AN ANALYTICAL STUDY OF GEOMORPHOLOGICAL, HYDROLOGICAL AND METEOROLOGICAL CHARACTERISTICS OF FLOODS IN THE MAHI RIVER BASIN: WESTERN INDIA

A thesis

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TILAK MAHARASHTRA VIDYAPEETH PUNE

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BY

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2019

DECLARATION

I hereby declare that the thesis entitled "An Analytical Study of Geomorphological, Hydrological and Meteorological Characteristics of Floods in the Mahi River Basin: Western India" completed and written by me has not previously been formed as the basis for the award of any degree or other similar title upon me of this or any other Vidyapeeth or examining body. I understand that if my Ph.D. Thesis (or part of it) is found duplicate at any point of time my research degree will be withdrawn.

Place: Pune
Date: 23rd October 2019

Uttam V. Pawar
(Research Student)

CERTIFICATE

It is certified that work entitled "An Analytical Study of Geomorphological, Hydrological and Meteorological Characteristics of Floods in the Mahi River Basin: Western India" is an original research work done by Mr. Uttam V. Pawar under my supervision and guidance for the degree of Doctor of Philosophy in Geography to be awarded by Tilak Maharashtra Vidyapeeth, Pune. To the best of my knowledge this thesis

- Embodies the work of candidate himself
- Had duly been completed
- Fulfils the requirement of the ordinance related to Ph.D. degree of the TMV
- Up to the standard in respect of both content and language for being referred to the examiner.

Place: Pune
Date: 23rd October 2019

Dr. Pramodkumar S. Hire
(Research Guide)

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ABSTRACT

AN ANALYTICAL STUDY OF GEOMORPHOLOGICAL, HYDROLOGICAL AND METEOROLOGICAL CHARACTERISTICS OF FLOODS IN THE MAHI RIVER BASIN: WESTERN INDIA

1) Rationale and significance of the study

The monsoon dominated rivers are characterized by the foremost annual flood events. These events have great significance in the field of fluvial and flood geomorphology, flood hydrology, flood hydrometeorology and hydraulic engineering. Therefore, analysis of the palaeofloods, historical floods and modern floods is an integral part in order to understand the hydrological, geomorphological and meteorological characteristics of the rivers. Nevertheless, palaeofloods, historical and modern flood records provide a base for the design of the hydraulic structures such as bridges and dams. The estimation of the design flood and its return period is indispensible in the field of hydraulic engineering. The southwest monsoon is a fundamental source of water for Indian agriculture, but due to the variability of the monsoon some parts of the country facing problems of the flood and some parts drought. In order to solve these problems hydrometeorological and hydrological studies at the river basin scale is the most crucial aspect in India. Besides, the flood caused several damages to properties and loss of lives every year in India. Therefore, flood studies also have importance in disaster management. Yet, flood studies on the Indian rivers are surprisingly limited.

Some of the large rivers of India such as the Brahmaputra, Kosi, Ganga, Teesta, Mahanadi, Narmada, Tapi, Godavari and Kaveri have received greater attention of the geomorphologists, hydrologist, meteorologist and engineers from India and abroad (Gupta, 1998; Kale, 1998; Hire, 2000). The Mahi River from Western India is notable for its large and flashy discharges during the monsoon season. The extraordinarily large floods have been experienced by the river. However, very little information is available regarding the causes and effects of large floods on the river. Hence, the present study was undertaken to understand the hydrological, geomorphological, meteorological aspects of floods on the Mahi River.

2) Introduction to the study area

The Mahi River is the third largest interstate west flowing river of the Indian peninsula that flows in western India. The source of the Mahi River is near Minda village of the Sardarpur tehsil in the Dhar district (Madhya Pradesh). It originates at an altitude of 500 m above mean sea level (MSL) on the Malwa Plateau. It flows for a length of 583 km and meets the Gulf of Khambhat in Gujarat. The average channel gradient of the river is 0.00086.

The Mahi Basin is mainly located in the western part of India. It extends between 22°30' to 24°20' N latitudes and 73°00' to 74°20' E longitudes. It is bounded by the Vindhya Ranges in the south, the Aravali Ranges in the north and northwest, the Malwa Plateau in the east and the Sabarmati Basin in the west. The drainage area of the Mahi River is 34842 km^2. It covers 6695 km^2 (19.22%) area of the Dhar, Ratlam and Jhabua districts in the Madhya Pradesh, 16453 km^2 (47.22%) area in the Banswara, Pratapgarh, Dungarpur and Udaipur districts of the Rajasthan and 11694 km^2 (33.56%) area in the Mahisagar, Panchmahal, Kheda and Vadodara districts of the Gujarat. The Som River, the Jakham River, the Anas River and the Panam River are the major tributaries of the Mahi River. The Som Basin and Anas Basin comprise individually 25% and 16% of the total area of the Mahi Basin. However, the Eru River, the Chap River, the Moran River, the Goma are the small tributaries of the Mahi River.

