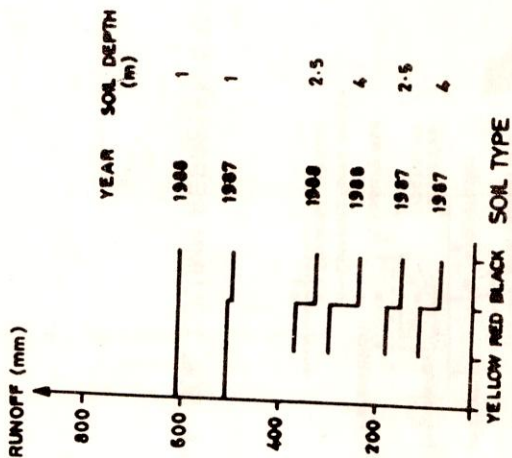


FIG.4.6: SURFACE RUNOFF AS A FUNCTION OF SOIL TYPE FOR THREE DIFFERENT DEPTHS.

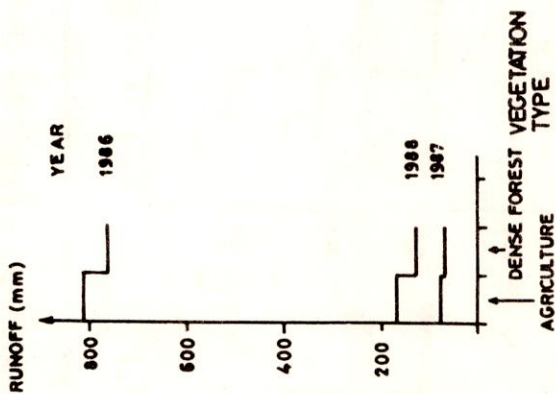


FIG.4.7: SURFACE RUNOFF AS A FUNCTION OF VEGETATION TYPE, REFLECTED IN THE DIFFERENT AREA INDEX

vegetation. The vegetation type may, therefore, influence both total runoff volume and shape of the hydrograph.

The quantitative effects of vegetation were tested by replacing the parameter values describing a dense forest with the corresponding parameters for an agricultural crop. The result is shown in Fig. 4.7. It should be noted that the potential evapotranspiration rate and the saturated hydraulic conductivity were not changed in the runs.

The effects of surface runoff were also tested, and the results indicated that the total long-term runoff is not influenced, but the hydrograph showed a more flashy response for the smoother surface.

From the summary of six sub-basins (Figs. 4.8 and 4.9) it can be seen that except for Sher sub-basin, the results are of a similar goodness and do not indicate any general difference in goodness between the validation and the calibration periods. The relatively poorer results from the Sher sub-basin may be due to the very poor rainfall data availability in the sub-basin.

The modelling results are considered satisfactory taking the general data availability and quality into account. Two key conclusions, which have been derived from the studies, may be emphasized here.

- (1) The main source of uncertainty with regard to runoff simulations is the limited amount of rainfall data. The uncertainty in the basin rainfall input data is generating an uncertainty in the simulated runoff, which can not be reduced by collection of other field data. Thus, the uncertainty due to incomplete rainfall data may be considered a lower uncertainty level for the simulated runoff.
- (2) The rainfall-runoff simulation results are of the same degree of accuracy as would have been expected with simpler hydrological models of the lumped conceptual type. However, in addition to runoff simulations, the SHE modelling provides detailed simulations of the various hydrological processes within the catchment by use of all existing data on topography, soil, vegetation, geology, meteorology etc.

It has been realized that SHE modelling using 2 km * 2 km grid squares do not provide a fully physically based and fully distributed description of the hydrological regime. For instance, the real river channel network is too dense to be accurately resolved in such a coarse discretization and many of the smallest channels could not be included in the model representation. The simplification has the following effects amongst others on the SHE process representation.

- (1) The surface water, which in the basin runs as overland flow over a relatively longer distance until it joins one of the lower order streams. Thus, what in reality should be channel routing is in the model represented as overland flow routing, implying that the overland flow resistance

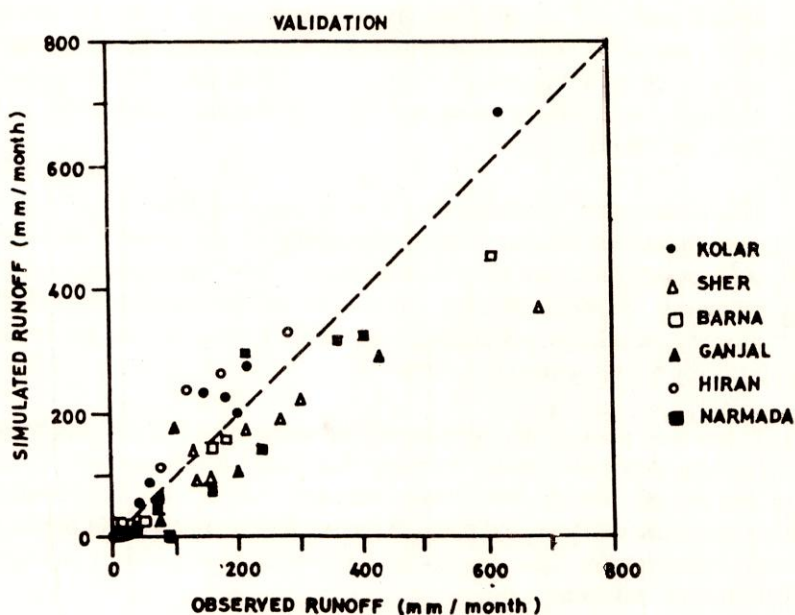
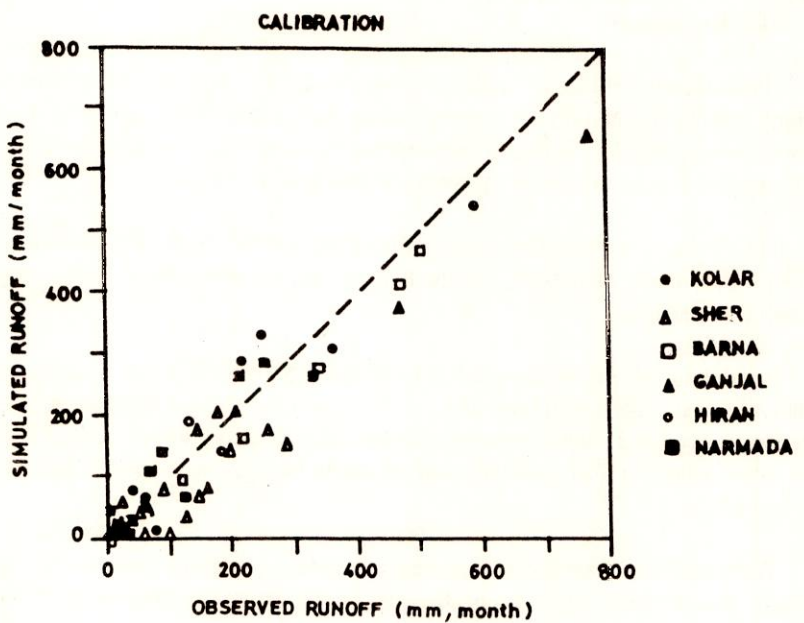


Fig.4-3: Simulated monthly monsoon (June-October) runoff compared with measured values for the calibration and validation periods. Results are from all six catchments.

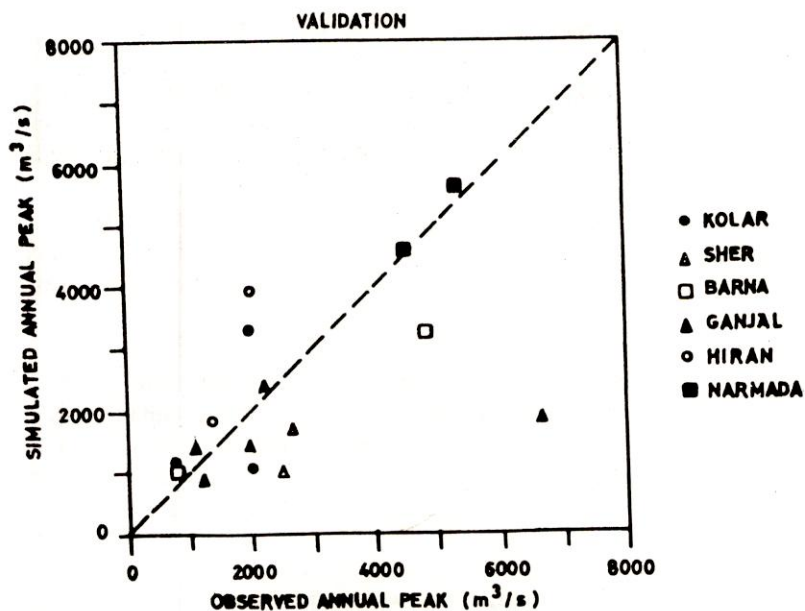
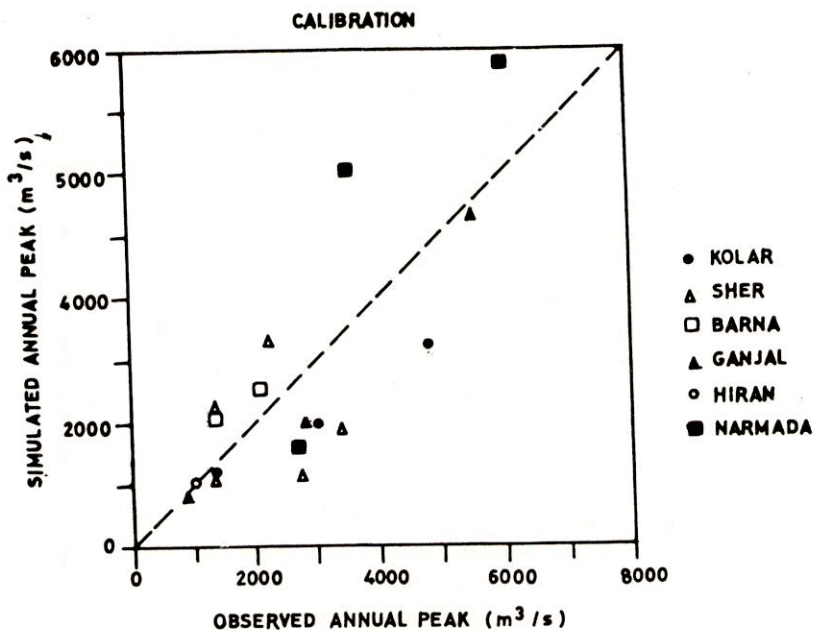


Fig.4.9 Simulated annual peak discharges compared with measured values for the calibration and validation periods. Results are from all six catchments.

shallow soil becomes completely dry during the dry season. The difference in runoff from the three soils is very small as shown by the curves for 1 meter.

(iii) Impact of vegetation type

Two important parameters characterising the vegetation type are the leaf area index and the root depth. Vegetations with deep roots can extract water from deeper areas of soil profile, and thereby create a larger moisture deficit in the profile. The antecedent moisture content at the beginning of the monsoon period is, therefore, generally lower in a dense forest compared with a grass area. The vegetation height affects the surface roughness for the atmospheric boundary layer above the canopy, and thereby, creates turbulence in the air, which will influence the transport of the moist air from the area. Furthermore, the albedo and thus the net energy available at a surface for evapotranspiration depends on the vegetation. The vegetation type may, therefore, influence both total runoff volume and shape of the hydrograph.

The quantitative effects of vegetation were tested by replacing the parameter values describing a dense forest with the corresponding parameters for an agricultural crop. The result is shown in Fig. 4.7. It should be noted that the potential evapotranspiration rate and the saturated hydraulic conductivity were not changed in the runs.

The effects of surface runoff were also tested, and the results indicated that the total long-term runoff is not influenced, but the hydrograph showed a more flashy response for the smoother surface.

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The modelling results are considered satisfactory taking the general data availability and quality into account. Two key conclusions, which have been derived from the studies, may be emphasized here.

- (1) The main source of uncertainty with regard to runoff simulations is the limited amount of rainfall data. The uncertainty in the basin rainfall input data is generating an uncertainty in the simulated runoff, which can not be reduced by collection of other field data. Thus, the uncertainty due to incomplete rainfall data may be considered a lower uncertainty level for the simulated runoff.
- (2) The rainfall-runoff simulation results are of the same degree of accuracy as would have been expected with simpler hydrological models of the lumped conceptual type. However, in addition to runoff simulations, the SHE modelling provides detailed simulations of the various hydrological

processes within the catchment by use of all existing data on topography, soil, vegetation, geology, meteorology etc.

It has been realized that SHE modelling using 2 km * 2 km grid squares do not provide a fully physically based and fully distributed description of the hydrological regime. For instance, the real river channel network is too dense to be accurately resolved in such a coarse discretization and many of the smallest channels could not be included in the model representation. The simplification has the following effects amongst others on the SHE process representation.

- (1) The surface water, which in the basin runs as overland flow over a relatively longer distance until it joins one of the lower order streams. Thus, what in reality should be channel routing is in the model represented as overland flow routing, implying that the overland flow resistance coefficient is not fully physically based but has to be estimated through calibration. With the calibrated resistance coefficients, the model provides good results, because the kinetics of overland flow and channel flow are, basically, the same.
- (2) In the simulation, the groundwater draining to the river channels as baseflow has to travel over a longer distance, because the river network is less dense in the model. Therefore, the simulated phreatic surface gradients are not fully correct, implying that the estimation of the hydraulic conductivity through calibration will somehow compensate for this. Like the above overland flow case, this has no effect on the quality of the simulated outlet hydrograph, because the basic dynamics (in this case linear) are preserved, but the parameter values cannot be taken directly from point field measurements, and the simulated phreatic surface elevations within the 2 km x 2 km grid cannot be assumed to be fully correct.

Some degree of lumping and conceptualization has taken place at the grid scale of the present model application, with the result that some (few) model parameters have to be assessed through calibration, and that a direct comparison between simulated variables at a 2 km x 2 km grid, and the same variables measured at a point scale in the basin may have little meaning. However, it may be stressed that in spite of the above comments, the present basin model is much more physically based and distributed than the traditional lumped, conceptual model, where the entire catchment is represented in effect by one grid square, and where the process representations due to averaging over characteristics of topography, soil type and vegetation type are fundamentally different from the basic physical laws. Although the present catchment representation may not be sufficiently detailed for some modelling purposes, such as soil erosion or stream-aquifer interaction studies, it is still well suited for other modelling studies, such as the prediction of the effects of land use changes, for which no real alternative to a physically based, distributed modelling approach exists.

(c) Conclusions regarding SHE applicability to Indian Hydrological Conditions

On the basis of the experience gained from the SHE studies of the six Narmada sub-basins and the irrigation command area study, the following main conclusions have been drawn regarding the applicability of SHE to Indian hydrological conditions.

- (1) The SHE has been verified on Indian data, although not for research catchments with good data coverage. However, such tests have successfully been carried out using data from other parts of the world. The present results indicate that the SHE is able to reproduce the rainfall-runoff process and give a physically reasonable representation of the intermediate hydrological processes for the characteristic monsoon environment.
- (2) The data requirements for SHE modelling are substantial. However, experience from the Narmada studies indicates that the main part of the required data already exists with different agencies representing meteorological, irrigation, agricultural, geological, and other professional fields, many of which are not usually contacted in traditional hydrological and water resources studies.
- (3) Field work in connection with SHE modelling is of major importance as a supplement to the data available from existing sources. For a feasibility study, the necessary measurements can be made in a matter of a few weeks. As far as the model parameters are concerned, the field work is likely to have most significance for evaluation of the soil hydraulic properties. However, very importantly, the field work may give an improved assessment of the overall hydrological regime and the importance of the various hydrological processes within the catchment.
- (4) The quantity and quality of the rainfall data is of the utmost importance for accurate simulation of catchment response. Uncertainty in the rainfall input most often defines the limit for simulation accuracy. It is, therefore, important to assemble and evaluate all rainfall records at a very early stage of a project.
- (5) Hydrological experience and judgement is very important in connection with data preparation and calibration of the SHE and interpretation of the results. Thus, the fact that SHE is more advanced and has a physically more correct process description than traditional hydrological models, does not imply that the input from the SHE modeller can be based on routine operation. On the contrary, SHE modelling most often deals with much more complicated hydrological problems than 'just' rainfall-runoff modelling and, therefore, requires, in general, more hydrological experience than does traditional hydrological modelling.
- (6) The SHE, owing to its generalized structure and process description, is in principle applicable to almost any hydrological regime in India and for most hydrological problems. However, owing to its complexity and data requirements, it is more costly to use than traditional, and simpler, hydrological models. Therefore, considering both hydrological and economic aspects, the SHE is recommended as the optimal tool for only some types hydrological problems: (a) For rainfall-runoff

modelling (extension of streamflow records from long historical rainfall series, flood forecasting, etc.) simpler models will in most cases be equally accurate and much cheaper to apply. Hence, SHE is not generally recommended for tackling problems, which are 'only' related to prediction of discharges from a catchment. (b) For problems dealing with prediction of the effects of man's activities, for which the traditional models are not applicable, SHE is particularly well suited and models of the SHE type are technically the only feasible option. Such types of application include: prediction of effects of land use change; simulation of interaction between surface water and ground water, e.g. conjunctive use; water management in irrigation command areas; prediction of effects of climate change; (c) SHE is well suited as the hydrological basis for water quality and soil erosion modelling, for which a detailed and physically correct description of the water flow process is required.

For details of the study, the reader may please refer NIH Report Nos. CS-28, 29, 30, 31, 32, 33, 34, 47 and 48.

4.2.2 Application of Tank model to two sub-basins of Narmada basin

The Tank model is a simple conceptual rainfall-runoff model developed in Japan. The model considers total rainfall as input and gives total runoff as output. The model has capability to simulate both flood and daily runoff. To take into account the variation of soil moisture in non-humid basins experiencing long dry period, the 4 x 4 Tank model structure has been used by considering such variations by dividing the basin into four zones. Tank model has been applied to simulate the daily runoff of two sub-basins viz. Jamtara and Ginnore of river Narmada. The Ginnore and Jamtara sub-basins have catchment area of 4816 and 16575 square kilometers. The daily rainfall, discharge and evaporation data, soil map, forest cover map and geologic map were available for the study. The model has been calibrated and validated for Ginnore sub-basin using the historical records of daily rainfall runoff and evapotranspiration data for the years 1972 to 1974. The parameters accounting the soil moisture for the model have been ascertained from the soil and geological information available for the basin. Comparison of observed and simulated runoff volume for typical floods of Ginnore sub-basin are given in Table 4.2.

From the study, it is observed that the 4 x 4 Tank model is a suitable daily rainfall-runoff model for simulation of daily runoff, particularly for non-humid basins, in India, which experience nearly 75% to 90% of annual rainfall during the monsoon season followed by long dry period in non-monsoon months. However, the model is a lumped model and does not consider the impact of land use changes and the structural changes on the components of hydrologic cycle. The calibrated and validated model may be applied for extending the daily runoff records or generating the daily runoff for the period for which the historical runoff data are not available

Table 4.2 : Comparison of observed and simulated runoff volume for typical floods of Ginnore sub-basin

Period	Total runoff volume in 10^6 m^3		Base flow volume in 10^6 m^3		Base flow % of total volume	
	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
For calibration						
1. 129 days from 15.8.72 to 31.12.72	1763.8	1766.9	60.3	63.3	3.4	3.6
2. 184 days from 1.7.73 to 31.12.73	3843.0	3143.5	221.5	183.6	5.8	5.8
For validation						
3. 116 days from 27.7.74 to 19.11.74	1038.9	1259.5	44.7	51.8	4.3	4.1

For details of the study, the reader may please refer NIH Report No CS-5.

4.3 Application of BATS Model

The land surface parameterization scheme - Biosphere Atmosphere Transfer Scheme (BATS) developed at National Centre for Atmospheric Research (U.S.A.) is a model which calculates the transfers of momentum, heat and moisture between earth's surface and the atmosphere; determines the values of wind, moisture and temperature in the atmosphere, within vegetation canopies and at the level of surface observations and determines (over land sea ice) values of temperature and moisture (moisture content of the soil, the excess rainfall that goes into runoff, etc.) quantities at the earth surface. This land surface parameterization scheme accounts for vegetative and soil control on evapotranspiration and runoff efficiencies and for effects of seasonally varying canopy cover.

The methodology coded in modified BATS for simulating the inhomogeneous precipitation field is not applicable to the Sher sub-basin. A new methodology based on the concept of Thiessen Polygon, used in estimating average areal precipitation over the catchment, is proposed to generate the precipitation field. A large number of sensitivity experiments are carried out using BATS to assess the subgrid scale variability of forcing variables on moisture and energy fluxes. The Sher sub-basin of Narmada basin is considered for the study. The sensitivity analysis are based on the precipitation field, generated using the proposed methodology. The analyses are carried out for a time horizon of 20 days with a time step of one hour.

The study mainly focuses on the sensitiveness of spatial variability of precipitation, soil texture, soil colour and soil temperature. Impact of inadequate spatial precipitation information on the moisture fluxes is also studied. Sensitivity analysis reveals that there is no need to consider explicitly the precipitation variability at subgrid scale for the computation of moisture fluxes, provided the average precipitation over the grid remains

same. It is found that detailed spatial variability of soil information appears to be more critical than that of precipitation field. The hydraulically controlled processes like runoff and soil moisture are more sensitive to soil texture; whereas, the radiative and thermal conductive fluxes, such as net solar radiation, longwave radiation, and ground and subsurface temperatures are highly sensitive to soil colour. Rainfall-runoff parameterization in the BATS seems to be inadequate for most real-life situations, because of nonlinear behaviour. However, an exhaustive numerical experiments are needed to establish it. Use of remote sensing data and/or a decision support system to quantify the areal variability of the forcing variables may improve the findings.

For details of the study, the reader may please refer to NIH Report No CS/AR-168.

4.4 Remarks

Application of computer based mathematical models for solving various hydrological problems have increased significantly during last two decades. A large number of hydrological models exist. However, many of the models function in basically the same way. A model represents the physical/chemical/biological characteristics of the catchment and simulates the natural hydrological processes. It is not an end in itself but is a tool in a larger process which is usually a decision problem. A model aids in making decisions, particularly where data or information are scarce or there are large numbers of options to choose from. It is not a replacement for field observations. Its value lies in its ability, when correctly chosen and adjusted, to extract the maximum amount of information from the available data, so as to aid in decision making process. The hydrological modeling is required not only for estimating the water yield and design parameters but also for understanding and evaluating the effects of developmental and other activities on hydrological regime of a river basin. The challenging task of preparing developmental plans for managing the limited resources of river basins for their optimal use necessitates application of multi-disciplinary approach system engineering for comprehensive planning of water resources projects. The use of physically based distributed modeling approach can provide such information and could also incorporate scenarios of proposed/likely land use changes in the river basin for use in planning/ operation of water resources projects.

A number of studies were carried out for the Narmada basin describing calibration, validation and simulation of lumped conceptual models as well as physically based models for some of the sub-basins of Narmada river basin. The entire land phase of the hydrological cycle has been modelled for the six sub-basins of the Narmada basin using the SHE model. These sub-basins include Kolar, Barna, Sher, Ganjal, Hiran and Narmada upto Manot. The SHE was developed from the perception that conventional rainfall/runoff models are inappropriate to many hydrological problems, specially those related to the impact of man's activities of land use change and water quality. These problems can be solved only through the use of models which have a physical basis and allow for spatial variations within a catchment. Flood hydrograph simulation study was carried out in Kolar sub-basin using event based model. Watershed Hydrology Simulation Model (WAHS) was also applied to simulate the flood event of the Kolar sub-basin. Excess rainfall and direct surface runoff modeling was carried out for some of the sub-basins using the geomorphological characteristics. Simple linear modeling of river flow was carried out in one of the case studies. Tank model has been applied to simulate the daily runoff of two

sub-basins viz. Jamtara and Ginnore of river Narmada. SCS method was used for modeling the runoff. BATS model was used to carry out the sensitivity analysis of the various hydrological parameters on the hydrological response using the data of few sub-basins of Narmada River basin. Impact assessment studies were also carried out for some of the sub-basins.

5.0 DESIGN FLOOD STUDIES

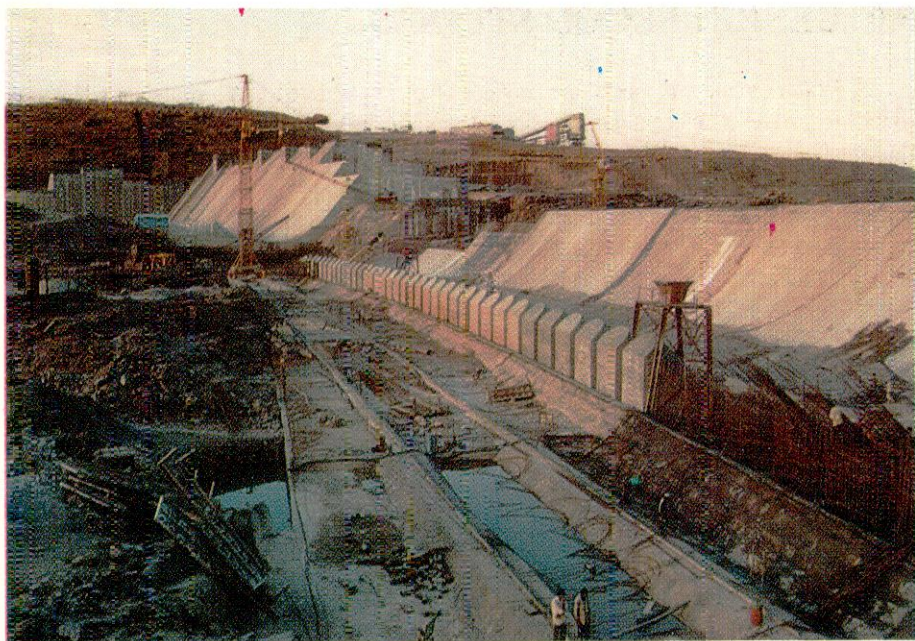
Water related projects are investigated, formulated and implemented by the concerned State Governments. Besides the guidelines issued by the Central Water Commission (CWC) for investigation and preparation of project estimates, Bureau of Indian Standards (BIS) has also prepared a number of standards and codes of practices for this purpose. For water resources development projects, the design flood study is one of the important aspects to be tackled by the hydrologists. The PMF computations using the deterministic approach as well as statistical approach are normally performed and design floods are determined based on the guidelines provided by the CWC.

5.1 Deterministic Approach

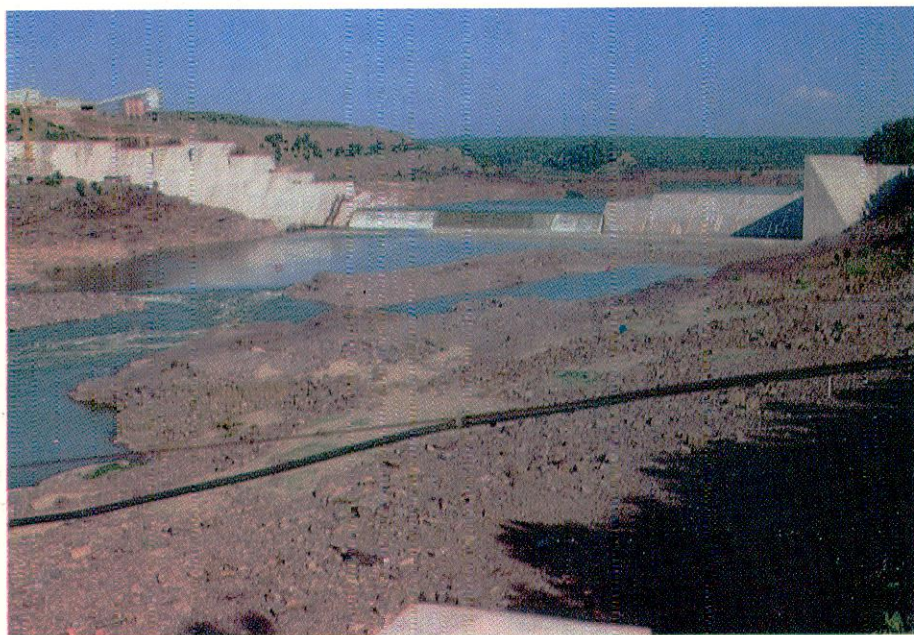
In the area of design flood estimates, the Institute has carried out the design flood studies for Narmada Sagar (now renamed as Indira Sagar) and Sardar Sarovar projects. A network model upto Narmada Sagar and Sardar Sarovar has been prepared considering the sub-basins and river reaches. The schematic diagram of the adopted network model for the Narmada basin is shown in Fig. 5.1. Unit hydrograph and flood routing parameters have been derived through calibration and validation of the model for gauged sub-basins and river reaches. For estimating the unit hydrograph parameters for ungauged sub-basins, regional relationships between unit hydrograph parameters and catchment characteristics have been developed and utilized. Values of calibrated Clark model parameters T_c and R used in the stream network model are given in Table 5.1. Fig. 5.2 shows the $(T_c + R)$ versus area relationship developed for the study area. The flood routing parameters for ungauged river reaches are also estimated using the similar approach. The values of calibrated Muskingum K used in the stream model are given in Table 5.2. Fig. 5.3 shows the relationship between Muskingum parameter K and $L/S^{0.5}$ for the study area. The design unit hydrograph and flood routing parameters together with design loss rate and baseflow are supplied to the model for the design storm critically distributed in time.

5.2 Statistical Approach

Flood frequency analysis based on annual peak floods as well as partial duration flood series data provides the estimates design floods for different frequencies. In case the data required for flood frequency analysis is of adequate length at-site flood frequency approach may be carried out following the methodology as discussed in Section 3.1.2 (a) for the annual maximum peak flood data. Flood frequency analysis has also been carried out for estimating the design floods for the design return periods using the commonly used probability distributions such as Gumbel Extreme Value Type-I distribution, Log normal and Log Pearson Type-III distribution. The annual maximum peak flood data available for Mortakka site have analysed for estimating the design flood of the desired frequencies for the Narmada Sagar dam. For estimation of design flood for Sardarsarovar dam the annual maximum peak flow records available for the Garudeshwar site have been analysed. For flood frequency analysis annual maximum as well as partial duration series have been analysed.



INDIRA SAGAR DAM UNDER CONSTRUCTION



AN OVERVIEW OF INDIRA SAGAR DAM
UNDER CONSTRUCTION (OCT. '98)

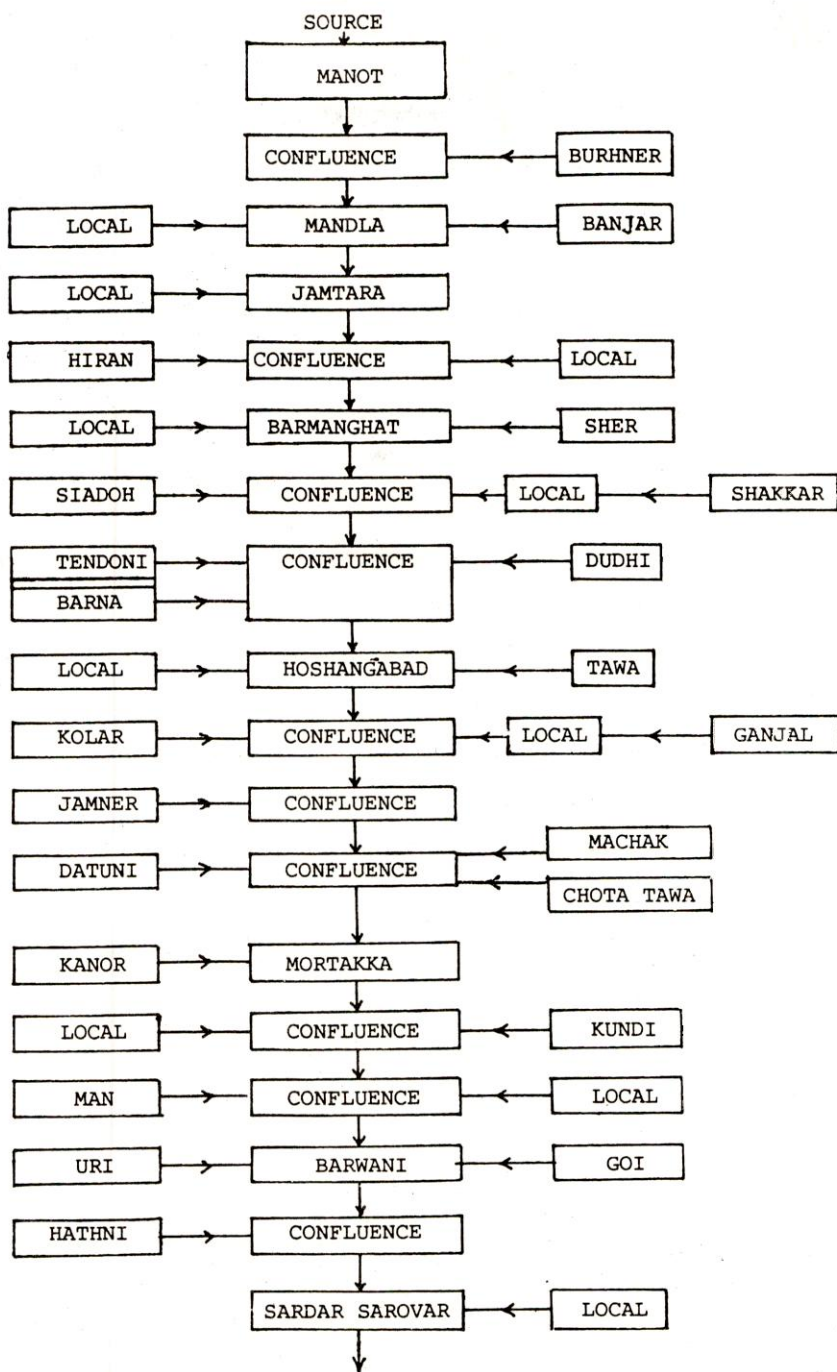


Fig. 5.1 : Stream Network Model - NARMADA BASIN

Table 5.1 : Values of calibrated Clark model parameters T_c and R used in the stream network model

Sl. No.	Sub-catchment			Area km ²	T_c (Hours)	R (Hours)
	No.	River	Gauge site			
1	1A	Narmada	Manot	4300	11.8	11.7
2	1B	Burhner	Mohegaon	3300	11.1	16.7
3	1C	Banjar	Haridaynagar	3370	11.2	16.9
4	1D	Local		375	1.2	1.8
5	1E	Local		5812	12.8	19.2
6	2	Hiran	Gubrakalan	4635	13.0	19.5
7	2A	Hiran Local		1608	6.0	9.0
8	3	Sher	Belkheri	1515	7.7	6.3
9	3A	Sher Local		1704	8.8	7.2
10	4	Siadoh		1168	5.8	4.7
11	5	Shakkar	Gadarwara	2269	11.6	9.5
12	5A	Shakkar Local		619	2.7	2.3
13	6	Tendoni		1554	8.0	6.5
14	7	Dudhi		2440	12.6	10.2
15	8	Barna		1927	9.9	8.1
16	9	Tawa	Bagratawa	6067	17.9	14.6
17	9A	Tawa Local		3066	14.9	12.2
18	10	Kolar		2105	10.7	8.8
19	11	Ganjal	Chidgaon	1821	9.2	7.5
20	11A	Ganjal Local		1875	9.4	7.7
21	12	Jamner		2072	10.6	8.6
22	12A	Datuni	Machak	4674	16.5	13.5
23	13	Chhota Tawa	Ginnore	5040	17.3	14.2
24	14	Kanor		4727	16.5	13.5
25	15	Man		3276	15.1	12.4
26	16	Kundi	Kagon	4009	16.1	13.1
27	16A	Local		2260	11.6	9.5

28	16B	Local		2789	13.8	11.3
29	17	Uri		1991	10.2	8.3
30	18	Goi		2110	10.7	8.8
31	19	Hathni		2274	11.2	9.3
32	20	Local		1300	6.5	5.5
33	20A	Local		1500	7.7	6.3

Table 5.2 Values of calibrated Muskingum K used in the stream model

S.No.	River reach	Length (km)	K (Hours)
1	Confluence of Burhner-Mandla	42	4.0
2	Mandla - Jamtara	111	7.0
3	Jamtara - Confluence of Hiran	62	5.0
4	Confluence of Hiran - Bermanghat	43	4.0
5	Bérmanghat - Confluence of Shakkar	38	6.0
6	Confluence of Shakkar - Confluence of Barna	60	6.0
7	Confluence of Barna Hoshangabad	78	15.0
8	Hoshangabad - Confluence of Ganjal	72	5.0
9	Confluence of Ganjal - Outlet of sub-basin 12	17	2.5
10	Outlet of 12 - Outlet of 12A	70	5.0
11	Outlet of 12A - Mortakka	65	4.0
12	Mortakka - Outlet of 16A	40	3.6
13	Outlet of 16 A - Outlet of 16B	70	4.6
14	Outlet of 16 B - Barwani	18	1.5
15	Barwani - Confluence of Hathni	43	3.0
16	Confluence of Hathni - Sardar Sarovar	86	6.0
17	Sardar Sarovar - Garudeshwar	14	1.5

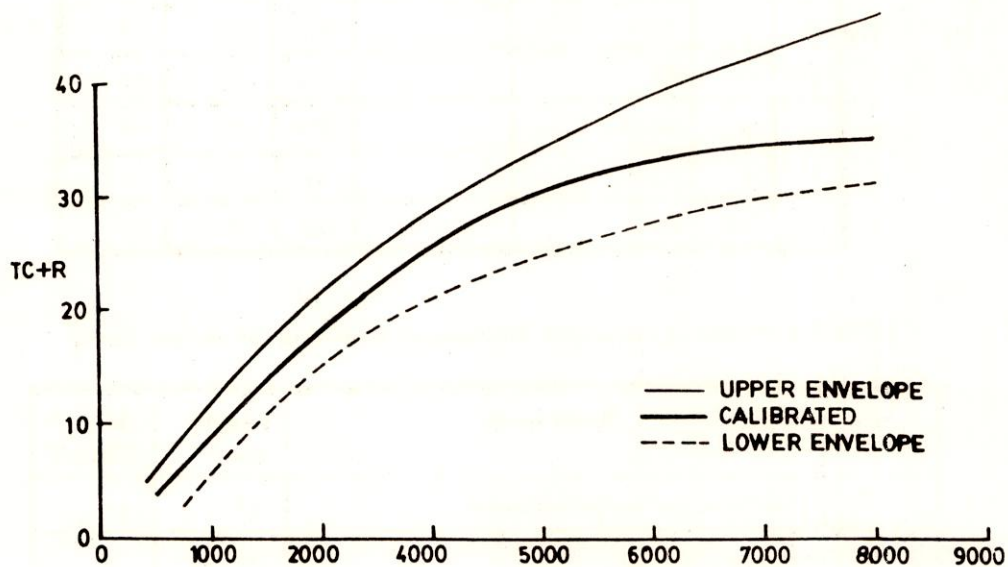


FIG.5.2 (TC+R) Vs AREA RELATIONSHIP

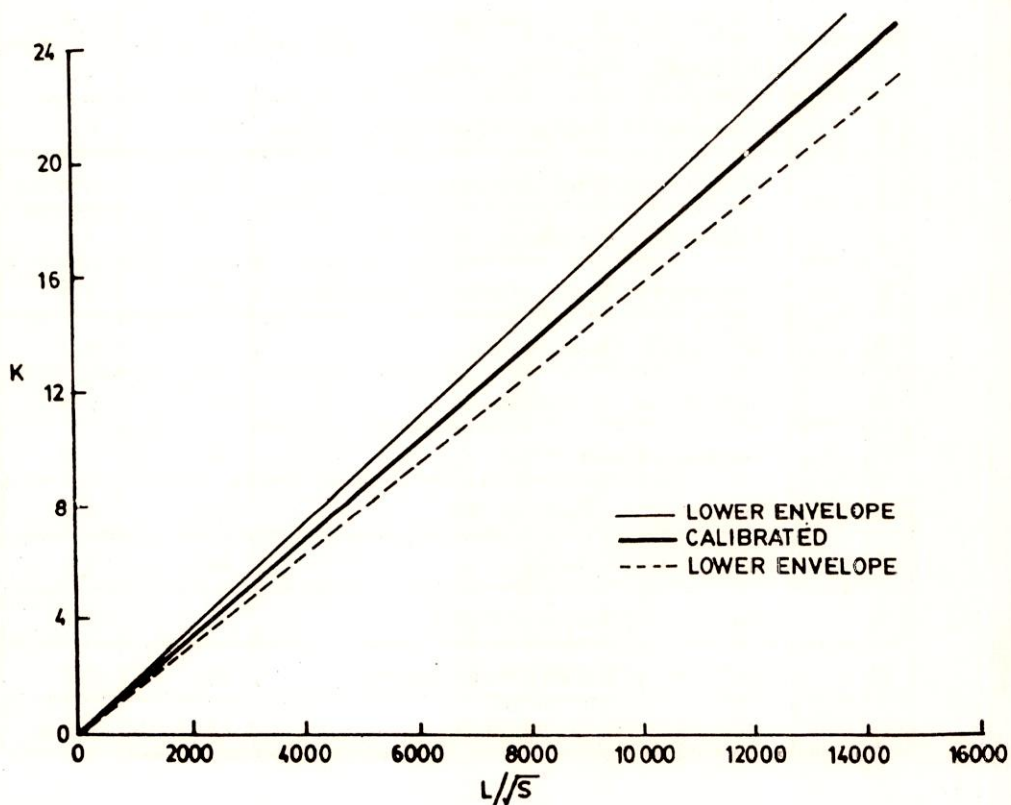


FIG.5.3 MUSKINGUM K Vs L/S RELATIONSHIP

The conclusions drawn from the study are mentioned below:

- (i) The storm of 1926-27 recommended by the Dam Review panel for Narmada with a break of 2 dry days in between the two component storms was compared with design storm based on 1926-27 storms adopted by NPDDC, Gujarat for Sardar Sarovar. Besides being only a 5 day storm as against the 12 day storm recommended for Narmada Sagar, the sub-catchment incremental depths of the 1926-27 combined storm are found to be different from those being used for Narmada Sagar.
- (ii) The total storm depths of the different alternate design storms recommended for Narmada Sagar and Sardar Sarovar are 2 to 2.3 times the recorded flood producing historical storms of 1970 and 1973.
- (iii) The flood peaks for different alternate design storms have been estimated and the conclusions and recommendations drawn are based on the presumption that concerned expert organizations have considered the possibility of storm of 1927 occurring over the Narmada basin and agreed to its applicability for design storm purposes by moving it critically from upstream to downstream.
- (iv) It is recognized that the reservoirs existing at Tawa and being constructed at Bargi will have some effect in reducing the flood flows. Similar flood moderation due to Narmada Sagar is expected on the floods at Sardar Sarovar when Narmada Sagar is completed. The non-consideration of this effect would result in somewhat higher estimates of design floods.
- (v) The bankfull discharge of Narmada at Mortakka and Garudeshwar is 60,000 cumecs and 68,000 cumecs respectively. Thus in the event of occurrences of design flood with much higher flows, the flood waters would spill over on to the flood plain, when the flood waters flow would be different and would somewhat reduce. A check involving estimation of Muskingum x based on the relationship developed by Cunge indicated that x value increases from downstream reaches to upstream reaches in Narmada basin from 0.3 to 0.4 and its values remain nearly same as those corresponding to bankful discharge even when the flow at expected design flood level occurs in the flood plain of the basin. It is expected that there may be some marginal reduction in magnitude of design flood due to flow of large proportion of flood waters in the flood plains.
- (vi) The losses during the two historical floods of 1970 and 1973 were of the order of 55 to 60 mm out of total storm rainfall 225 to 240 mm. Since these were very heavy storms resulting in highest recorded floods, it would not be inappropriate to assume that the magnitude of losses would have reached nearly maximum possible level for soil cover conditions in the basin. Thus in the event of a design storm with still higher rainfall, the losses are likely to be nearly at the same rate and the total losses would also be nearly equal to those occurring during these historical storms.

The assumption of 1.0 mm/hr loss rate has given a total loss ranging from 75 mm in a 5 day storm of 380.0 mm to 177.0 mm in a 12 day storm of 987.8 mm rainfall.

- (vii) The tentative flood estimate for Sardar Sarovar project based upon frequency analysis approach and design storm 1973-1970 recommended by India Meteorological Department were made and reported in July 1982. The peak flood of 113300 m³/sec. (40 lakh cusecs) was recommended as the tentative spillway design flood and higher value of 127400 m³/sec. (45 lakh cusecs) was recommended for checking the reservoir system. The 10,000 year flood of 173775 m³/sec. (61.36 lakh cusecs) could not be reconciled with the design storm volume of 412 mm which indicates likely upper limit of the total volume of the flood hydrograph and as such this value was not recommended as a possible tentative peak flood estimate.
- (viii) The tentative design flood estimate for Narmada Sagar Project based upon frequency analysis approach and 1973-1944 storm recommended by India Meteorological Department were made and reported in Aug. 1983. On the consideration of reconciliation of design storm volume, the recommended tentative design flood were 81073 m³/sec. (28.63 lakh cusecs) as the spillway design flood, and 104973 m³/sec. (37.07 lakh cusecs) as the flood peak for checking the reservoir system.

Presuming that the various aspects of the design storm including transposition of storms from other locations, their critical placement from upstream to downstream, maximization and time distribution have been carefully examined by concerned experts from the meteorological and other relevant points of view, with respect to Narmada basin in general and Narmada Sagar and Sardar Sarovar projects in particular, the following recommendations for design floods to be adopted for Narmada Sagar and Sardar Sarovar were made.

- (i) For Narmada Sagar out of the two design storms for which corresponding flood was estimated, the 1926-27 storm is the most critical. From the values of peak floods estimated with the nine combinations using different ($T_c + R$) and K, it is seen that the change in the value of K has no significant effects on the peak flood. The value of the peak flood for the calibrated K is thus 142466 cumecs varying between 134722 cumecs to 147463 cumecs.
- (ii) One important point which has been seen is that the peak flow at Narmada Sagar for the storm of 1926-27 recommended for Sardar Sarovar is higher than the peak flow resulting from 1926-27 storm recommended for Narmada Sagar. The value of peak flood at Narmada Sagar corresponding to the Sardar Sarovar 1926-27 design storm is 156618 cumecs (55.30 lakh cusecs). This discrepancy may be due to the independent analysis carried out by Sardar Sarovar and Narmada Sagar authorities and due to the different time distribution of rain depths for the sub-basins for the design storms considered by them.

Considering that the 1926-27 storm combination is reasonably realistic from meteorological point of view to occur over the catchment or Narmada a value of 142466 cusecs (50.30 lakh cusecs) is recommended for Narmada Sagar with range of variation from 134722 cumecs (47.58 lakh cusecs) to 147463 cumecs (52.08 lakh cusecs).

For the Sardar Sarovar project of the three storms used in the flood estimation, 1926-27 has the highest overall storm depths. The July 1927 storm moved critically and 1973-1970 storms have almost identical overall storm depths. However, the July 1927 storm has resulted in highest estimate of peak flood due to its distribution in space and time somewhat synchronising with movement of floods in the river.

- (i) As in the case of Narmada Sagar the effect of change in value of K is found to be negligible. The effect in the variation of (T_c+R) , however, is quite significant. The peak flood for calibration K and calibrated (T_c+R) is 210137 cumecs with values ranging from 197556 cumecs to 221630 cumecs.
- (ii) The peak flood magnitude of 210137 cumecs has increased by 2.0% when the values of $R/(T_c+R)$ are changed from 0.6 and 0.45 to 0.55 and 0.4 and decreased by 2.5 percent when the values are changed from 0.6 and 0.45 to 0.65 and 0.5.
- (iii) The effect of change of loss rates to 1.5 mm/hr and 2.0 mm/hr instead of 1.0 mm/hr results in the decrease of the peak flood magnitude of 210137 cumecs by 5% and 10% respectively.
- (iv) As stated earlier, based on Cunge's approach, the analysis carried out indicated that values of Muskingum routing parameter x increases from downstream to upstream and would be in the range of 0.3 to 0.4, even when flood enters the flood plains. Desai, et al., (1984) have assumed values of x ranging between 0.18 to 0.2 for different sub-reaches in their study. The effect of adopting these lower values of x was studied. It is seen that when value of $x = 0.2$ is adopted for all the subreaches, it results in decrease of the peak flood magnitude of 210137 cumecs by about 6%.

Based on the above conclusions and considering that the appropriateness of transposing/maximizing the July 1927 storm have been examined from meteorological point of view by concerned authorities, a peak flood value of 210137 cumecs (74.20 lakh cusecs) is recommended with range of variation from 197556 cumecs (69.77 cusecs) to 221630 cumecs (78.27 lakh cusecs).

The Institute has conducted a sponsored project entitled: '*Design Flood Estimation for Narmada Sagar and Sardar Sarovar Project*' and details of the study and conclusions are available in the final project report.

5.3 Remarks

The design flood studies carried out for the Narmada basin at the Institute are based on deterministic and statistical approaches. In the deterministic approach, a network model upto the proposed dam site has been formulated considering the lateral flow computed by the Clark model unit hydrograph approach from the various sub-basins to the Narmada river system. These lateral flows have been routed through main river reaches using the Muskingum channel routing method. For calibrating the parameters of the network model historical rainfall and flood records have been used. The design storm has been superimposed over each of the sub-basin and the design flood estimates have been obtained using the network model. The floods for design frequencies have also been estimated applying the at-site flood frequency analysis approach analysing the annual maximum flood as well as partial duration flood data.

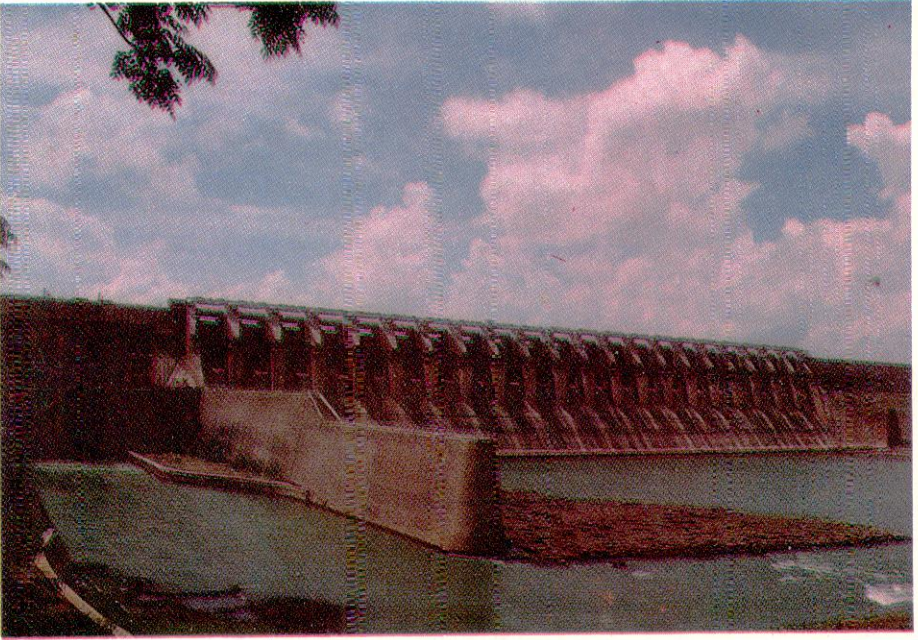
6.0 RESERVOIR OPERATION STUDIES

Reservoirs are constructed across rivers to change the spatial and temporal availability of water in accordance with the requirements of mankind. To attain the maximum benefits from a multipurpose scheme, it is imperative to regulate the reservoirs in the most efficient and judicious manner. In view of the uncertain nature of monsoon, it is essential to use our available water resources in the most judicious manner. Efficient utilization of the water resources requires that the reservoirs must be operated in the most optimal and scientific way. Efficient regulation of the reservoirs can lead to increased benefits from the reservoir as well as significant reduction in damage due to floods.

6.1 Multiobjective Optimization Operation of Bargi Dam

The present study deals with the development of reservoir operation policies for the Bargi reservoir (Rani Awanti Bai Sagar) in the Narmada basin. Bargi is a major reservoir with the total capacity of 3.9 B Cum. This reservoir is meant to serve for irrigation, water supply for domestic and industrial purposes and firm hydropower generation to the extent of 363 M kwh annually. Two canal systems take-off from the Bargi reservoir. The construction of the left bank canal is nearing completion while the construction of the right bank canal is in progress. A power house with two units of 45 MW capacity each has already been installed in the river bed and power is being generated through this power house. The data used in the study included: a) monthly inflow series of 40 years, b) water supply, irrigation, hydropower demands, c) E-A-C table of dam, and d) normal monthly evaporation depths.

In this study, the facilities that are in operation at present have been considered for policy development for Bargi reservoir. Power generation through river bed power house and full irrigation demands of the left bank canal have been considered. A linear programming model has been developed for the reservoir for getting the feasible solutions. The simulation analysis of the reservoir operation has been carried out using the 40 years of historical data. A rule curves based policy has been adopted for the operation and the various curves based policy has been adopted for the operation and the various curves have been optimized using the reliability analysis. Simulation of the operation has also been carried out with the presently followed operation policy and the comparison between the two policies has been made. Trade-off analysis has been carried out between the irrigation demand satisfaction and the hydropower generation and various trade-off curves for different hydropower reliability have been developed. These curves can be used by the authorities in deciding about the proportions of irrigation and hydropower releases. For the conservation regulation of the reservoir, four rule curves have been recommended for different purposes and the operation procedure for the reservoir has been explained. There is no flood control zone in this reservoir as the FRL corresponds to the top of spillway gates. Hence, no separate flood control policy has been developed for this reservoir. However, an upper rule curve has been derived to keep the reservoir level below FRL as long as there is no effect on the conservation performance of the reservoir.



BARGI DAM



POWER HOUSE - BARGI DAM

The scope of this study includes policy development for conservation purposes only. The concept of rule curves was adopted for the operation of this reservoir. Simulation and optimization analysis of the operation of Bargi reservoir was carried out. A number of simulation runs were taken and the final recommended rule curves were tuned to achieve the targets to the maximum extent possible. The performance of the reservoir with the recommended policy was compared with the presently followed policy. The recommended rule curves (Table 6.1) for the reservoir gave better performance than the presently followed policy.

A software for simulating the operation of a multi-purpose multi-reservoir system, developed at NIH was used in this study. This software had to be modified to take care of the special configuration of the Bargi reservoir, namely, two canal systems with independent command areas taking-off from one reservoir, the sill levels of two canals being at different elevations, and the existence of canal bed power plants. The operation of the reservoir with the recommended policy was simulated using 40 years of historical inflow data series.

6.1.1 Recommended Conservation Operation Procedure for Bargi Reservoir

The recommended rule curves for the reservoir are presented in tabular form below. The procedure for conservation operation of the Bargi reservoir using these four rule curves A, B, C and D is as follows:

For a particular month:

1. Try to maintain the reservoir at rule level A while meeting all the demands in full. If the reservoir level overtops the rule level A, spill the excess water and bring the reservoir level back to level A.
2. If it is not possible to maintain the reservoir level at A, meet all the demands as long as the reservoir is at or above level B.
3. If it is likely that the reservoir level will go below level B, the supply for various demands will have to be curtailed. In the months from March to June, give higher priority to irrigation and for reservoir level between the rule level B and rule level C, meet full irrigation demands and 75% of target power demands. In other months, for reservoir level between level B and C, curtail supply for irrigation to 75% of target demands and meet full power demands as long as the reservoir level could be maintained above rule level C.
4. If the reservoir is at or below rule level C, then for months from March to June curtail supply for irrigation to 75% of the target irrigation demands and stop supply for hydropower completely. For other months, stop irrigation supply completely and supply water to power plants to meet 75% of the target demands. Meet full water supply demand in this range of reservoir level.

5. If the reservoir is at or below rule level D, make release to meet only full water supply demand for as longer the duration as possible. In this case, stop supply for all other demands completely.
6. It is advisable to periodically review the situation within a month and modify the previous decision (for the remaining duration of that month) and follow steps (1) to (5) to operate the reservoir.

Table 6.1 : Recommended Rule Curve Levels (m) for Bargi Reservoir

Month	Rule Curve			
	(A)	(B)	(C)	(D)
Jan.	2419.50	416.25	412.50	403.85
Feb.	418.00	413.00	410.75	403.80
Mar.	416.50	411.00	407.75	403.75
Apr.	415.00	408.00	406.25	403.70
May	413.00	405.25	404.75	403.70
June	415.00	404.00	403.75	403.60
July	418.00	407.25	406.00	403.60
Aug.	422.50	417.50	415.50	403.80
Sep.	422.76	419.00	417.00	404.00
Oct.	422.76	420.50	417.50	404.00
Nov.	422.00	419.75	415.25	403.95
Dec.	420.50	418.50	414.00	403.90

Some of the important conclusions from this study are as follows:

1. The upper rule levels that are specified in the presently followed operation policy are too low and the water is spilled at the cost of conservation demands. The recommended policy gives the optimum upper rule curve for the reservoir.
2. In the months of August and September, the reservoir is filled to its capacity in a number of months, yet full demands for the water year can not be fully met. Hence, the inflow in the reservoir during the period from October to February is also critical for satisfying full conservation demands.
3. The present study has been carried out based on the water supply demands, hydropower demands and the demands from the left bank canal. The right bank canal demands have not been taken into consideration. From the analysis, it appears that the RBC demands can be satisfied in the months. However, since the sill level of RBC is quite high, it seems difficult to meet its demands for longer durations.
4. It is better to give higher priority to irrigation over hydropower in the months from March to June. This considerably improves the reliability for irrigation though the

reliability for hydropower is marginally reduced. In other months, hydropower can be given higher priority over irrigation.

The project report of the Bargi reservoir does not provide for flood protection from this reservoir. Hence, no separate study for flood control operation of this reservoir has been carried out. However, the upper rule levels in all the months have been lowered below the FRL, to the extent possible, as long as the conservation requirement of the reservoir is not affected. It is required to maintain the reservoir at the upper rule level and spill the additional water at the rate of inflow so that the reservoir can be kept at this level.

For details of the study, the reader may please refer NIH Report No TR/BR-143.

6.2 Development of Operation Policy For Tawa Dam

In this study, rule curves based policy has been adopted for the conservation regulation of Tawa dam. Rule curves are developed for three levels such as upper rule level, middle rule level (critical for irrigation), lower rule level (critical for water supply and upstream use). The generalised simulation model developed by the Water Resources System Group at N.I.H. is used to simulate the system operation and to refine the rule curves. A number of simulation runs have been taken by adjusting the rule curves and the final rule levels have been arrived to satisfy the target demands to the maximum extent possible. The current operating policy of the reservoir is also simulated and the results are compared with the recommended rule curves based policy.

The operation of the reservoir with the recommended policy has been simulated using 23 years of inflow data series. Some of important conclusions from the simulation study are as follows:

1. The presently followed operating policy (SLOP) gives more critical failures than recommended rule curve policy. The recommended policy gives the irrigation rule curve to distribute the deficit equitably much in advance.
2. The average annual incidental hydropower and the average annual release are improved by the recommended operating policy. In the months of August and September, the reservoir is filled to its capacity in number of years.
3. The volume reliability for irrigation and water supply is improved by the recommended operating policy. The value is improved by 1% over the current operating policy.
4. The present study has been carried out based on the water supply demands and upstream use demands and the irrigation demands from the left bank canal and right bank canal. From the analysis, it appears that the demands can be satisfied almost in all the months except for the drought years 1951-52, 1952-53 and 1957-58.

- 5 Detailed simulation studies are carried out and the results are presented for the upper rule levels, in the months of August, September and October, which are assumed to be less than actual FRL at the interval of 0.2 m up to 1m to enable the operator to select a set of rule curve levels to avoid or to reduce the submergence in the upstream of the reservoir.

The presently followed rule curves and the recommended rule curves are presented in Table 6.2 and 6.3. Using the presently followed rule curves and the SLOP policy, it is observed that the monthly time reliability for water supply and upstream use and irrigation comes out to be 100% and 88.6% respectively. The volume reliability comes out to be 94%. Out of the 281 months, there are 27 critical failure months (when the total release is less than 75% of the total demand). The reliability of the reservoir for meeting partial demands is also carried out. With this policy, the reliability for supplying 75% assured supply for irrigation comes out to be 100%. Using the recommended policy, the monthly time reliability for water supply and upstream use and irrigation comes out to be 100% and 84% respectively. The volume reliability comes out to be 95%. Out of the 281 months, there are 4 critical failure months.

Table 6.2 : Initial Rule Curve Levels (m) for Tawa Reservoir

Month	Upper Rule Curve	Irrigation Rule Curve	Water Supply & Upstream use Rule Curve
Jan.	348.30	348.30	335.80
Feb.	346.00	345.50	335.80
Mar.	343.80	342.90	335.80
Apr.	342.80	339.70	335.60
May	341.20	338.10	335.40
June	354.40	349.20	334.20
July	354.40	346.90	334.20
Aug.	354.40	348.70	334.20
Sep.	354.40	352.70	334.20
Oct.	353.60	353.60	334.60
Nov.	351.90	351.90	335.70
Dec.	350.20	350.00	335.80

Table 6.3 : Recommended Rule Curve Levels (m) for Tawa Reservoir

Month	Upper Rule Curve	Irrigation Rule Curve	Water Supply and Upstream Use Rule Curve
Jan.	351.30	347.70	335.80
Feb.	350.30	344.10	335.80
Mar.	348.80	341.30	335.80
Apr.	347.90	336.60	335.60
May	346.90	336.10	335.40
June	354.40	342.00	334.20
July	354.40	343.90	334.20
Aug.	354.40	348.40	334.20
Sep.	354.40	352.70	334.20
Oct.	354.40	353.20	334.60
Nov.	353.80	351.90	335.70
Dec.	352.70	348.10	335.80

From the analysis, it is observed that the presently followed policy gives higher reliability than the recommended policy for meeting the full as well as partial demands. However the presently followed policy gives more critical failures than the recommended policy. So the recommended policy tries to distribute the deficit equitably in all the months. As soon as shortage of water is anticipated, the supply is curtailed much in advance so that reduced supply can be maintained throughout the year. The recommended operating policy improves the volume reliability for irrigation and water supply by 1% over the current operating policy. The recommended operating policy improves the average annual release and also the incidental power generation. By comparing the two simulation tables, it is observed that the recommended operating policy reduces the spill considerably over the current operating policy. So the recommended policy gives the optimum upper rule level which gives the storage space for flood absorption without affecting conservation demands.

For details of the study, the reader may please refer NIH Report No CS/AR-18.

6.3 Remarks

The Institute has developed a software for simulating the operation of a multi-reservoir system. The software was used for Bargi and Tawa reservoirs. Reliable and better results relating to reservoir operation have been obtained. It would be desirable that the software is used for other reservoirs in Narmada Basin elsewhere for optimal reservoir operation.

7.0 DAM BREAK STUDIES

More and more dams have come up or are being constructed with the aim of using the available water resources optimally for developmental purposes or for protecting the lives and properties from the fury of floods. With the assured water resources facility and flood protection provided by the dam, the increase in population and the encouragement for improving the overall economy of the country have led to various developmental activities at the downstream of the dam. This has resulted in the settlement of large population and properties on the flood plain and adjoint areas. However, in the eventuality of a dam failure, the disaster would be catastrophic with the flood flow not only occupying the erstwhile floodplain area, but the area adjoining to it. Therefore, it is the responsibility of the organisations involved with the safety of the dams, to prepare dam break Emergency Action Plans (EAP). The purpose of a dam break EAP is to give the authorities of the dam, and any communities downstream from the dam that would be inundated by any portion of a dam break flood wave, the means to identify emergency conditions threatening a dam, expedite effective response actions to prevent failure, and reduce loss of life and property damage should failure occur.

One of the aspects of the EAP is to describe the anticipated dam failure scenarios and the corresponding arrival times of dam break floods at different locations of interest downstream of dam alongwith a description of downstream areas that could be inundated. This requires the performance of dam break analysis as the basis for delineation of possible flood inundation areas.

The dam break analysis involves the following component steps:

- (i) Development or identification of the inflow hydrograph to the reservoir at the time of failure.
- (ii) Routing the inflow hydrograph through the reservoir.
- (iii) Development of the failure condition of the dam.
- (iv) Calculating the outflow hydrograph from the failed dam, and
- (v) Modelling the movement of the flood wave downstream to determine the magnitude of maximum discharge and maximum water level and their arrival time, inundated area, etc.

Many types of dam break models exist ranging from simple computations based on historical dam failure data that can be performed manually to complex models that require computer analysis. The purpose of each model is to predict the characteristics such as peak discharge or stage, volume, and flood wave travel time of a dam break flood. With the availability of improved computational facilities, the empirical models have been replaced by physically based dam break analysis models which simulates the breach on the dam, and routes the flood through the reservoir considering the breach, and subsequently routes the

flood hydrograph from the failed dam through the downstream valley. Nevertheless, the empirical models can give first estimate of the expected endangered area, but are, however, inadequate to define these areas since wave height varies considerably with local narrowing of the valley. Interested readers may refer to Costs (1988) to get to know the details of various empirical models available for dam break analysis.

Simple theoretical estimates of dam break hydrographs originated with Ritter (1892) who used the method of characteristics to obtain a closed form solution for a dam of semi-infinite extent upon a horizontal bed with zero bed resistance. Both experimental and theoretical consideration, however, have shown that the neglect of bed resistance invalidates the Ritter solution as the computed peak discharge tend to be larger than the actual discharges. Ritter's model was improved by various investigators, accounting for bed resistance, however considering the breach to occur instantaneously. Recognising this practical aspect, time dependent breach formation was accounted in dam break models.

The theoretical formulation of Dam Break Model comprises of two mechanisms: (i) Breach formation, and (ii) Routing. The breach in a dam is characterized by its size, shape, and time of formation. In the case of earthen dams, the time of formation is much larger than that in the case of concrete dams. The DAMBRK Model assumes that if the time of formation is less than 10 minutes, the failure is treated as sudden and if it is greater than or equal to 10 minutes, the failure is assumed to be gradual. The sudden failure conforms with the failures of concrete dams and the gradual failure with the earthen dams. the breach may form due to overtopping implying that the water level in the reservoir has been at a lower level than the top of the dam at the time of failure. The failure of earthen dams which exceedingly outnumber all other types of dams is taken up for illustration. The modelling approach assumes a finite size of breach in a dam structure and it gradually increases as time progresses until it is fully developed. The computing time interval being of the order of 10 minutes, the size is linearly varied with time.

The above described breach acts as a weir and the flow over this weir depends on the depth of flow measured from the breach crest at a time. The three different processes which affect the flow computation makes the dam break modelling more complex. These processes include routing of the time varying inflow through the reservoir, breach formation with time, and routing of the flow through the downstream channel. The first component is for computing the water level in the reservoir at the dam site (upstream face) to ascertain the depth of flow above the crest of the breach, the second component is for determining the size of the breach with progressing time, and the third component is for determining depth and quantity of flow at the dam site, for ascertaining the effective depth of flow over the weir, and at downstream locations of the river. These components are integrated through mathematical equations which are solved using an iterative scheme and thus, the quantity of flow and the level attained all along the downstream river are computed.

7.1 Sensitivity Analysis of NWS Dam Break Model for the Bargi Dam

The dam break analysis of Bargi dam has been carried out using the National Weather Service Flood Forecasting Model. In this study a sensitivity study of the model parameters as input has been presented in order to study the impact of the model parameters and inputs on the dam break flood wave characteristics and on the routing process on the downstream area of the dam.

7.1.1 Data availability

The Bargi Dam which is also known as Rani Avanti Basi Sagar Project is a multipurpose project and aims at harnessing the Narmada for irrigation, power generation, water supply and fisheries. The project covers the areas of Jabalpur, Narsingpur, Satna and Rewa Districts falling in Narmada and Ganga basins, which will be benefitted by this dam. The dam comprises of masonry dam and earthen flanks on both sides. The length of masonry dam is 827.20 m with 385.7 m of central overflow portion. The spillway portion is provided with 21 nos. 13.716 m x 15.25 m radial gates. The dam has been divided into 37 blocks and two key blocks. The length of the earthen portion of the dam on left flank 2.77 m includes two saddles in extreme left and on the right flank it is 1.77 km.

The information on the downstream cross-section of the river valley was available at Jamtara, Bermanghat, Sandia, Hoshangabad and Indira Sagar project (Punasa). It is worth mentioning that the lateral inflows are not considered in the routing of dam break flood through the downstream valley of the dam and interpolated cross-sections are used where the distance between the available cross-sections was too large.

The Bargi Dam site, latitude 22°56'30" longitude 79°55'30", drains a catchment area of 14,555 sq.km. Systematic gauging of the river is being done at Jamtara since 1949 and hydrology of this project has been based on above gauge data. Jamtara is 15 km. downstream of Bargi Dam site and catchment area at this location is 16.576 sq.km. Reference to project report (PR-15) can be made for the other features/details of the dam/basin.

7.1.2 Methodology

The dam break analysis include: (i) routing of inflow hydrograph through the reservoir, (ii) a breach mechanism of the dam failure, and (iii) routing of the computed dam break flood wave through the downstream valley of the dam. The reservoir routing is performed by using either a storage or dynamic routing techniques. The channel routing is carried out using dynamic routing technique which involve the solution of population St. Venant's equations. The National Weather Service's Dam Break Flood Forecasting Model (NWS DAMBRK) model applies the Preissman technique for solving these equations. The flow through the breach of the dam is simulated by using weir equations. Some dam break studies have been carried out using DAMBRK model at National Institute of Hydrology

(NIH), Roorkee. The NIH publications on these studies include the application as well as theoretical aspects of the model.

From the study following conclusions are drawn:

- (i) The breach width has direct bearing on the dam break flood peak computations. As the breach width increases, the flood peak increases linearly.
- (ii) As the time to breach development increase the dam break flood peak discharge reduces but is insignificantly from practical application point of view. This insignificant variation is due to the larger surface area of the reservoir.
- (iii) As the side slope of the breach increase the peak discharge increases. The peak discharge is not much sensitive to the variation in this parameter value.
- (iv) The elevation of the bottom breach does have a great bearing on the flood peak computations. The increase in the elevation leads to the reduction in peak discharge. This is due to the reduction in breach size.
- (v) The variation in initial water surface elevation does not lead to significant variation in dam break flood peak magnitude.
- (vi) The roughness of the channel valley reach, just downstream of the dam site greatly affects the flood peak discharge magnitudes; the increase in the roughness decreases the peak discharge and vice versa. The greater 'n' impedes more the passage of flow through a site than a smaller 'n'.
- (vii) The effect of the variations in contraction and expansion coefficients is negligible on the flow characteristics. It is attributed to negligible head loss due to generally uniform channel leading to minor difference in velocity heads.
- (viii) The variation in inflow has little bearing on the dam break flood peak. This, however, is due to keeping the initial water level at the top of the dam leading always to the failure of the dam. The impact of inflow is suppressed due to the flows through breach and the spillway which are much greater than the inflow.
- (ix) The dam break flood peak is almost insensitive to the variations in storage at the dam site but affects the peak discharges at other locations. The dam break flood peak discharge occurs at the time which is of the order of time of failure. Therefore, the rising limb of this hydrograph remains almost unchanged. Which severely changes is the recession limb of the hydrograph which is greatly affected by the storage in the reservoir. This change in the dam break flood hydrograph greatly affects the downstream flow characteristics.
- (x) The reduction in the capacity of the spillway reduces the dam break flood peak due to the reason that given the size of the breach characteristics, the dam break flood peak is controlled by the spillway capacity.

7.2 Dam Break Study of Barna Dam

The dam break study of Barna dam located in Madhya Pradesh has been carried out using the popular National Weather Service Dam Break Flood Forecasting (NWS DAMBRK) model to assess the likely maximum flood discharge and elevation to be attained at Bareilly township (about 22 km. downstream of the dam) in the eventuality of the dam failure. Besides computing the dam break flood hydrograph, a sensitivity analysis of various DAMBRK inputs has been carried out and their effect on maximum discharge and elevation profile is evaluated. The conclusions drawn from the study are given below:

- (i) The effect of roughness was less pronounced at higher discharges than at lower discharges and the downstream location of concern was more affected by the Manning's roughness than the dam break flood hydrograph at the dam site. Also, the effect was more pronounced in the river reach with mild slope (before 17 km) than in the steep river reach (after 17 km) as shown in Fig. 7.1.
- (ii) The variation in the magnitude of expansion coefficient in the prescribed range did not affect elevations except in the most downstream part (after approximately 25 km from dam).
- (iii) The effect of time of failure on the maximum water elevation was much less pronounced than the maximum discharge.
- (iv) The greater breach width produced greater magnitudes of discharge and corresponding elevation at locations in the river reach and vice versa. The effect almost diminished in the steep river reach (after 17 km) as shown in Fig 7.2.
- (v) The effect of breach elevation on both maximum water elevation and discharge was insignificant for the cases examined.
- (vi) The effect of side slope variation from 0.015 to 0.045 on both the maximum water elevation and discharge was insignificant.
- (vii) The inflow variation from 50% of design flood to 150% of design flood affected significantly both the maximum discharge and water surface elevation profiles. The effect on discharge was more pronounced in the river portion having steep slope (after 15 km) and the converse was true in the case of elevation.

For details of the study, the reader may please refer NIH Report No CS/AR-20/96-



DHUADHAR FALLS, JABALPUR



BARNA DAM (MAJOR PROJECT)

Fig. 7.1 Sensitivity of Manning's roughness n to maximum discharge.

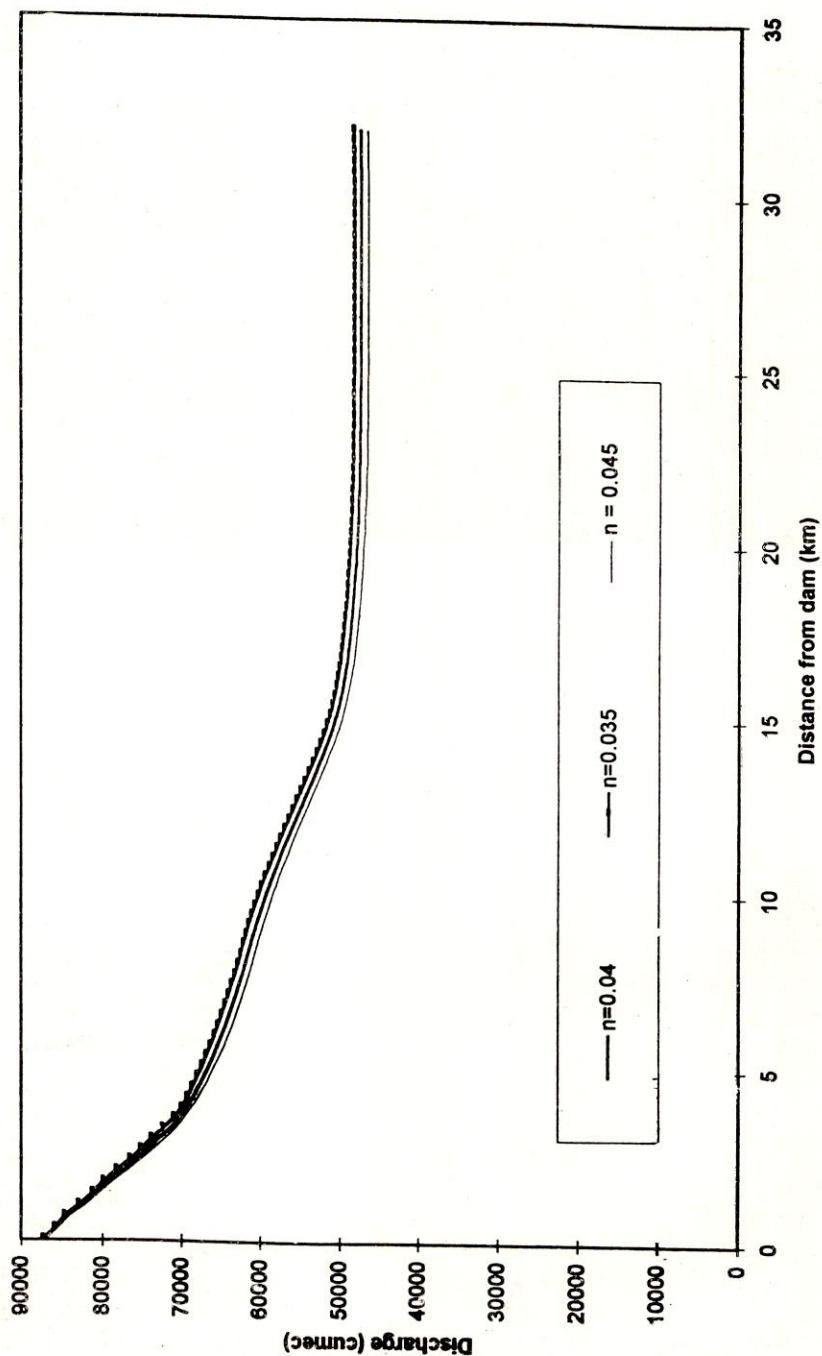
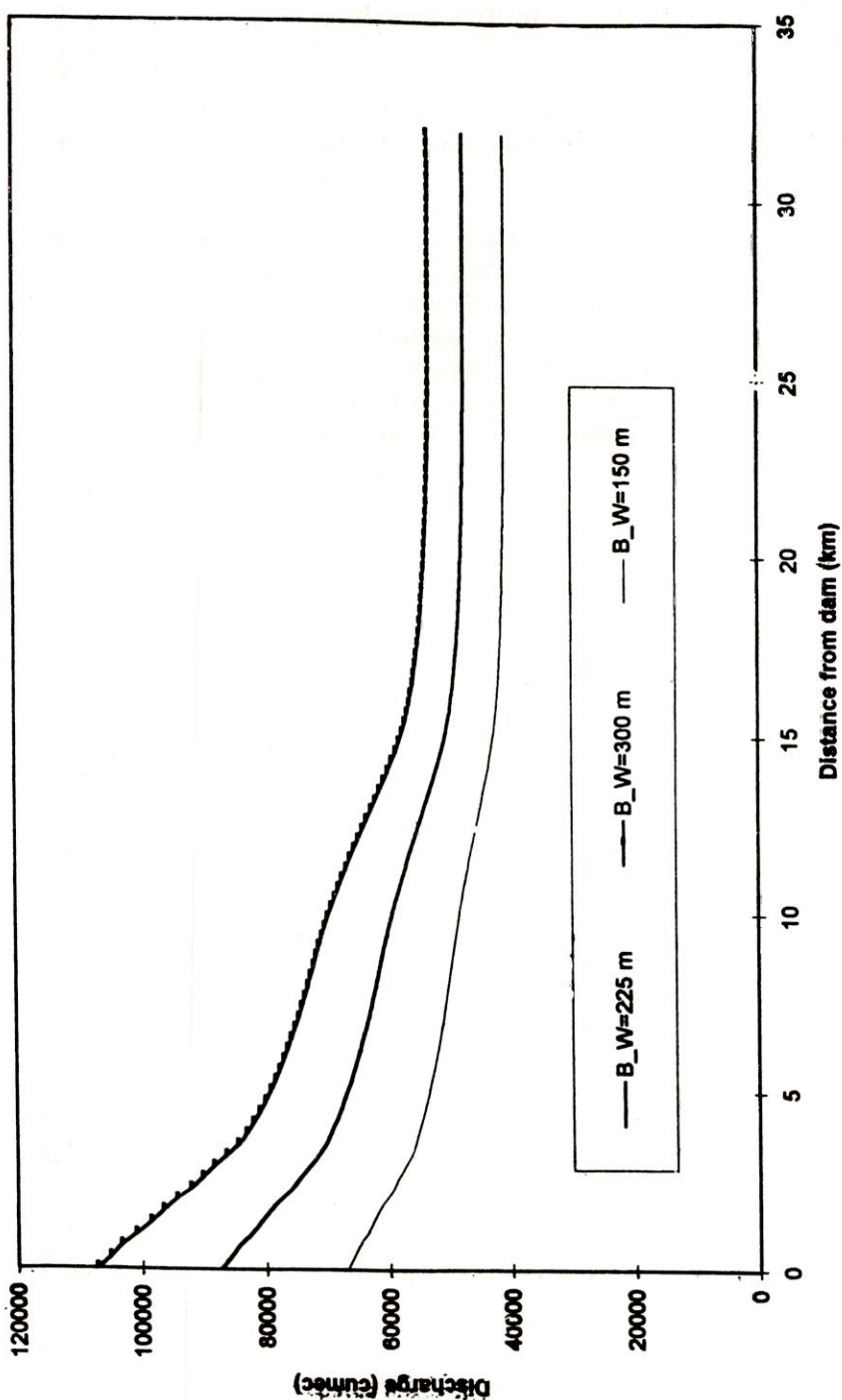


Fig. 7.2 Sensitivity of breach width (B_W) to maximum discharge.



7.3 Remarks

The dam break analysis of Bargi dam has been carried out using the National Weather Service Flood Forecasting Model. In this study a sensitivity study of the model parameters as input has been presented in order to study the impact of the model parameters and inputs on the dam break flood wave characteristics and on the routing process on the downstream area of the dam. The conclusions drawn from the study have already been mentioned above.

The dam break study of Barna dam has also been carried out using the National Weather Service Dam Break Flood Forecasting (NWS DAMBRK) model to assess the likely maximum flood discharge and elevation to be attained at Bareilly township (about 22 km. downstream of the dam) in the eventuality of the dam failure. Besides computing the dam break flood hydrograph, a sensitivity analysis of various DAMBRK inputs has been carried out and their effect on maximum discharge and elevation profile is evaluated. The conclusions drawn from the study have already been described above.

8.0 APPLICATION OF REMOTE SENSING, GIS AND GEOMORPHOLOGY

It is a well known fact that the climate and geomorphological characteristics of a basin affect its response to a considerable extent. Thus, linking of geomorphological parameters with hydrological characteristics of a basin provides a simple way to understand their hydrological behaviour. Quantitative study of geomorphological parameters is pre-requisite for taking up hydrological simulation studies using these parameters.

The geomorphological properties represent the attributes of a watershed, which can be employed in synthesizing and understanding its hydrological behaviour. The geomorphological properties of channel network are generally referred to the basin composition which represents the topographical and geometric properties of the basin. The linear, areal and relief aspects of the watershed are some of the important characteristics which are considered generally in science of geomorphology and particularly in hydrological studies.

In humid regions, agricultural lands are subject to excessive erosion due to water and unsuitable topography. In the regions, ravines or gullies are found near river or stream courses. The ravines extend upto few meters to several kilometers. Skeletal soils are found in hills. Gravelly to fine textured soils are found near river banks. At several locations, deep clays are found. Land capability classification is done in an area in humid region. It considers the properties that decide the ability of the land to produce common cultivated crops and pasture plants virtually on permanent basis. This classification is made primarily for agricultural purposes. It enables the farmer to use the land according to its capability and treat it according to its need.

Keeping above in view, number of related studies were undertaken on these aspects in the Narmada Basin which are described below:

8.1 Geomorphology of Kolar Sub-basin for Hydrological Studies

In this study, an attempt has been made to present a comprehensive review of various geomorphological characteristics, emphasizing their need in various hydrological studies. A computer software has been developed for quantifying some of the important geomorphological parameters. The application of the developed computer program has been illustrated by estimating some of the important geomorphological parameters for Kolar sub-basin of Narmada basin. It provides an effective way for the derivation of the most important geomorphological parameters of a watershed, which are frequently used in hydrological studies, particularly for simulating the hydrologic response of ungauged watersheds.

The topographic map of the Kolar sub-basin of river Narmada was prepared using the Survey of India toposheets. The river network was ordered using Strahler's ordering scheme. It was observed that the Kolar river is a fifth order stream. The mean lengths, which have been computed as the ratio of the total length of specific order streams and the

total number of streams of that order, are 3.97, 6.52, 11.6, 14.05 and 21.89 km for order one, two, three, four and five respectively. The number of streams for different orders are 76, 24, 7, 3 and 1 respectively. It indicates the increasing trend in the mean length with the higher order of streams and number of streams of different order shows decreasing trend from lower to higher order streams.

The bifurcation ratio and the length ratio for Kolar sub-basin are 2.92733 and 1.51959 respectively. These non-dimensional parameters reflect the hydrological characteristics particularly affecting the time of peak characteristics and may be considered for the purpose of hydrological modelling.

The length of C.G. of the catchment along the main stream upto the outlet of the catchment is 18.27 km. This characteristic has been frequently used in hydrological modelling using regional unit hydrograph based approaches together with other measures. The other linear measures which have been computed for Kolar sub-basin are perimeter of the sub-basin, length of the main stream and watershed eccentricity.

The mean areas are found as 11.28, 29.07, 87.85, 117.96 and 881.36 sq.km. respectively for different order streams. It shows that there is an increasing trend in the mean areas of different order streams with the increase in the stream order. Computed sub-basin area is 903.88 sq.km. The other areal measures, which also include the non-dimensional measures, are elongation ratio, circularity ratio, area ratio, drainage density, constant of channel maintenance, form factor and stream frequency. These areal measures govern the peak and shape of the sub-basin response hydrograph. Such areal measures may be used in the modelling of hydrological response using geomorphological features without considering the runoff records.

The third important measures, which represent the geomorphological characteristics of the sub-basin, are relief measures. These measures include slope of the main stream, basin relief, relief ratio, relative relief, ruggedness number and Taylor & Schwarz slope. Most of them are non-dimensional measures except e.g. basin relief. The relief measures have significant importance specially in the modelling of mountainous catchment where velocity of flow is considerably high. The relief parameters govern the overland flow and stream flow processes of a sub-basin. Therefore, these measures can be used to model the flow processes of the sub-basin.

The limited number of geomorphological parameters covering the linear, areal and relief aspects of the sub-basin have been estimated for Kolar sub-basin using the developed software. However, the software may be suitably modified for the estimation of other parameters which have not been included in the present study. The geomorphological parameters, thus estimated, can be utilized for developing the hydrological models to simulate the hydrologic response of the basin.

For details of the study, the reader may please refer NIH Report No TF-99.

8.2 Fluvial Geomorphological Characteristics of Four Sub-Basins of Upper Narmada

In this study, various geomorphological parameters representing linear, areal and relief aspects of four sub-basins of upper Narmada are evaluated. The relations between stream order versus number of streams, mean stream length, and mean drainage area are established. Inter comparison of these basins is attempted based on various geomorphological parameters. Effect of map scale is also evaluated by treating one of the basin as special case and for that, various geomorphological parameters have been evaluated in 1:250,000 and 1:50,000 map scales.

Systematic description of the geometry of a drainage basin and its stream channel system requires the following measurements (i) linear aspect of drainage network, (ii) areal aspect of drainage basin, and (iii) relief aspect of channel network and contributing ground slopes. Here, the first two categories of measurement are planimetric (i.e. treat properties projected upon a horizontal datum plane) and the third category treats the vertical inequalities of the drainage basin forms.

Linear aspects include number of streams of given order (N_w), bifurcation ratio (R_b), length of main channel (L_a), mean stream length (L_w), stream length ratio (R_L), length of overland flow (L_o), length of channel between outlet and a point near to C.G. (L_c), basin length (L_b), watershed eccentricity (τ), basin perimeter (P), wandering ratio (R_w) and fineness ratio (R_{fn}). Areal aspects include drainage area (A), drainage density (D), constant of channel maintenance (C), stream frequency (F), circularity ratio (R_c), elongation ratio (R_e), form factor (R_f), unity shape factor (R_u) and watershed shape factor (W_s). Basin relief aspects include total relief (H), relief ratio (R_h), relative relief (R_p), ruggedness number (R_n) and main channel slope (S_m).

For the present study, four sub-basins of upper Narmada are selected. They are Narmada upto Manot, Burhner upto Mohegaon, Banjar upto Hridenagar and Sher upto Belkheri. The upper Narmada has a complex relief. High ranges of above 900 meters exist over a small area near the source of Narmada river. Areas varying in height between 600 and 900 meters lie along eastern and middle portions of the boundary. The upper Narmada has a continental type of climate. It is very hot in summer and cold in winter and receives most of the rainfall from South-West monsoon from June to October. Mean annual rainfall varies approximately from 800 to 1600 mm.

The catchment boundaries and river system were drawn from Survey of India toposheets covering upper Narmada basins. For evaluating different geomorphological parameters, the river system of the basins were ordered according to Strahler ordering scheme. It is observed that Narmada upto Manot and Burhner upto Mohegaon are sixth order basins while Banjar upto Hridenagar and Sher upto Belkheri are fifth order basins in 1:250,000 map scale. However, in 1:50,000 scale, the Sher basin is of seventh order. It was seen that number of streams for first order increases phenomenally with change of scale for Sher basin. Main reason for this is increase in resolution with change of map scale from 1:250,000 to 1:50,000. Since a watershed of a given order can be modelled as a

collection of sub-elements, the number of streams and mean stream lengths of each order is an important concept in Hydrology. The other linear measures evaluated for the basins are given in Table 8.1.

Table 8.1 : Geomorphological Parameters based on Linear Aspects

Parameter	Narmada upto Manot	Burhner upto Mohegaon	Banjar upto Hridenagar	Sher upto Belkheri	
Scale →	1:250000	1:250000	1:250000	1:250000	1:50000
P	440.000	320.000	355.000	170.000	172.000
L_a	239.000	138.000	185.000	77.000	78.500
L_c	140.000	70.000	78.000	35.000	35.500
L_b	126.250	96.300	104.250	53.750	54.300
R_w	1.893	1.433	1.775	1.433	1.446
R_{fn}	0.543	0.431	0.521	0.453	0.456
R_L	2.148	1.786	2.393	1.514	1.549
τ	0.796	0.599	0.696	0.600	0.650

The stream length ratio and bifurcation ratio are important dimensionless parameters. These dimensionless parameters are very useful in synthesizing hydrograph characteristics. Length of channel between outlet and a point near to center of gravity is an important parameter used extensively for deriving synthetic unit hydrographs for small basins. Length of main channel is an important parameter employed extensively for calculating time of concentration of the catchment in conjunction with average slope. Watershed eccentricity τ indicates compactness of the basin. Higher value of τ indicates less compactness of the basin which in turn indicates flat peaked hydrograph of the basin and vice versa. Out of the four basins, the value of τ is highest for Manot basin which indicates flat peaked hydrographs compared to other three basins. Most of the linear measures were found to remain fairly constant with change in map scale in case of Sher sub-basin. Various areal measures evaluated for the study basins are listed in Table 8.2.

Total drainage area of a basin is a very important geomorphological parameter and has been used widely in various hydrological simulation studies. Elongation ratio and circularity ratio are shape parameters and give a feel of the basin shape compared to a circle. As the value of elongation ratio and circularity ratio approaches to one, the shape of the basin approaches towards a circle. Some of the important relief measures evaluated for the basins are listed in Table 8.3.

Table 8.2 : Geomorphological Parameters based on Areal Aspect

Parameter	Narmada upto Manot	Burhner upto Mohegaon	Banjar upto Hridenagar	Sher upto Belkheri	
Scale →	1:250000	1:250000	1:250000	1:250000	1:50000
A	4980.000	4103.000	3472.000	1456.880	1456.000
D	0.804	0.593	0.538	0.760	4.220
C	1.244	1.686	1.858	1.315	0.240
R_A	4.198	3.936	4.797	4.786	4.365
R_c	0.323	0.504	0.346	0.634	0.620
R_e	0.631	0.750	0.638	0.801	0.790
W_s	3.002	1.909	2.783	1.788	1.820
R_u	1.789	1.503	1.769	1.408	1.420
R_f	0.312	0.442	0.319	0.504	0.490
C_f	0.211	0.152	0.108	0.196	2.460

Table 8.3 : Geomorphological Parameters based on Relief Aspect

Parameter	Narmada upto Manot	Burhner upto Mohegaon	Banjar upto Hridenagar	Sher upto Belkheri	
Scale →	1:250000	1:250000	1:250000	1:250000	1:50000
H	542.000	509.000	372.000	447.600	447.600
R_h	0.004	5.4E-3	1.02E-2	9.5E-3	9.5E-3
R_p	0.001	1.6E-3	2.0E-3	2.6E-3	2.6E-3
R_n	0.436	0.301	0.200	0.340	1.890
R_m	6.9E-4	2.1E-3	1.3E-3	3.3E-3	3.2E-3

Relief measures are indicative of the potential energy of a drainage system present by virtue of elevation above a given datum. Main channel slope is one of the important relief measures and has been used widely in various hydrological studies, particularly for estimation of time of concentration of basin. The relief parameters govern the overland and stream flow processes of a basin. Ruggedness number combines the qualities of slope steepness and length, and is formed of the product of relief and drainage density. Relief parameters are important in hydrological studies in mountainous areas and often used in modelling hydrological responses of these areas.

It was concluded that most of the important geomorphological parameters such as area, length of main stream, length to C.G., basin perimeter and dimensionless parameters such as area ratio, bifurcation ratio, length ratio etc. remain fairly constant with change of scale of measurement. However, noticeable differences were observed in drainage density, constant of channel maintenance and stream segment frequency with change of scale of measurements.

This study is an effort in the direction of developing regional Geomorphological Instantaneous Unit Hydrograph studies. The geomorphological parameters, thus estimated, may be used for developing the hydrological models to simulate hydrological response of the basin. Such models are very useful and are being widely used for simulating hydrological response of ungauged basin or basin with limited data.

For details of the study, the reader may please refer NIH Report Nos. CS/AR-128, CS/AR-159, and CS/AR-201.

8.3 Land Capability Classification in a Part of Narmada Basin

In this study, land capability classification is carried out considering several soil characteristics and associated land features. The major soil characteristics considered are texture, depth, permeability and salinity of the soil. The important associated land characteristics are landuse, slope of the land, erosion etc.

Bargi project is a major multi-purpose water resources project in upper Narmada basin. The project provides irrigation to area in Jabalpur and Narsinghpur districts of Madhya Pradesh. Land capability mapping is very important for proper management of agricultural lands. The command area of Bargi left bank canal is selected for land capability mapping. The areal extent of the command is 307302 Ha. The Bargi left bank canal takes off from the left flank of Bargi dam and runs upto the Shakkar river covering a distance of 137.2 km. The command area under Bargi LBC lies in Jabalpur and Narsinghpur districts.

An approach given by Central Soil and Water Conservation Research and Training Institute is adopted in this study for land capability classification. The map is prepared in different physiographic units in the command. Various input maps of physiography, landuse/cover and soil are prepared using IRS LISS II FCC data of pre- and post-monsoon dates. The maps from satellite data are checked using ancillary data such as topographic maps and soil data. The maps are input in a GIS ILWIS (Integrated Land and Water Information System) using digitizing table. The maps are overlaid and statistics for the area are generated using GIS ILWIS.

Ground water data (pre-monsoon, post-monsoon and Rabi season) are available for Bargi command for the period 1984 to 1992. Detailed soil survey is carried out in the command. Soils in Jabalpur and Narsinghpur districts are classified respectively as medium and deep black. The soils are dark yellowish brown to light yellowish brown in undulating and rolling topography. Near the banks of rivers, the soils are yellow. The soils are of coarser texture and skeletal along the banks of river and nallas.

Soil permeability data are available for 51 stations. The permeability classes are specified as moderate and rapid, slow and very slow. EC data are available from 1:2 dilution EC tests. The EC in the command is generally below 1 mhos/cm. Data on calcium carbonate content and effervescence tests are available for the command area. IRS LISS II FCC paper prints and IRS LISS I CCT is available for the study area.

All the parameters required for the analysis for land capability classification have been generated and stored in GIS. The parameters generated are soil characteristics such as soil texture, permeability, conductivity, slope of land, soil erosion and gully erosion. These parameters were then classified according to the land capability classification criterion given by Tejwani (Using and Interpreting Soil Information for Land Capability, Irrigability and Range Site Classification and for Highways, Soil Conservation Digest, Vol. 4, No. 2, October 1976). These parameters were overlaid in GIS and a land capability map was generated. Within a land capability class, the sub-class is determined by hazard e.g. erosion, soil hazard.

Physiography of the region is mapped by visual interpretation of IRS LISS II FCC. Hill and alluvium have 4209 Ha and 307682 Ha areal extent respectively. No area is interpreted as waterlogged in the command. A clear boundary exists between yellow and black soils in the FCC. The boundary is not visible in post-monsoon date FCC. The urban area is delineated in post-monsoon image. Forest area is delineated in both pre- and post-monsoon FCC. The texture varies from smooth to medium. Salt affected area is mapped using pre-monsoon date IRS LISS II FCC. Salt affected cultivated area has patchy pattern. The salt affected area has not been checked either from ancillary data or field visit. Other categories are checked using topographic maps.

There are 13 land capability sub-classes identified. Land capability map with respect to soil properties and land capability map with respect to erosion factor are used as input map. There are five phases in the study area. Five statistics tables are generated for each map. Statistics are generated for phase areas for different maps. Statistics are also generated for command area for all the maps for which phase area statistics are generated.

The majority of the area in the command is under black soil. Thus major area is classified in category IVS in the study area. Erosion occurs near the banks of the river and nallas and in piedmonts. Thus the areas are classified in categories IV and VI depending on the severity of erosion. Near the banks of river and nallas, some area is under skeletal soils. These areas are classified in category VS, since they possess stoniness in the soil. Other areas near the bank of river and nallas are having suitability class II and III. In these areas, different degree of erosion occur. Soil grades from coarse to fine texture. Such areas are better suitable than other areas for agricultural activities.

Area under yellow (alluvial) soils from IRS LISS II FCC are of larger extent than area obtained from field survey data in all phases except phase II. In phase II, the yellow (alluvial) soil area obtained from satellite data is 50 % of the area under yellow soil from field data. In phases III, IV and V, the yellow soil area is obtained three times in satellite data as compared to that in field data.

Very small area is mapped as salt affected area in the command. The area mapped could not be checked from ancillary data, since all relevant soil properties were not decided from ancillary information. However, the salt affected areas did not change the land capability map for the command as this area has been mapped as clay soils which already rank low in the suitability classes for land capability.

For details of the study, the reader may please refer NIH Report No CS/AR-178.

8.4 Integration of GIS and Remote Sensing in Soil Erosion Studies

The present study was carried out for the estimation of soil erosion using Universal Soil Loss Equation. The different parameters required for USLE were generated in GIS using Remote Sensing data and ancillary data. These parameters are crop management factor, Rainfall erosivity factor, Soil erodibility factor, Length slope factor and Conservation Practice factor. For the present study a part of Banjar subbasin in upper Narmda basin was selected. Drainage network, Landuse and Elevation map for Banjar subbasin are shown in figures (Figs. 8.1-8.3). This study area is covered in the Mandla district of M.P. The landuse classification map of this area was prepared using satellite data. This land use map was subsequently used in the estimation of crop management factor. For rainfall erosivity factor rainfall data were collected and using standard relationships, this factor was determined. For length and slope factor, a digital elevation map (DEM) was prepared using Survey of India toposheets and then slope and length etc. were calculated.

In the study Integrated Land and Water Information System (ILWIS) was used. This software was developed at the computer centre of International Institute of Aero Space Survey and Earth Sciences (ITC), Enschede, the Netherlands. The data generated in this system was integrated in the form of USLE model to produce the soil erosion in the study area. This estimation was performed for three cases i.e. without management, in monsoon season and in non monsoon season. The maximum potential soil loss estimated using the physical components of the USLE (RKLS) indicated very high values. The soil predicted from under existing land use units during the monsoon season shows that the erosion in the area is high in some portion. The soil loss computed for non monsoon season was not so severe.

This study shows the model like USLE can be integrated in GIS and the results can be produced in map form. Once the data base is prepared in GIS, we can manage some of the parameters for management of soil erosion. Different scenarios can be applied and their effects can be analysed.

For details of the study, the reader may please refer NIH Report No CS/AR-186.

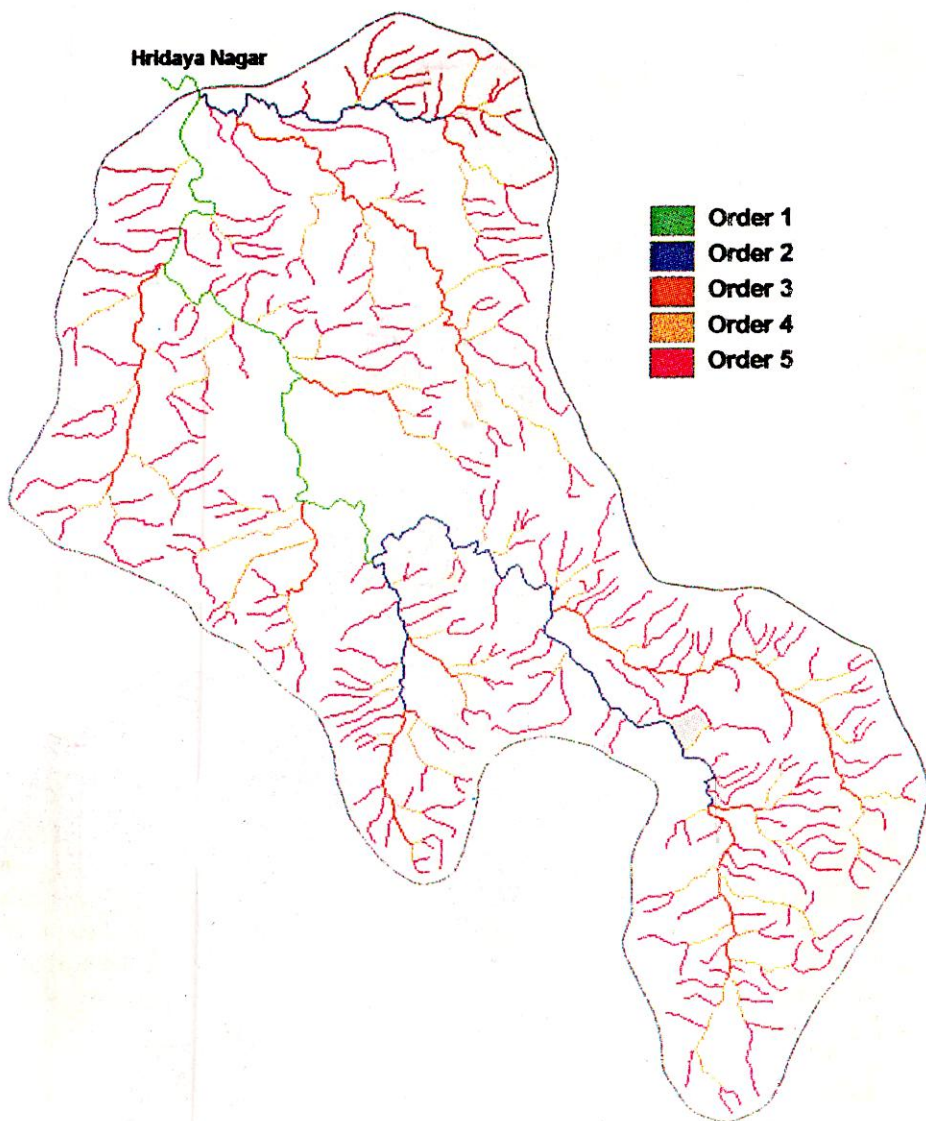


FIG. 8.1 : DRAINAGE NETWORK MAP WITH ORDER
OF BANJAR SUB-BASIN

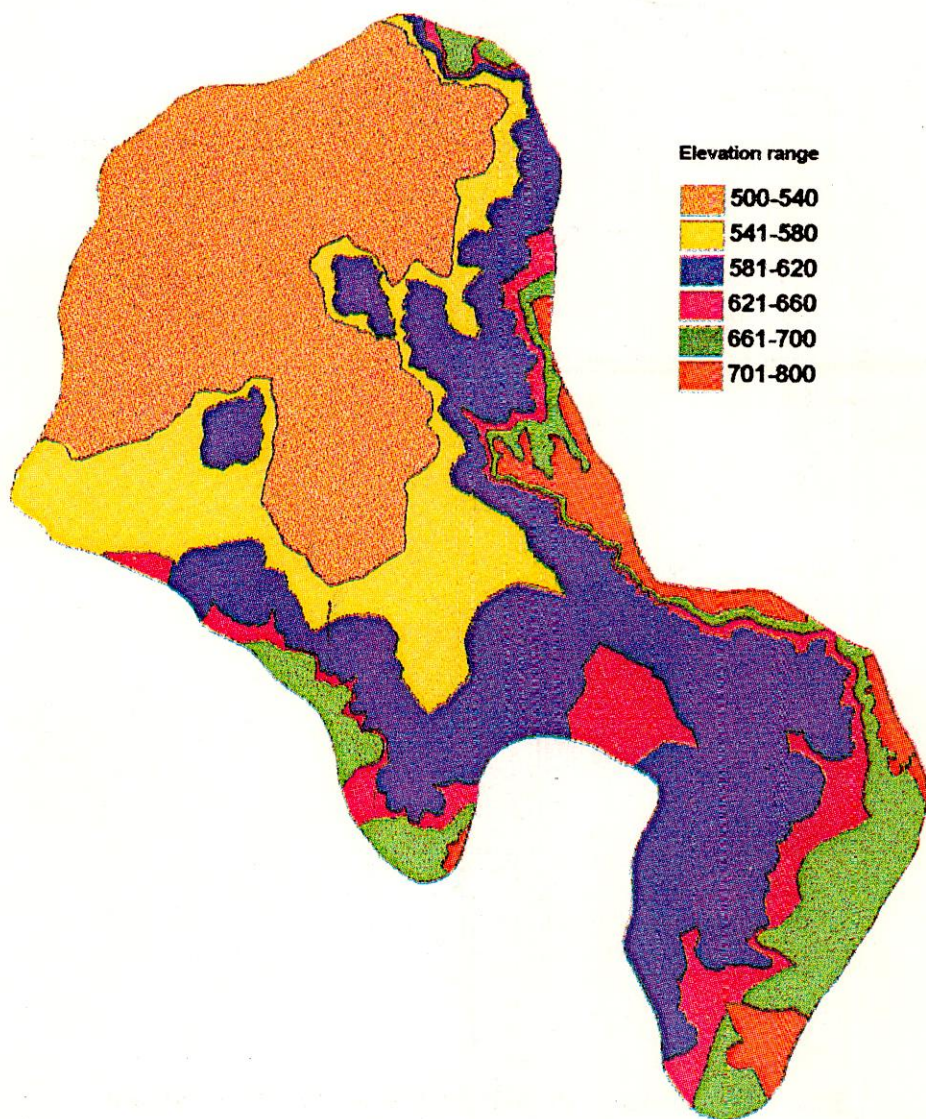


FIG. 8.2 : DIGITAL ELEVATION MAP OF BANJAR SUB-BASIN

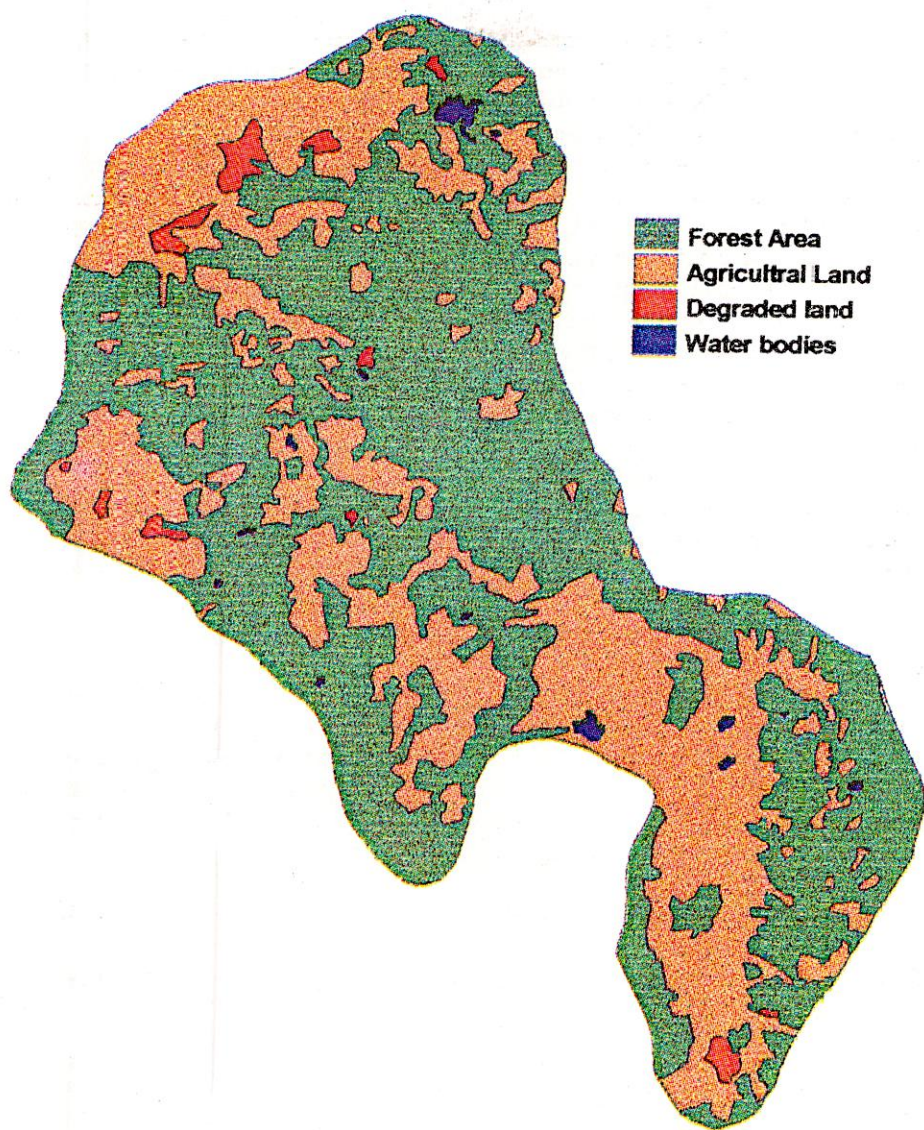


FIG. 8.3 : LAND USE MAP OF BANJAR SUB-BASIN

8.5 Runoff Modelling Using SCS Method

The SCS curve number technique is used to obtain runoff volume from land use/cover, soil and rainfall data. The technique is applied to Temur catchment of Narmada basin. The catchment lies between latitudes 22°35'N and 23°02'N and longitudes 79°40'E and 79°58'E. The area of the catchment upto gauge discharge site is approximately 813 sq. km. Landuse/cover and soil maps are derived from visual interpretation of IRS LISS II FCC paper prints. The landuse/cover map is verified from Survey of India topographic maps. Land treatment, crop type in agricultural area and hydrological conditions of forest are assumed. From daily rainfall data, rainfall maps are obtained using moving average interpolation technique. Thrice daily discharges are obtained from gauge discharge relationship and gauge data. The base flow is separated using a technique for complex storms. From these, direct runoff volume is determined. Curve numbers are derived from various hydrological conditions and crop types, landuse/cover and soils. Error varies from -8.6 to 26.5% in modified method and from 3.7 to 37.1% in original method.

The gauge discharge rating curve is obtained from available daily gauge at 8 hrs. and discharge data. The gauge data ranges from 0.4 metres to 3.66 metres and the discharge data ranges from 11.38 to 253.15 cumecs. The relationship derived is given below:

$$Q = 82.714 (H - 0.3)^{0.827}$$

Runoff computations is completed for rain storm of August 11 to 18, 1983. Rainfall data are interpolated from daily data at raingauge stations: Jamtara, Bargi and Lakhnadon in a GIS, Integrated Land and Water Information System (ILWIS). In ground water separation for complex storms, 8 hourly recession constants for direct and groundwater runoff are taken as 0.67 and 0.97 respectively. Runoff computed for few assumed crops and hydrological conditions affecting runoff are presented in Table 8.4.

For details of the study, the reader may please refer NIH Report No TR/BR-125.

8.6 Application of Remote Sensing Technique for Water Logging Study in Tawa Command Area

Irrigation projects involving interbasin transfer of water without adequate drainage has disrupted the equilibrium between the ground water recharge and discharge resulting in accretions to the ground water table. The Tawa command area faces problems of water logging resulting from over irrigation and seepage losses through distributary system. The study was undertaken to assess waterlogged area in Tawa command using IRS satellite data.

A rapid and accurate assessment of the extent of waterlogged areas can be made from using remotely sensed data. Visual interpretation of IRS-LISS-I FCC of 20 Nov. 1989 and 23 March 1989 (Path 27 Row 52) were carried out to prepare land use, drainage map and delineation of waterlogged area in the Tawa command area. IRS-LISS-I digital

Table 8.4 : Computed direct runoff and error of prediction

Landuse			Direct runoff (modified method)	% error	Direct runoff (Original method)	% error
Small grain: straight row, good	Fallow: barren	Wood: fair	31.23	8.4	34.33	19.1
Row crops: straight row, poor	Fallow: barren	Wood: poor	36.45	26.5	39.5	37.1
Row crops: straight row, poor	Fallow: barren	Wood: Poor	35.42	22.9	38.19	32.5
Row crops: contoured and terraced, crop residue, good condition	Fallow: crop residue, good condition	Wood: fair	27.8	-3.5	31.23	8.4
Row crops: contoured and terraced, crop residue, good condition	Fallow: crop residue, good condition	Wood: poor	29.41	2.0	33.16	15.1
Close-seeded crop: contoured and terraced, good condition	Fallow: crop residue, good condition	Wood: fair	26.35	-8.6	29.90	3.7
Close-seeded crop: contoured and terraced, good condition	Fallow: crop residue, good condition	Wood: poor	27.97	-2.9	31.83	10.4
Small grain: contoured and terraced, crop residue, good condition	Fallow: crop residue, good condition	Wood: fair	29.61	2.7	32.85	14.0
Small grain: contoured and terraced, crop residue, good condition	Fallow: crop residue, good condition	Wood: poor	31.23	8.4	34.78	20.7
Row crops: contoured and terraced, crop residue, good condition	Fallow: Barren	Wood: fair	28.25	-2.0	31.64	9.8

data (CCT's) of 29 May 1988, 20 Oct. 1988 and 20 Nov. 1989 were analysed to assess the areas affected by waterlogging and the areas potential sensitive for waterlogging. An attempt has been made to validate the IRS derived waterlogged area with the available water table depth data.

The IRS-IA-LISS data have been proved to be very useful for the assessment of waterlogging. Density slicing is a useful technique to make an assessment of waterlogged areas.

The results obtained from this study indicate that in Oct. 1988 an area of 80 sq. km. was affected by waterlogging and about 140 sq. km. area was sensitive for waterlogging, where water table lies in between 1 to 3 m. It is suggested that periodic assessment of waterlogging using remotely sensed data should be carried out at a regular interval.

For details of the study, the reader may please refer NIH Report No CS/AR-158.

8.7 Remarks

The geomorphological parameters may be used for developing the hydrological models to simulate hydrological response of the basin. Such models are very useful and are being widely used for simulating hydrological response of ungauged basin or basin with limited data. Modern techniques like remote sensing and GIS can provide useful information for hydrological modelling and monitoring. Use of remote sensing techniques has been demonstrated for water logging, soil erosion and hydrological simulation in Narmada basin by undertaking the above studies. The model like USLE can be integrated in GIS and the results can be produced in map form. Different scenarios can be applied and their effects can be analysed.

9.0 GROUND WATER ANALYSIS AND MODELING INCLUDING WATERLOGGING AND DRAINAGE STUDIES

Ground water is a major source of water supply for a large portion of the world population. The evaluation, rational development and management of ground water resources, which is very essential to feed the growing population, requires a thorough knowledge of the subsurface environment and an understanding of the hydrological processes that governs the occurrence, movement and yield of ground water.

As per National Water Policy, the development of ground water resources is to be limited to the utilization of the renewable part of the naturally occurring ground water. The present development policy does not envisage utilization of secular reserves (static ground water resource) which is many times the dynamic ground water resource.

During the past four decades, there has been phenomenal increase in the growth of ground water abstraction structures due to implementation of technically viable schemes for development of the resource backed by liberal funding in availability of power and diesel, good quality seeds, fertilizers, government subsidies, etc. Further additional dependence is being laid on the resource during drought periods. Ground water development has, therefore, occupied an important place because of its role in stabilizing Indian agriculture and as means for drought management.

The earlier practice of planning surface irrigation without much consideration of ground water status has often been resulted in waterlogging and salinity problems in the command areas after a time due to gradual rise of ground water. The impact of surface water development on the existing ground water regime therefore needs to be studied for judicious use of surface water and ground water to derive optimal benefits.

9.1 Ground Water Balance before Introduction of Irrigation in the Canal Command Area

The upland alluvial valley of Narmada river in Madhya Pradesh is one of the most promising area for development of its surface water and ground water resources. Ground water, till recently, was the main source for irrigation and the area recorded a phenomenal rise in the number of tubewells during the last decade. Also, a new fillip has been given to the development of surface water resources. Bargi dam, the longest masonry and earthen dam in Madhya Pradesh, has been constructed across river Narmada with a network of canal system for surface irrigation and power irrigation. The Left Bank Canal (LBC) is 137.2 Km long and designed to irrigate about 1.57 lakh hectares of land in Jabalpur and Narsinghpur districts of Madhya Pradesh. The command area forms a part of Narmada alluvial valley which is quite rich in its ground water resources. A network of branch canals and distributaries are being constructed extending upto river Narmada to achieve the targeted area under surface irrigation.

In view of the hydrogeological setup of the area, it is apprehended that with a widespread canal irrigation, problems of waterlogging followed by salinity hazards may crop up in the area in the long run. The advent of surface irrigation may also have a dampening effect on the present development of ground water resources because of its availability at lower tariffs, thereby indirectly aggravating the waterlogging problem in the area. The impact of surface water development on the existing ground water regime therefore needs to be studied for judicious use of surface water and ground water to derive optimal benefits.

The purpose of this study was to present the ground water availability in the Bargi Left Bank Canal (LBC) command area. Ground water recharge has been estimated for pre-Bargi LBC situation i.e. before introduction of extensive irrigation in the canal command area.

The required data pertaining to the study was obtained from Feasibility Report of Bargi Left Bank Canal Project (Government of Madhya Pradesh). The Bargi Left Bank Canal takes off from the left flank of Bargi dam covering a distance of 137.2 km. The design capacity of canal is $124.65 \text{ m}^3/\text{s}$. The command area under Bargi LBC lies in Jabalpur and Narsinghpur districts of Madhya Pradesh. There are 4 branch canals, 11 distributaries, 16 minors and 4 sub-minors serving the complete command. The mean annual and monsoon rainfalls in the command area are 1290 mm and 1200 mm respectively. The alluvial soils cover almost the entire command area, deep and medium black clays are predominant. Madhya Pradesh Irrigation Department has identified 7 zones considering soils and topographical situation within the Bargi Left Bank Canal command area for phase-wise irrigation development.

The ground water available (pre-Bargi LBC situation) is due to percolation of rain water. There is very little irrigation and recharge due to seepage of irrigation water may be neglected for the assessment of ground water availability before large scale irrigation is introduced through Bargi LBC system.

There are nearly 40 permanent observation wells in and around the command area where the water level fluctuations are recorded by the State Ground Water Organisation. The average water level fluctuation between pre-monsoon and post-monsoon season ranges from 1 m to 6.4 m. The value of specific yield for silty/clayey alluvial area (Bargi LBC command belongs to this type of soil) ranges between 5 and 12 percent. The specific yield values, as recommended by Madhya Pradesh Irrigation Department, were adopted for the assessment of annual ground water recharge by water table fluctuation method.

Based upon the gross area, specific yield and annual water table fluctuation for the seven irrigation zones, the net annual ground water recharge has been estimated in the command area by ground water level fluctuation approach. The net annual utilizable ground water recharge (70 percent of the gross recharge) was estimated as 341.13 MCM.

The development of ground water resources in the central and northern parts of Bargi LBC command (where already good aquifers exist) would result not only in proper utilization of available water resources but also the pumpage from ground water storage

will provide a sub-surface drainage to the areas which are likely to be waterlogged. The large scale ground water development in the area adjacent to Narmada river would steepen the sub-surface gradient of ground water flow and prevent any waterlogging in the southern areas where surface water irrigation is being done from the main Left Bank Canal.

A rational approach is imperative to develop the water resources of the Bargi Left Bank Canal command area in such a manner that the adverse effects of uncontrolled surface water irrigation can be avoided. Proper conjunctive use of surface water and ground water is necessary to efficiently utilize the water resources without endangering the command area with waterlogging and salinity problems in future.

9.2 Identification of Aquifer Parameters in Narmada Basin

The quantitative evaluation of groundwater and management of aquifers depend largely on the correct determination of aquifer parameters. The reliability of ground water models (predictive model/ management model) is enhanced by better aquifer parameter identification. Pump-test occupies a prominent position among the various methods available for identification of aquifer parameters. The important aquifer parameters are transmissivity, T and storage coefficient, S . Graphical methods of identifying the aquifer parameters have been proposed by many investigators. These methods involve considerable subjectivity on the part of analyst as personal errors are involved. It becomes practically difficult to determine the parameters by curve matching when observed data points show a flat curvature. In Jacob method, the observed drawdown data do not follow straight line if argument of the well function is greater than 0.01 and also if the data contain observational errors. In order to overcome these problems associated with traditional curve matching/graphical method, numerical methods that use the objective criteria for the matching of theoretical and observed drawdowns have also been suggested.

All the above methods are applicable for constant rate of pumping and can not be used for variable rate pumping. Several investigators have presented analytical and graphical methods for analysis of variable rate pumping test data. These methods are applicable for drawdown observed at an observation well located some distance away from the pumped well. For the determination of the aquifer parameters using the drawdown observation in the pumped well, the 'well loss' and the 'effective radius' of pumped well need to be taken into account. Using the observation data at the pumped well, instead of S , $r_e^2 S$ (r_e = effective radius of well, S = storage coefficient) should be determined.

The study deals with the identification of T and S by analysing the observed drawdown in a confined aquifer due to pumping a tubewell at a variable rate. Marquardt algorithm has been used with analytical derivatives for optimizing the parameters and finally a software has been developed for this purpose. Another method has also been evolved for identification of T and S using constant rate pumping test data. This method is based on least square regression and, in fine, explicit expressions for T and S have been obtained. Aquifer parameters have been identified for the five test sites in Narmada basin.

9.2.1 Development of Methodologies

1. A model has been developed for the determination of confined aquifer parameters (transmissivity and storage coefficient), from the drawdown observations obtained during a variable rate pump-test. Marquardt algorithm has been used for optimizing the aquifer parameters.
2. Explicit expressions have been obtained for estimation of transmissivity and storage coefficient making use of least square regression and Theis equation. The advantage of this method are i) the well loss is accounted automatically, ii) initial guess of the parameters are not required, iii) calculations are simple and can be performed on a calculator.
3. A new graphical method has been developed for the estimation of confined aquifer parameters from short duration constant rate pumping test data. The method is especially suited when the observation well is at large distance and the Cooper and Jacob method fail to give reliable estimates of the aquifer parameters.

9.2.2 Application

Methodologies developed above are directly applicable to the field-problems.

For details of the study, the reader may please refer NIH Report No TR/BR-130.

9.3 Processing of Ground Water Data

Ground water is a major source of water supply for a large portion of the world population. For its evaluation, rational development and management, various types of ground water data are collected and stored in various forms. To represent the data in more informative and useful form, processing of this data is necessary. Ground water maps provide large amount of information about the occurrence and movement of ground water. The distributed ground water models require the spatial and temporal variation of aquifer parameters. Ground water data, which is usually measured at random points, require interpolation.

This study deals with the processing of ground water data for the Jabalpur district of Madhya Pradesh. Ground water maps have been prepared. Polynomial interpolation technique has been used for interpolation of ground water levels. The ground water depth measurement was started in the year 1974 from 52 observation wells. The measurement is done twice a year i.e. pre-monsoon and post-monsoon. From the year 1986 onwards, observations of ground water depth are taken at 102 points. Due to lack of pump test data, the processing of ground water data was incomplete in some respect.

Ground water maps provide a bank of information on gravitational water in the upper part of the lithosphere and also provides the basis for learning about and understanding the relationship between ground water and its geological and hydrological environment. A great deal of information, both qualitative and quantitative, can be obtained

from maps which show depth to ground water and related data such as elevation of the water table. Ground water maps have been prepared for the Jabalpur district using SURFER software.

Depth to water table map, also known as isobath map, show the configuration of depth to water table from ground surface. Isobath lines are lines of equal depth to water table. These maps indicate at a glance the areas affected by high water table problems which is usually the criterion for determining the need for subsurface drainage. Prepared at regular intervals, these maps indicate the seasonal variation of affected areas. Ground water depth maps for the years 1974, 1980, 1985, 1990 and 1993 were prepared for both pre-monsoon and post-monsoon seasons.

Water table contour map shows the configuration of the water table surface at a specified time. A water table contour line is the locus of points on the water table surface for which hydraulic head is constant. The contour lines of water table map are in fact equipotential lines. Hence, the direction of the ground water flow, which is perpendicular to the equipotential lines, can be directly obtained from these maps. These maps are also useful in determining the location and extent of high water table areas. It also provides direct visual information on the slope of the water table. Water table contour maps for the years 1974, 1980, 1985, 1990 and 1993 were prepared for both pre-monsoon and post-monsoon seasons.

Ground water fluctuation map is prepared by plotting, for a given span of time, the change of water level in observation wells and drawing lines of equal change. Ground water level fluctuation directly reflects the storage change in ground water. In this study, ground water fluctuation was calculated from the year 1974 to 1985 and from 1987 to 1993 for both pre-monsoon and post-monsoon periods. The ground water fluctuation within a year, i.e. from pre-monsoon to post-monsoon was also calculated for the years 1974, 1980, 1985, 1990 and 1993.

A time series is a chronological sequence of observations of a specified variable. In some cases, the observations are continuous over time, and in other cases, the observations are made only at discrete time intervals. A ground water depth time series reflects all natural hydrological processes as well as the influence of man upon the aquifer. The plots prepared in this study includes time series plot of mean water depth for pre-monsoon and post-monsoon, mean ground water fluctuations and the time series plot of water table depth for a few particular observation points. It was observed that the mean ground water depth for pre-monsoon period is almost same over the years. On the other hand, there are small variations in mean ground water depth for post-monsoon season.

Least square polynomial approximation technique was applied to ground water level data for the pre-monsoon and post-monsoon data for the year 1993. It was found that for both periods, a polynomial equation of degree 2 (i.e. number of coefficients 6) fits the data best.

For details of the study, the reader may please refer NIH Report No. CS/AR-171.

9.4 Groundwater-Tank Interaction in Jabalpur District

Jabalpur district in Madhya Pradesh is bestowed with many tanks of sizes ranging from 0.1 to 0.4 sq.km. and capacity varying from 2 to 20 million cubic metres. There are about 100 such tanks and many amongst them are being used as a source of irrigation after being developed by the Irrigation department of Madhya Pradesh Government. These tanks cater for a command area of approximately 640 sq.km. of agricultural land. The contribution of these tanks to ground water has been estimated for pre- and post-monsoon seasons from 1989 to 1993.

The ground water contours are similar between season to season and amongst different years. As such it could be inferred that the ground water regime has been stabilised over years due to developing the tanks as sources of minor irrigation by the Irrigation department. Ground water contours are flat in the northern portion of the district and the contours are within 1:1000 to 1:500 in slope, whereas the contours in the southern portion and specially along the southern district boundary the contours are steep and is 1:100 or less.

It has been observed from the ground water contours for different years i.e., 1989 to 1993 that tank water is contributing to ground water in both pre- and post-monsoon seasons. The respective share of this contribution from each mound has been estimated by the equation:

$$Q = \text{Transmissivity} * \text{Circumference of the mound} * \text{Ground water gradient}$$

The gradient is calculated by dividing the difference of ground water potential values at the outer and inner ring by the distance between them. As there is no pump test data available in the area for the determination of transmissivity of the aquifer, the transmissivity values of 1000 sq.m. per day and 100 sq.m. per day have been assumed for the northern and southern portions of the district respectively on the basis of the contour slopes. Locations in the contours wherein the ground water mounds have occurred are quite naturally the places where sizable tanks are located either on the mound or very near to the mound. It is observed that interaction of tanks with ground water is quite conspicuous along the boundary of the district especially in the southern half. It has been estimated that the average contribution from the tanks to ground water are 1.4 and 1.7 million cubic metres in pre- and post-monsoon seasons respectively.

For details of the study, the reader may please refer NIH Report No CS/AR-165.

9.5 Remarks

A rational approach is imperative to develop the water resources of the Bargi Left Bank Canal command area in such a manner that the adverse effects of uncontrolled surface water irrigation can be avoided. Proper conjunctive use of surface water and ground water is necessary to efficiently utilize the water resources without endangering the command area with waterlogging and salinity problems in future.

The tanks in the Jabalpur district are contributing water to ground water and are influent with respect to ground water. The proper inventory and monitoring of all the tanks including their physical size, depth, capacity, command area, water level, nearby ground water levels in the direction of flow, siltation status etc. should be done at proper interval of time say atleast twice a year i.e., before the onset of monsoon and after the end of monsoon. Pump tests should be organised in different portions of the district to ascertain the transmissivity and specific yield of the aquifer and their spatial variations in different parts of the district. The extent of hydraulic connection should be drawn between the water bearing formations and the tanks from the lithologs and geophysical methods.

The selection of experimental sites for conducting infiltration tests should not be based on the reconnaissance survey but it should be selected on the basis of soil series. Sufficient infiltration tests in a grid pattern are required for deterministic approach to be followed for ascertaining infiltration rate in a sub-basin.

The study of identification of aquifer parameters deals with the identification of T and S by analyzing the observed drawdown in a confined aquifer due to pumping a tubewell at a variable rate. Based on least square approach, another method has also been evolved for identification of T and S using constant rate pumping test data. Aquifer parameters have been identified for the five test sites in Narmada basin. The developed methodologies are directly applicable to the field problems.

10.0 WATER QUALITY STUDIES

Rivers and streams support a multitude of human uses, including water supply for municipal, industrial, and agricultural uses, recreational opportunities, and a means of waste disposal. The quality of stream water is directly affected by the amount of waste discharged into the stream, and this quality governs the extent to which the water can be used for other purposes, such as recreation or water supply.

The advent of basinwise planning for water pollution control has conceived the need for determination of the status of river basin with respect to pollutant loads. This need has been culminated in the widespread use of models of river basins for planning purposes. The use of river basin models has a requisite for large data base on which verification of the model can be made and modelling constraints determined. The availability of such a data base can also permit a statistical evaluation of the data which would provide further insights into the status of the river basin. Since the data from river basins usually involve a number of variables, interpretation through standard statistical techniques is not satisfactory and usually requires a multivariate approach.

10.1 Prediction of Water Quality Parameters using Statistical Approach in Upper Narmada Basin

As water moves through the drainage basin, it come across through different hydrological processes e.g. storage, and transfer pathways, and the quality of water leaving the drainage basin will be considerably different from that of the moisture entering the catchment as precipitation. The various processes controlling stream water quality may be in a delicate balance and a slight modification to the catchment such as a change in landuse, could generate significant changes in water quality.

The present study is an attempt to provide a hydrological overview for better understanding of the quality dimension of the hydrological processes operating within the catchment ecosystem. About 12 years water quality data observed at the Manot site of upper Narmada basin is used to carry out the statistical analysis. The analysis has been carried out in three phases. In the first phase, quality-quantity relationships have been developed relating the concentration of quality parameters to the magnitude of stream flow for various water quality determinants. In the second phase, probability distributions have been plotted which give the information about the probability of violation of allowable limits of various water quality parameters. In the third phase, multiple regression models have been developed for various water quality parameters which may be used for filling the missing data values.

The important urban centers in the Narmada basin are Mandla, Jabalpur, Hoshangabad, Khandwa, and Khargone in Madhya Pradesh; and Bharuch in Gujarat. There are 40 large and 70 medium scale industrial units operating besides large number of small scale units in the basin. In this study, the Manot site at 203 km. of Narmada, catchment area of 14556 sq.km. in Narmada basin has been selected.

About 12 years data (1980-1992) have been collected from various sources like CWC, M.P. State Pollution Control Board, Central Pollution Control Board etc. The data consisted of stream flows and 19 water quality parameters e.g. pH, conductivity, total dissolved solids, Fe^{++} , Al^{++} , NH_4^+ , NO_3^- , PO_4^- , oxygen demand in 4 hours, turbidity, Na^+ , K^+ , Ca^{++} , Mg^{++} , CO_3^- , HCO_3^- , Cl^- , SO_4^- and hardness etc. Some of the data contained missing values.

By visual interpretation of the graphical representation of the data, it was observed that pH has an increasing trend i.e. the acidity is increasing with time and 90 % of the data shows that pH is more than 7 which indicates that the Narmada water at Manot is alkaline and its alkalinity is going on increasing which may affect beneficial uses of water adversely. The scatter plots of NO_3^- , Na^+ , K^+ , Ca^{++} , Mg^{++} and HCO_3^- show that their individual ion concentrations are very low. However, the stream flow does not have any such abrupt change in the quantity of stream flow.

Analysis of the water quality data is carried out in three different ways.

- (a) Quality-Quantity relationship
- (b) Frequency distribution
- (c) Regression based modelling

10.1.1 Quality - Quantity relationship

The scatter diagrams of stream discharge versus water quality constituents concentration, when plotted on logarithmic graph paper, indicated that an equation of the form:

$$C = K Q^b$$

in which Q is the stream discharge, C denotes the water quality constituent concentration, and k and b are regression parameters, could be used for estimating quality for a given quantity. The quality-quantity relationships, as described by the above equation, are developed for various water quality determinants. The coefficients K and b are presented in Table 10.1.

10.1.2 Frequency Distribution

The cumulative probability (cumulative relative frequency) distribution was made for various water quality determinants. The following conclusions were drawn :

- (a) The probability of stream flow remaining less than 10 cumec is about 50 % and there is very rare chance for exceeding the stream flow beyond 1000 cumec.
- (b) Conductivity of stream water at Manot remains always less than 1000 micro-mho/cm which is classified under class-I water (USA classification)

and considered good to excellent - suitable for most plants under different soil conditions.

- (c) The total dissolved solids concentration remain 40 mg/L to 200 mg/L, which is suitable for most of the beneficial uses of water.
- (d) Hardness is within the limits of 250 mg/L, and the probability of hardness exceeding 250 mg/L is rare. However, for the specific uses like textile industries and power generation etc., some degree of treatment is essentially required.
- (e) The chloride concentration is within the limit of 250 mg/L. The probability of exceeding chloride concentration beyond 80 mg/L is very remote.
- (f) The probability of exceeding nitrate concentration beyond 25 mg/L is very less. The allowable limit according to BIS (Bureau of Indian Standards) is 45 mg/L.
- (g) The water quality parameters like SO_4^{2-} , turbidity, HCO_3^- etc. are also within the prescribed limits of BSI and the probability of violation is very less.
- (h) The concentration of various cations e.g. Na, K, Ca, Mg are also well within the allowable limits for various designated uses of water.

Table 10.1 : Coefficients of Quality-Quantity Relationships for Various Water Quality Determinants

S.No.	Water Quality Parameter	K	b
1.	Conductivity (micro-mho/cm)	$10^{5.765}$	-0.104
2.	Total dissolved solids (mg/L)	$10^{5.252}$	-0.074
3.	Turbidity (mg/L)	$10^{0.446}$	0.600
4.	Sodium (mg/L)	$10^{2.437}$	-0.186
5.	Potassium (mg/L)	$10^{0.061}$	-0.015
6.	Calcium (mg/L)	$10^{3.426}$	-0.052
7.	Magnesium (mg/L)	$10^{2.644}$	-0.161
8.	Bicarbonate ion (mg/L)	$10^{5.102}$	-0.085
9.	Chloride (mg/L)	$10^{2.473}$	-0.008
10.	Sulphate (mg/L)	$10^{4.478}$	1.539
11.	Hardness (mg/L)	$10^{4.419}$	-0.084

10.1.3 Regression based Modelling

All the statistical analyses procedures are performed using the system for statistics micro computer software package, SYSTAT. In order to generate proper and relevant multiple regressions, simple Pearson coefficients were calculated for the independent variables. The results of the statistical analysis produced the following models.

$$\text{Hardness} = 57.81 - 0.73(\text{Na}^+) - 0.12(\text{Turbidity}) + 0.24(\text{Conductivity})$$

$$\text{Cl}^- = 8.18 + 0.06(\text{Conductivity}) + 0.90(\text{Ca}^{++}) - 0.277(\text{HCO}_3^-) - 0.23(\text{SO}_4^{--})$$

$$\text{HCO}_3^- = 41.4 + 3.78(\text{Ca}^{++}) - 1.56(\text{Cl}^-) - 2.16(\text{NO}_3^-)$$

$$\text{K}^+ = 2.76 + 0.016(\text{Ca}^{++}) - 0.43(\text{NH}_4^+) - 0.29(\text{pH}) + 0.014(\text{PO}_4^{--})$$

$$\text{Na}^+ = -6.15 + 0.15(\text{NO}_3^-) + 0.03(\text{HCO}_3^-) + 0.056(\text{TDS})$$

$$\text{NO}_3^- = -0.35 - 2.22(\text{NH}_4^+) + 0.14(\text{Na}^+) + 2.21(\text{Fe}^{++})$$

$$\text{TDS} = -21.93 + 6.67(\text{pH}) + 0.50(\text{Conductivity}) - 2.92(\text{PO}_4^{--})$$

$$\text{Conductivity} = 61.51 + 1.59(\text{Cl}^-) + 6.22(\text{Mg}^{++}) - 0.38(\text{Turbidity}) + 0.8(\text{TDS})$$

$$\text{Turbidity} = 46.33 + 0.047(\text{Q}) - 0.33(\text{HCO}_3^-) - 9.28(\text{NH}_4^+)$$

These multiple regression models may be used for filling the missing data values which is an important step for further analyses such as time series analysis, stream quality forecasting, pollutant concentration frequency analysis, etc.

For details of the study, the reader may please refer NIH Report No CS/AR-174.

10.2 Identification of Sampling Sites for Water Quality Monitoring

Assessment of water quality conditions over a wide area with respect to time and space requires the monitoring activities to be carried out in a network. The location of a permanent sampling station is probably the most critical factor in a monitoring network which collects water quality data. If the samples collected are not representative of the water mass, the frequency of sampling as well as the mode of data interpretation and presentation becomes inconsequential.

The sequential water sampling sites to be used in the search for a pollution source have been identified for the Narmada basin. Four different criterias e.g. tributaries, BOD, NPK and pesticides were used to locate the sampling locations. Four hierarchies have been used in the study. However, higher level of hierarchical stations can be identified subjected to the economic considerations. It was found that for the detection of single pollution source, one had to go upto the seventh level of hierarchies.

Each of the four networks presented namely tributary based, BOD loading, NPK loading and pesticides loading based differs somewhat but it shares a common approach towards the selection of reaches in which to sample. It must be emphasized that locations of sampling stations determined above are not to be strictly applied. Therefore, an engineering judgement is required to locate monitoring sites which satisfy most of the requirements and minimise the financial requirements. In this procedure, the proposed monitoring networks may be used as guidelines in pinpointing the appropriate sampling sites.

Further, it is observed that the present monitoring network is self-sufficient as far as the middle and upper basin is concerned. But it certainly needs improvement in the downstream portion of the basin particularly for controlling the pesticides, nutrient related problem in the lower basin.

For details of the study, the reader may please refer NIH Report No CS/AR-12/96-97.

10.3 Remarks

The present monitoring network is self-sufficient as far as the middle and upper basin is concerned. But it certainly needs improvement in the downstream portion of the basin particularly for controlling the pesticides, nutrient related problem in the lower basin. The multiple regression models may be used for filling the missing data values which is an important step for further analyses such as time series analysis, stream quality forecasting, pollutant concentration frequency analysis, etc.

11.0 FIELD AND LABORATORY INVESTIGATIONS

Six sub-basins of Narmada river were chosen for simulation of hydrologic response using the SHE model described in Section 4.2.1 earlier. During the simulation of these basins, it was realised that the quantum of information on soil properties available was extremely inadequate particularly for a model like SHE. It is well known that correct and detailed information about soil properties is very crucial input for a physically based distributed rainfall-runoff model. The Kolar river basin upto Satrana gauge-site was selected for field and laboratory investigation.

11.1 Field Investigations in Kolar Sub-basin of River Narmada

The main objective of the field investigation activity was to improve the knowledge about soil parameter values based on measurement campaign carried at different locations in the catchment, which in turn would reduce the uncertainty about input parameters and consequently about the results of simulation of the SHE. Although the programme was focused on the assessment of spatial distribution on soils and their physical properties, other parameters like vegetation cover, leaf area index, ground water levels survey, geometry of the river channels and topography of the catchment were also investigated.

The catchment area of Kolar river upto Satrana gauge-discharge site covers an area of 828 sq.km. This area has wide variations in topography, soil and land use. On the basis of three traverses, in the upper, middle and lower zones of the catchment, 9 potential sites (3 sites per traverse) were identified. The traverse design assumed that the network of sites will cover the major soil and topographical divisions of the basin. During the course of investigation, one additional traverse was included in view of unusual variation in soil depth. Measurements were carried out in the field and soil samples were analyzed in the laboratory.

To determine properties of undisturbed soil samples, 15 soil cores were taken at the sampling sites. These samples were collected for laboratory analysis of grain size distribution, and soil moisture versus tension relationship through pressure plate apparatus.

The information about the soil profile and soil depth was obtained at the sampling sites. Other information gathered includes the vegetation type and density, cropping pattern, water level in wells, ground surface roughness and dimension of river channel.

11.1.1 Infiltrometer Tests

The in-situ infiltrometer tests were conducted at various sites using double ring cylindrical Infiltrometer. The representative value of final infiltration rate at each site was taken as the asymptotic infiltration rate at 24 hours after the test started. This is obtained by extrapolating the actual time vs. infiltration curve. This best linear fit curve is plotted on a double log scale. The final infiltration rate thus calculated corresponds to the value

obtained from linearized equation at time 24 hours. The summary of the analysis of infiltration tests is given in Table 11.1.

11.1.2 Land Use and Soil Maps

Based upon the survey conducted, new soil map and land use map were prepared. Initial estimates of soil depth distributions, based on field investigation, is given below:

Land use class	Percent of basin	Soil Depth
Agriculture on deep soil	2.9	8.0
Agriculture on moderate deep soil	11.9	1.7
Agriculture on medium deep soil	8.2	1.0
Agriculture on shallow soil	19.1	0.5
Forest upland	3.9	0.5
Forest lowland	46.9	0.3
Wasteland	8.1	0.3

Table 11.1 : Summary Results of Infiltrometer Tests

Site Name	Surface Soil Type	Best Fit Equation on Log-Log Scale	Last Observation		Extrapolated rate at 24 hr (cm/hr)
			Time (min)	Rate (cm/hr)	
Khajuri	Black	$i = -0.415t + 1.808$	165	9.40	3.140
Bardha	Black	$i = -0.567t + 2.504$	165	20.26	5.150
Saras	Black	$i = -0.395t + 1.323$	180	3.61	1.188
Birjisnagar	Black	$i = -0.593t + 1.568$	165	2.17	0.497
Semli Jadid	Black	$i = -0.510t + 1.722$	180	5.06	1.294
Sagoni	Black	$i = -0.354t + 1.335$	180	3.61	1.649
Khari	Black	$i = -0.401t + 1.787$	135	8.68	3.310
Satrana	Yellow	$i = -1.049t + 1.933$	180	0.38	0.040
Birpur	Yellow	$i = -0.457t + 1.526$	285	3.26	1.210
Birpur Colony	Yellow	$i = -0.364t + 1.606$	180	6.51	2.862
Bamladar	Red	$i = -0.475t + 2.902$	195	79.62	25.137
Khamkhera	Red	$i = -0.525t + 1.489$	120	3.62	0.678

11.1.3 River Cross-sections

Previously, information of the river cross-section was available only at one location (Satrana gauge-discharge site). This survey provided information for 4 more locations.

For details of the study, the reader may please refer NIH Report No TR-81.

11.2 Laboratory Analysis of Soil Samples from Kolar Sub-Basin of River Narmada

The main thrust of the field programme particularly in respect to soil parameters and relationships was concentrated on the evaluation of the following.

- (a) Unsaturated zone saturated hydraulic conductivity (for vertical flow);
- (b) Unsaturated zone moisture content/hydraulic conductivity relationship;
- (c) Unsaturated zone moisture content/tension relationship;
- (d) Saturated zone hydraulic conductivity (for horizontal flow);
- (e) Soil depth and profile;
- (f) Root zone depth.

During the field investigation programme, a total of 12 sites distributed in the Kolar basin upto Satrana gauging site (area 828 sq.km.) were investigated and soil cores and distributed samples were taken.

11.2.1 Particle Size Distribution

Since the soil in the area consists of both coarse and fine grains, sieve analysis as well as sedimentation analysis was used. The results of particle size analysis using both sieve analysis as well as hydrometer analysis were plotted to get a particle size distribution curve and the percentages of clay, silt, sand and gravel in the respective samples were ascertained, as given in Table 11.2.

Table 11.2 : Particle Size Analysis

Sl. No.	Sample No.	Particle Size Distribution (percent by weight)			
		Clay	Silt	Sand	Gravel
1.	N1	40.79	32.32	26.51	0.48
2.	N2	17.20	14.85	54.73	13.22
3.	N3	25.84	27.04	35.24	11.88
4.	N4	21.00	45.00	19.50	14.50
5.	N5	45.00	39.50	12.90	2.60

6.	N6	56.40	40.10	2.82	0.68
7.	N7	55.60	33.90	8.03	2.47
8.	N8	39.10	33.60	21.32	5.98
9.	N9	36.37	27.13	22.21	14.29
10.	N10	29.00	27.50	8.29	35.21
11.	N11	12.50	40.00	20.00	26.75
12.	N12	69.00	27.75	2.86	0.39

11.2.2 Permeability

For the determination of the coefficient of permeability for the 12 disturbed samples collected from Kolar basin, the falling head permeability test was used. The results are given in Table 11.3.

Table 11.3 : Permeability and Degree of Saturation for Kolar Basin

Sample No.	Permeability (cm/sec)	Degree of Saturation
1	3.900×10^{-6}	33.75 %
2	610.000×10^{-6}	-
3	306.900×10^{-6}	43.02 %
4	30.920×10^{-6}	-
5	0.783×10^{-6}	33.81 %
6	5.063×10^{-6}	34.49 %
7	12.912×10^{-6}	39.73 %
8	4.690×10^{-6}	37.67 %
9	1.590×10^{-6}	34.36 %
10	1.643×10^{-6}	33.77 %
11	6.717×10^{-6}	36.57 %
12	0.350×10^{-6}	37.24 %

11.2.3 Retention Curves

Three typical samples representing yellow, red and black soils were analyzed through pressure plate apparatus for moisture retention behaviour. The moisture retention characteristics representing relationship between moisture tension (pressure in bars) and moisture content (percent by volume) are given in Table 11.4.

Table 11.4 : The moisture retention characteristics representing relationship between moisture tension and moisture content

Pressure (Bar)	Moisture Content (% by volume)		
	Sample 1	Sample 2	Sample 3
0.0	0.621	0.403	0.438
0.5	0.546	0.285	0.345
1.0	0.540	0.280	0.342
2.0	0.538	0.278	0.340
3.0	0.537	0.277	0.337
15.0	0.533	0.272	0.330

Based upon the above study, it was concluded that detailed guidelines/manual is necessary for soil sampling and laboratory analysis.

For details of the study, the reader may please refer NIH Report No TR-82.

11.3 Infiltration Study of a Sub-basin

Knowledge of infiltration characteristics of the basin helps in estimating the quantity of rainfall excess resulting from a stream. In watershed management studies, infiltration indices obtained from soils under various types of plant cover and land use are helpful in providing a basis for judgement so as to optimize watershed conditions for water yield and soil erosion. Infiltration is also considered to be the basic criterion in the design of surface irrigation as well as ground water irrigation.

Infiltration studies were carried out in a doab area of Sher river, Berurewa river and left bank canal of Bargi dam near Narsinghpur. Keeping in view the types of soils, five places were selected for carrying out point infiltration tests in Narsinghpur district of Madhya Pradesh. The types of soil covered are clay, clay loam and sandy clay loam. The infiltration test in fourth type of soil i.e. loam, which is found in a small patch of area nearly 1025 hectares, could not be conducted due to inaccessible approach to the area.

The infiltration experiments were conducted by automatic infiltrometer developed at the Institute (Fig. 11.1). The automatic electronic infiltrometer is a microprocessor based developed equipment to conduct infiltration studies in-situ under controlled conditions. Normally, people use double ring infiltrometer with some device to measure drop in water level and to supply the water, to keep water level constant, either manually or automatically. The automatic electronic infiltrometer can be programmed for storing the water level readings automatically from 1 minute to 99 minutes. The data can be retrieved on PC by connecting an interface with PC from the equipment.

The infiltration tests were conducted on the basis of type of soil without considering the effect of slope for test point. Those test points are located at village Kheri (clay loam),

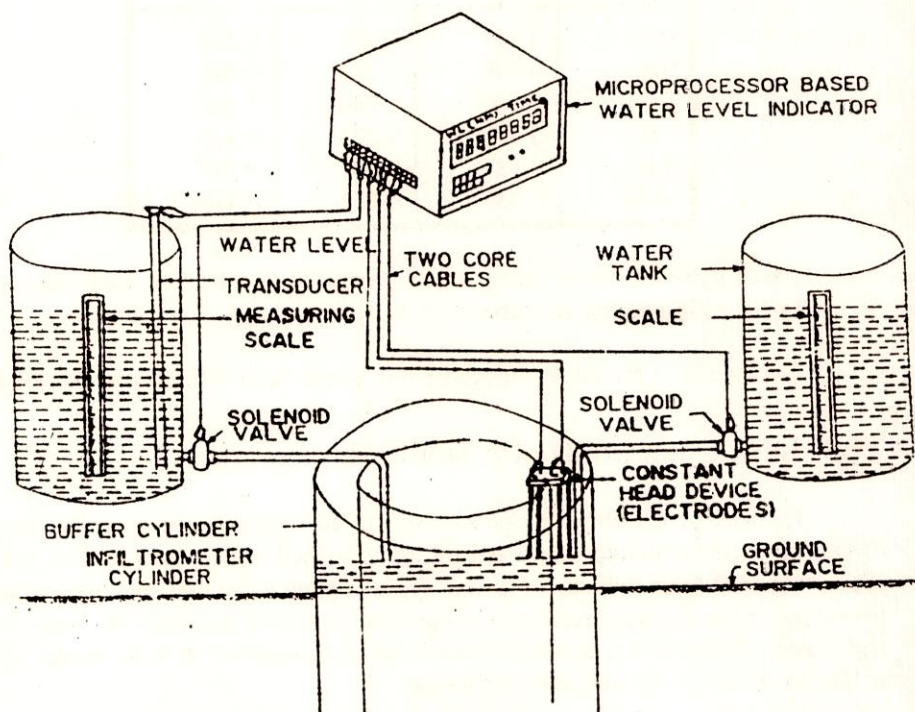
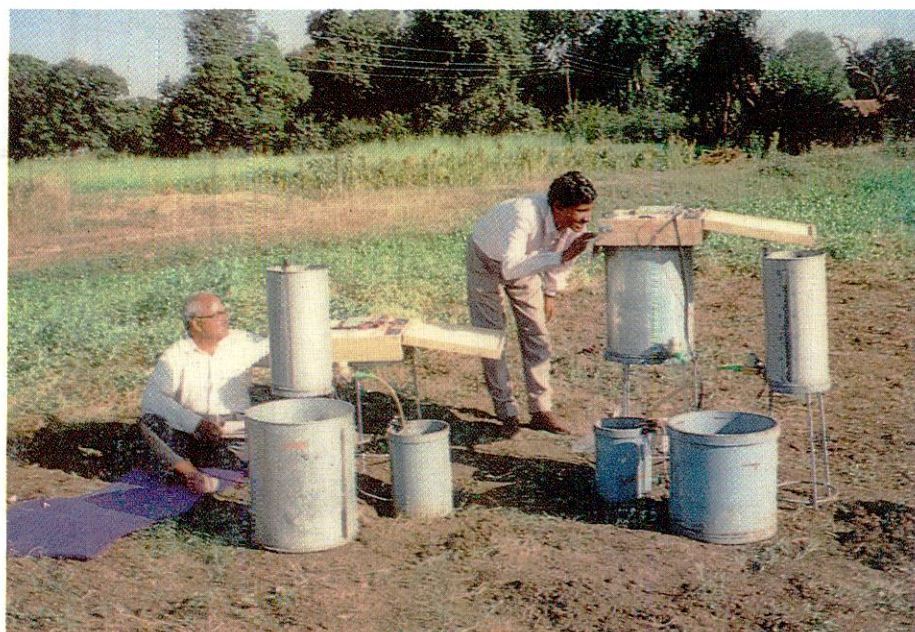


FIG.11.1 — MICROPROCESSOR BASED DOUBLE RING INFILTRATOR WITH
CONSTANT HEAD DEVICE
(AUTOMATIC ELECTRONIC INFILTRATOR)



VIEW OF TEST LOCATION AT VILLAGE JALLAPUR



VIEW OF TEST LOCATION AT VILLAGE BAHORIPAR



VIEW OF TEST LOCATION AT VILLAGE KHERI



VIEW OF TEST LOCATION AT VILLAGE BHUTPIPARIYA

Rampipariya (sandy clay loam), Jallapur (clay), Bhootipariya (clay) and Bahoripar (clay). For each site, the graph between cumulative infiltration with elapsed time was drawn. The constant infiltration rate in clay loam is 0.32 cm per hour. Similarly, in sandy clay loam in saturated conditions, it is observed 0.28 cm per hour. While in clay, it is varying from 0.12 to 0.14 cm per hour.

For details of the study, the reader may please refer NIH Report No CS/AR-170.

11.4 Estimation of Hydrological Soil Properties of Narsingpur District

This study dealt with the estimation of hydrological soil parameters of the doab between Sher and Barau river and Bargi left bank canal falling in Narsingpur District. The soil properties determined were soil texture, saturated hydraulic conductivity using guelph permeameter (for in situ measurement) and from Johnsons graph, matric flux potential, alpha and soil moisture characteristic curves.

Based on the soil classification of Soil Survey Department of Govt. of M.P., a base map for soil classification was prepared and at twelve locations distributed soil sampling and insitu measurement of saturated conductivity was performed. The soil samples were brought to the Soil Water Laboraroty of the Institute and the textural analysis of all the samples was carried out. The matrix flux potential, alpha parameter and saturated hydraulic conductivity as given by Johnson were also determined in this study.

For details of the study, the reader may please refer NIH Report No. CS/AR-167.

11.5 Remarks

The correct and detailed information about soil properties is very crucial input for a physically based distributed model. Field investigation activity was carried out by the Institute with a view to improve the information about soil parameter values based on measurement campaign carried at different locations in the catchment, which in turn would reduce the uncertainty about input parameters and consequently about the results of simulation of the SHE. Although the programme was focused on the assessment of spatial distribution on soils and their physical properties, other parameters like vegetation cover, leaf area index, ground water levels survey, geometry of the river channels and topography of the catchment were also investigated. The detailed guidelines/manual is necessary for soil sampling and laboratory analysis.

12.0 DROUGHT STUDIES AND LOWFLOW MODELING AND FORECASTING

In this section, the drought studies and the low flow modelling and forecasting studies attempted by the Institute in Narmada Basin have been described.

12.1 Drought Studies

The frequent occurrences of severe droughts in past few decades in the country have drawn the attention of planners and administrators. In view of the poor documentation and less understanding of the hydrological aspects associated with drought, the Drought Studies Division of the Institute has conducted studies on hydrological aspects of drought in the 36 districts in India. These studies were started from 1985-86. The major objective of these studies was to document the impacts of drought from hydrologic point of view. In the Narmada basin the five districts namely Betul, Khargon, Jabua, Dhar, Shahdol lying in Madhya Pradesh have been considered as drought prone.

In order to study the hydrological aspects of drought the hydrometeorological data were subjected to various kinds of analysis including rainfall departure, probability analysis, dry spell analysis, groundwater fluctuation analysis and analysis of change in availability of water storage in reservoirs. Available models were also applied to identify the probable periods for onset and termination of drought and to make the estimate of drought intensity. Districtwise drought analysis is presented in the published reports.

Based on the analysis of rainfall records for the period from 1951 to 91, it was inferred that the seasonal rainfall departure during drought years varies from -25% to -76%, however, monthly departure varies from -25% to -90%. In general 4-12 drought spells were found in most of the districts. The analysis yielded the duration of dry spells from 21-28 days at 75% probability level. The groundwater level trends were found declining in most of the districts. The trends of ground water table in the Dhar and Jabua in Narmada Basin are shown in Fig. 12.1.

12.1.1 Drought impacts on agriculture – case study

Impacts of recurring droughts on agriculture and socio-economic aspects have also been studied for Khargon district in Madhya Pradesh. It was found that the Khargon district faced a seasonal rainfall deficiency of 41.41% during the water year 1985-86, and caused reduction in total cropped area by 37.5%. The consequent reduction in average crop yield was found in the order of about 50% as compared with average values during 1976-80. The cumulative impact of drought in the year 1985-86 on crop yield and cropped area are presented in Table 12.1. Further, it was found that the crops of groundnut, bajra and wheat were worst affected from both yield and cropped area point of view. Analysis of groundwater regime indicated a falling trend in groundwater levels over the years as a result of rainfall deficiency. In order to reduce the crop damages due to water stress during

STATE - MADHYA PRADESH

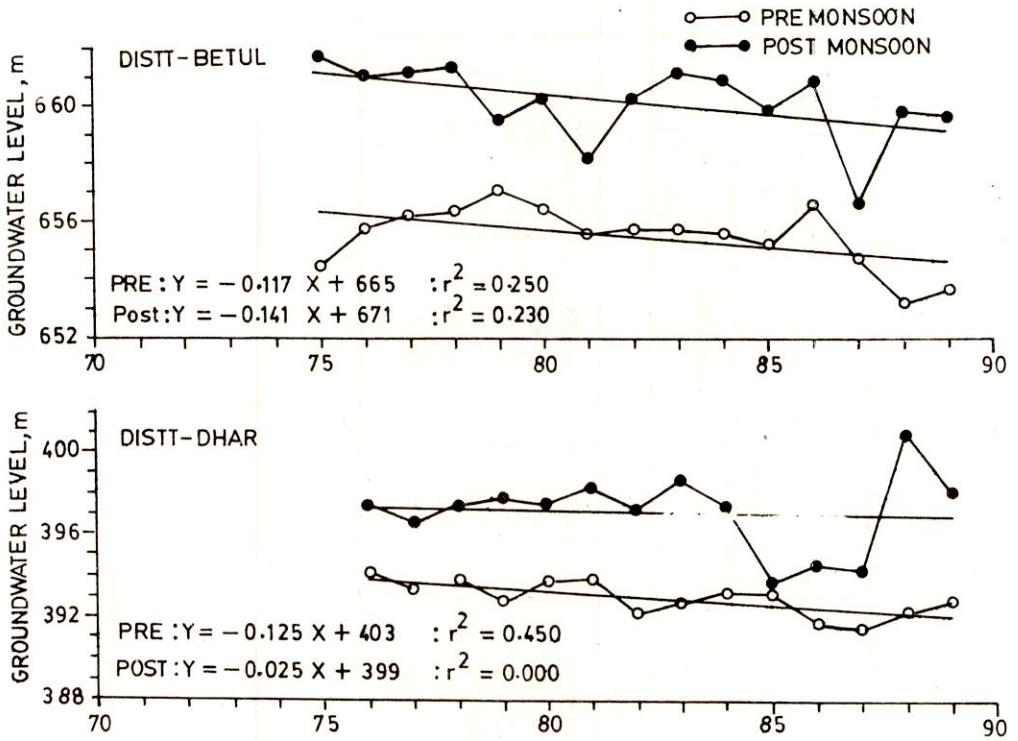


FIG.12-1GROUNDWATER LEVEL FLUCTUATION FOR PRE AND POST-MON. SEASONS.

Table 12.1 : Cumulative Impacts on Crop Yield and Cropped Area

Sl. No.	Name of crop	Average yield (kg/ha.) (on the basis of 1976-80)	%age departure of the yield of 1985-86 with respect to yield of 76-80	Yield in 1985-86 as fraction of 1976-80	Average area under the crop for year 1976-80 (thousand ha)	%age departure the area under crop year 86 with that av. year 1976	Cropped area in 85-86 as fraction of 1976-80	Cumulative impact
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1.	Jowar	617.33	-56.53%	0.43	146.23	+27	1.27	0.55
2.	Rice	610.30	-56.88%	0.43	18.91	-19	0.80	0.34
3.	Groundnut	720.00	-63.47%	0.37	62.98	-39	0.60	0.22
4.	Bajra	255.00	-66.39%	0.34	33.39	-26	0.73	0.25
5.	Wheat	1361.00	-52.98%	0.48	39.87	-37	0.63	0.30
6.	Maize	809.50	-60.25%	0.40	38.64	-4	1.05	0.42
7.	Cotton	335.00	-37.73%	0.63	162.94	+8	1.08	0.68

drought, the suitable cropping pattern and the water management strategies were evolved for the area.

For details of the study, the reader may please refer NIH Report No CS-38 and CS/AR-150.

12.2 Forecasting of Low Flows for River Narmada at Mortakka

For development of our agriculture based economy and to meet the demands of the growing population; in terms of irrigation, drinking water, hydropower generation and industrial use etc. modelling and forecasting of river flows during non-monsoon months is essential. Efficient management of existing water resources projects and optimal planning of the future projects also attach great importance to low flow modelling and forecasting. Ideally, a distributed model based on the principle of physical laws representing the movement of water through its different phases should be developed for any modelling exercise for low flow forecast. However, it remains a fact that the physical laws for representing the formation and propagation of runoff through its various processes have not yet been perfected. No doubt, for the more complicated problems the use of physically based models acquires a great importance. But the physically based models require extensive data input and enormous computational facilities. On the other hand, there are many problems for which necessary solutions can be obtained with desired degree of accuracy required for the purpose, with relatively less sophisticated, lumped, conceptual or statistical models, which require very limited data generally available in the field.

The lowflow forecasts are generally based on the following principles: presence of a relationships between the river and its associated ground water storage; effect of the preceding hydrometeorological conditions upon the river discharge at the time under consideration; availability of stored water from natural storage on and below the ground surface for low flow replenishment. In addition, the effects of existing regulatory structures are also to be given due consideration. Low flow forecasting using statistical approach and the model for low flow forecasting are discussed below.

For a rain fed river basin of moderate size, the major contribution during the non-monsoon period is from ground water and the other contributions are almost negligible. In such cases, an exponentially decaying curve may prove to be a very reasonable approximation of the river flow condition. However, in case of a larger river system, where snow melt contribution is also quite significant (in addition to ground water) adoption of the simple recession curve or a snow melt model may not give a reasonable forecast of low flow. Also in a large river system there are a number of factors contributing to the river flows and the interacting processes are very complicated. As a result, it becomes almost impossible to model the various components in accordance with the concepts of a physically based model. In such cases, it is desirable to adopt a statistical model which may be either of the following two types:

- a) Where the independent variables are mainly the element representative of different contributing factors such as rainfall, snow cover, temperature, ground water storage, vegetation, evaporation, humidity, morphological factors, morphometrical factors,

hydrogeological factors, factors due to human activity such as urbanisation, irrigation, hydraulic works, water transfer schemes, hydro-electric stations, navigation, drainage works and land use changes etc; or

- (b) Where the previous state of the river flow is taken into consideration without identifying the various contributing factors.

In this study, the forecast of monthly flow for a river system is assumed to be dependent on the flow of previous month at the same site, i.e.:

$$Q_i = a_i Q_{i-1}^{b_i} \quad (12.1)$$

where, Q_i is the monthly flow forecast for the i th month, Q_{i-1} is the flow for the month prior to the Q_i th month, a and b are the parameters of the model for the i th month; and the same are evaluated by least square regression analysis from the historical observed monthly data of the concerned gauging site.

For the purpose of illustrating the model efficacy monthly sample data of 16 years i.e. 1949-50 to 1965-66 have been used to estimate the model parameters. The various equations developed for formulating the low flow forecasts for the seven months of the low flow period i.e. November, December, January, February, March, April and May using the historical data for the river Narmada at Mortakka are given below:

$$Q_{Nov} = 1.892 Q_{Oct}^{.744} \quad (12.2)$$

$$Q_{Dec} = 3.635 Q_{Nov}^{.670} \quad (12.3)$$

$$Q_{Jan} = 2.470 Q_{Dec}^{.761} \quad (12.4)$$

$$Q_{Feb} = 2.120 Q_{Jan}^{.786} \quad (12.5)$$

$$Q_{Mar} = 0.516 Q_{Feb}^{1.078} \quad (12.6)$$

$$Q_{Apr} = 0.669 Q_{Mar}^{1.027} \quad (12.7)$$

$$Q_{May} = 1.889 Q_{Apr}^{.735} \quad (12.8)$$

To begin with, the initial forecast is prepared for the month of November for which the flow data of the month of October have been used. For the forecast of flow during the

month of December, the flow forecast of month November is taken as input. Similarly the forecasts are estimated for the subsequent months up to the month of May. The forecast have been updated every month with the availability of more and more observed data. As a matter of fact, the revision of forecast can be taken up after every month as soon as the additional observed data are available. The observed discharge and forecasts have been compared for the four test years and percentage errors between them have been computed.

For details of the study, the reader may please refer NIH Report No TR/BR-112.

12.3 Remarks

In the Narmada basin the five districts namely Betul, Khargon, Jhabua, Dhar, Shahdol lying in Madhya Pradesh have been considered as drought prone, and the studies have been carried out using the relevant data of these districts. The major objective of these studies was to document the impacts of drought from hydrologic point of view. For studying the hydrological aspects of drought the hydrometeorological data were subjected to various types of analysis including rainfall departure, probability analysis, dry spell analysis, groundwater fluctuation analysis and analysis of change in availability of water storage in reservoirs. Impacts of recurring droughts on agriculture and socio-economic aspects have also been studied for Khargon district in Madhya Pradesh. Analysis of groundwater regime indicated a falling trend in groundwater levels over the years as a result of rainfall deficiency. In order to reduce the crop damages due to water stress during drought, the suitable cropping pattern and the water management strategies were evolved for the area.

Low flow forecasts have been formulated based on the statistical approach for the river Narmada at Mortakka. To begin with, the initial forecast is prepared for the month of November for which the flow data of the month of October have been used. For the forecast of flow during the month of December, the flow forecast of month November is taken as input. Similarly the forecasts are estimated for the subsequent months up to the month of May. The forecast have been updated every month with the availability of more and more observed data. The revision of forecast can be taken up after every month as soon as the additional observed data are available. The observed discharge and forecasts have been compared for the four test years.

13.0 CONCLUDING REMARKS

Based on the experience from the hydrological studies of the Narmada river basin, the data being collected for any major river basin must be regularly analysed in order to ascertain the changing hydrological and hydrometeorological characteristics of the basin due to natural and man-made changes, and their impact on various components of the hydrological cycle. There is a need to develop\adopt software packages for data processing and analysis. Such packages may be utilised for computerising, processing and analysing the data being collected from the field at regular interval.

For research and development studies, representative watersheds may be selected in each major river basin, which may be properly instrumented and the detailed data collected for developing the methodologies or mathematical models for simulating various components of the hydrological cycle. Emphasis should be laid on greater use of remote sensing and geographical information system techniques in order to obtain the spatial data i.e. soil and vegetation related data required for the purpose of mathematical modelling. It is also desirable to bring out suitably compiled information of water resources and hydrology for each river basin regularly every year or every five years as feasible.

LIST OF TECHNICAL REPORTS BROUGHT OUT BY THE INSTITUTE ON VARIOUS AREAS ON THE BASIS OF STUDIES CONDUCTED ON NARMADA RIVER BASIN

1. DATA PROCESSING AND ANALYSIS

1. Study of hydrometeorological aspects of Narmada basin (CS-3) [S.M. Seth, K.S. Ramasastry]
2. Rating curves for gauging sites on Narmada river (CS-6) [S.M. Seth & A.B. Palaniappan]
3. Processing of hydrological data for Manot sub-basin using HYMOS (CS/AR-179) [Hemant Chowdhary & R.D. Singh]
4. Hydrological data book for Narmada basin (upto Bargi Dam) 1981-90 (TN-114) [Vijay Kumar & A K Bhar]
5. Hydrological network design for Narmada basin (TR-58) [S.M. Seth & Rakesh Kumar]
6. Development of disaggregation techniques (TR/BR-126) [R. Mehrotra]

2. SMALL CATCHMENT HYDROLOGY

7. Derivation of GIUH for small catchments of upper Narmada and Tapi sub-zone (sub-zone 3c) -Part I (TR/BR-132) [Hemant Chowdhary & R.D. Singh]
8. Excess rainfall and direct surface runoff modelling using geomorphological characteristics (TR/BR-113) [Hemant Chowdhary & R D Singh]
9. Regional flood frequency analysis for upper Narmada and Tapi subzone 3C (TR/BR-133) [Rakesh Kumar & R D Singh]
10. Development of regional flood frequency relationships and flood formulae for various subzones of zone 3 of India (TR/BR-149) [Rakesh Kumar & R D Singh]
11. Relationship between frequency of rainfall and frequency of flood for a catchment of upper Narmada and Tapi subzone 3(c) (CS/AR-206) [Rakesh Kumar]

3. HYDROLOGICAL MODELING

12. Simulation of daily runoff of two sub-basins of river Narmada using Tank model (CS-5) [S M Seth & B. Dutta]
13. Application of SHE model to the Ganjal sub-basin of Narmada (CS-28) [Rakesh Kumar, S M Seth, P K Garg, T. Vijay, Digambar Singh & M K Sharma]
14. Application of SHE model to Narmada (upto Manot) basin (CS-29) [C P Kumar, S M Seth, B K Purendara, Rajan Vatsa, S L Srivastava, Sanjay Mittal & Raju Juyal]
15. Application of SHE model to Hiran sub-basin of river Narmada (CS-30) [S K Singh, S M Seth, S K Verma & P K Agarwal]
16. Application of SHE model to Sher sub-basin (CS-31) [V K Lohani & S M Seth]
17. Application of SHE model to Barna sub-basin of river Narmada (CS-32) [R D Singh, S M Seth, P K Garg & Digambar Singh]

18. Application of SHE model to Kolar sub-basin of river Narmada (CS-33) [S K Jain]
19. Study of impact of soil and land use changes on hydrologic regime using SHE model (CS-34) [S K Jain]
20. Kolar basin simulation studies using the SHE model (CS-47) [S K Jain & S M Seth]
21. Application of SHE for irrigation command area studies (CS-48) [V K Lohani & S M Seth]
22. Flood hydrograph simulation in Kolar sub-basin using event based distributed rainfall-runoff model (CS/AR-130) [R D Singh & Hemant Chowdhary]
23. Application of WAHS model to Kolar sub-basin (CS/AR-136) [M K Jain, Naresh Kumar & K S Ramasastry]
24. Sensitivity analysis using BATS (CS/AR-168) [Divya & A K Keshari]

4. DESIGN FLOOD STUDIES

25. Design Flood Estimation for Narmada Sagar and Sardar Sarovar Projects (1985) _ Final Project Report [S M Seth, K S Ramasastry, B. Dutta, A B Palaniappan, M. Perumal, R D Singh, N K Goel]
26. Design flood estimation for Narmada Sagar project using partial duration series (CS-11) [S M Seth & N K Goel]

5. RESERVOIR OPERATION STUDIES

27. Multi-objective optimization of operation of a dam (TR/BR-143) [S K Jain, M K Goel, A R Senthil Kumar & P K Agarwal]
28. Development of operation policy for Tawa dam (CS/AR-18/96-97) [A R Senthil Kumar, S K Jain, M K Goel & R K Nema]

6. DAM BREAK STUDIES

29. Preliminary dam break analysis of Bargi dam (CS/AR-185) [S K Mishra, R D Singh & Rajesh Agarwal]
30. Dam break analysis of Barna dam (CS/AR-20/96-97) [S K Mishra & R D Singh]

7. APPLICATION OF REMOTE SENSING, GIS AND GEOMORPHOLOGY

31. Geomorphology of Kolar sub-basin for hydrological studies (TR-99) [R D Singh & Vibha Jain]
32. Land capability classification in a part of Narmada basin (CS/AR-178) [D S Rathore, Sanjay K. Jain & V K Choubey]
33. Application of remote sensing techniques for water logging study in Tawa command area (CS/AR-158) [V K Choubey & Tanveer Ahmad]
34. Integration of remote sensing and GIS in soil erosion studies (CS/AR-186) [Sanjay K Jain]
35. Geomorphological characteristics of Narmada (upto Manot) basin (CS/AR-128) [M K Jain & U K Singh]
36. Fluvial geomorphological characteristics of four sub-basins of upper Narmada (CS/AR-159) [M K Jain & U K Singh]

37. Rainfall runoff modelling of upper Narmada basins using a geomorphologic technique (CS/AR-201) [M K Jain & R D Singh]
38. Runoff modelling using SCS method (TR/BR-125) [D S Rathore]

8. GROUND WATER ANALYSIS AND MODELLING, WATERLOGGING AND DRAINAGE

39. Ground water balance before introduction of irrigation in the canal command area (TR/BR-119) [C P Kumar]
40. Processing of ground water data (CS/AR-171) [Vijay Kumar & A K Bhar]
41. Groundwater - Tank interaction in Jabalpur District, M.P. (CS/AR-165) [A K Bhar]
42. Identification of aquifer parameters in Narmada basin (TR/BR-130) [S K Singh & Sobha Ram]

9. WATER QUALITY STUDIES

43. Prediction of water quality parameters using statistical approach in upper Narmada basin (CS/AR-174) [Aditya Tyagi & K K S Bhatia]
44. Identification of sampling sites for water quality monitoring in Narmada basin (M.P.) (CS/AR-12/96-97) [Aditya Tyagi, M K Sharma & K K S Bhatia]

10. FIELD AND LABORATORY INVESTIGATIONS

45. Field investigations in Kolar sub-basin of river Narmada (TR-81) [S K Jain, S M Seth, Rakesh Kumar, A K Singh, P K Garg, T. Vijay, D. Singh, G.H. Jorgenson & M. Erlich]
46. Laboratory analysis of soil samples from Kolar sub-basin of river Narmada (TR-82) [S M Seth, S L Srivastava, Sanjay Mittal, Rajan Vatsa, P K Garg & T. Vijay]
47. Estimation of hydrological soil properties of Narsinghpur district (CS/AR-167) [M K Shukla, B. Soni, S L Srivastava & Dinesh Kumar]
48. Infiltration study of a sub-basin (CS/AR-170) [B P Roy, Hukam Singh, Mohar Singh & S K Yadav]

11. DROUGHT STUDIES AND LOW FLOW MODELLING AND FORECASTING

49. Forecasting of low flows for river Narmada at Mortakka (TR/BR-112) [M E Haque & Rakesh Kumar]
50. Hydrological aspects of drought upto 1987-88 - A case study in Madhya Pradesh (CS-38) [V K Lohani & S K Goyal]
51. Hydrological aspects of drought upto 1988-89 - A case study in Madhya Pradesh (CS/AR-150) [R P Pandey, Avinash Agarwal, Yatveer Singh & K S Ramasastri]



LIST OF PAPERS PUBLISHED/ACCEPTED FOR PUBLICATION/SENT FOR PUBLICATION BASED ON STUDIES CONDUCTED ON NARMADA BASIN

1. Bhar, A.K., 1996. A preliminary assessment of ground water tank interaction in Jabalpur district, Madhya Pradesh. *Hydrology Jour.*, IAH, Vol. V(XIX), No.4, Oct-Nov.
2. Choubey, V.K., 1993. Monitoring surface water conductivity with IRS-1A data : A case study from Central India. *IAHS Publ. No. 219*, pp.317-326.
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6. Jain, M.K., S.M. Seth and T. Ahmad, 1997. Rainfall runoff modelling of Kolar basin using a distributed approach. *Proc. Intl. Symp. on Emerging Trends in Hydrology*, Department of Hydrology, University of Roorkee, Roorkee, India, Sept. 25-27.
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THE LIST OF ORGANISATIONS WHICH PROVIDED THE DATA AND OTHER DETAILS FOR THE STUDIES CONDUCTED ON NARMADA BASIN

1. M.P. Irrigation Department
 - a) Director, Hydrometeorology
 - b) Upper Narmada Circle
 - c) Superintending Geologist
 - d) Various concerned Circles, Divisions and Sub-divisions
2. Narmada Valley Development Authority
 - a) Superintending Engineer, Circle No. 2
 - b) Joint Director (Agriculture)
3. Central Water Commission, New Delhi.
4. J.N.K.V.V. Agricultural University, Jabalpur.
5. India Meteorological Department, Delhi and its offices in Pune, Nagpur and Bhopal.
6. Central Ground Water Board - North Central Region.
7. Survey of India, Dehradun.
8. Narmada Control Authority, Delhi, Bhopal and Indore.
9. All India Soil and Landuse Survey Organisation, New Delhi and Nagpur
10. Director, Department of Agriculture, Bhopal and Zonal Agricultural Research Stations at Powerkheda, Khandwa and Adhartal
11. M.P. Groundwater Survey Board, Bhopal and its other offices
12. State Forest Research Institute, Jabalpur
13. College of Agriculture, Indore.
14. Institute of Deciduous Forest, Jabalpur.
15. Offices of Statistics and Land Record in the concerned Districts.