The Mahi River and its tributaries are intensely fed by the Indian summer monsoon rainfall. Therefore, the Mahi Basin is significantly controlled by southwest monsoon (June-October). The annual average rainfall of the Mahi Basin is 889 mm. More than 97% of the annual rainfall occurs during the monsoon season (June-October). July (33%) is the rainiest month throughout the basin followed by August (32%). The July and August months accounts for nearly 65% of the total annual rainfall of the Mahi Basin. Rainfall of the Mahi Basin is significantly influenced by the low pressures systems (LPS) formed over the Bay of Bengal and moves west and northwest directions. These LPS(s) are accountable to boost rainfall of the Mahi Basin.

The geologic sequences of the Mahi Basin are highly varied and complex. It shows rocks of different periods from Precambrian to Quaternary. In the upper parts of the Mahi Basin rocks are belonging to the Deccan traps, lower Vindhya, Aravali Supergroup, Bhilwara Supergroup, sandstone of Cretaceous and Lunawada group. However, a lower part of the Mahi Basin is covered by deposits of the Quaternary sediment and alluvial tract of the Gujarat plain.

3) Research questions

The research work has attempted in order to find out the answers to the following questions based on the field surveys, available secondary data and appropriate research techniques.

- What are the hydrologic characteristics of the floods on the Mahi River and its major tributaries?
- How the fluvial and flood geomorphic characteristics of the Mahi River and its tributaries change with respect to discharges?
- What are the flood hydrometeorological characteristics of the Mahi Basin? and how synoptic conditions affect the fluvial and flood regime characteristics of the Mahi River and its tributaries?
- What are the palaeoflood hydrologic characteristics of the Mahi River?

4) Hypothesis

The present study has been based on a hypothesis that has given the direction to the work. The following hypothesis is formulated for the present research work.

- Fluctuations in the monsoon rainfall during the last century show significant variations in the flood hydrological, flood geomorphological and flood hydrometeorological characteristics of the Mahi Basin.

5) Main objectives of the study

The primary objective of the present study is to analyze the hydrological, geomorphological and meteorological data of the Mahi River and its tributaries to understand the characteristics of floods. The subsidiary objectives are;

- To understand the hydrological characteristics of floods on the Mahi River and its major tributaries in terms of magnitude, frequency and distribution.

- To evaluate the geomorphic effectiveness of floods on the Mahi River and its tributaries relating to channel morphology, sediment transport, hydraulics and hydrodynamics.
- To examine the association of the synoptic conditions, global teleconnection and long term fluctuations in monsoon and floods in the Mahi Basin.
- To integrate the modern, historical and palaeoflood data to establish the long-term fluctuations in the flood magnitude and frequency.

6) Data and methodology

(I) Flood Hydrology

In order to understand fluvial and flood regime characteristics of the Mahi River and its major tributaries, daily discharge and annual maximum series (AMS) data were collected from Central Water Commission (CWC), Gandhinagar. The AMS data have been made available for four sites on the Mahi River namely, Mataji, Paderdi Badi, Wanakbori and Khanpur and three sites on its tributaries such as the Anas River at Chakaliya, the Som River at Rangeli and the Jakham River at Dhariawad. The record length for these sites ranges between 26 and 51 years.

The daily discharge and annual maximum series (AMS) data have been analyzed by using some of the basic quantitative techniques such as mean, standard deviation, skewness, coefficient of variations, time series plots, etc. Besides, the flood frequency magnitude index (FFMI) was also calculated to assess the variability of flood frequency and flood flashiness of the Mahi River and its tributaries. Flood frequency analysis of the Mahi River and its tributaries has been performed by applying the Gumbel Extreme Value type I (GEVI) probability distribution to the AMS data. Further, flow duration curves and flood hydrographs have also been obtained to understand the flood characteristics of the Mahi Basin.

(II) Flood Geomorphology

The data of hydraulic parameters of the Mahi River and its tributaries have been obtained by the nineteen cross-sections from field surveys and Central Water Commission (CWC), Gandhinagar. Information regarding channel slope (S), channel length (L), and catchment area (A) for the sites were obtained from toposheets, field surveys, CWC and Google Earth. Besides, in order to understand at-a-station hydraulic geometry of the Mahi River and its major tributary data regarding hydraulic geometry variables associated with AMS were obtained from CWC, Gandhinagar. Besides, suspended sediment data for the three sites on the Mahi River namely, Mataji, Paderdi Badi and Khanpur were obtained from CWC, Gandhinagar. Further, during field surveys, dimensions of the largest boulders were measured to understand stream power during floods.

The cross sectional data of the Mahi River and its tributaries have been analyzed by applying hydraulic variables such as channel width and depth, cross-sectional area, wetted perimeter, hydraulic radius and width-depth ratio. The hydraulic geometry equations have been derived for six gauging sites on the Mahi River and its tributaries by applying hydraulic parameters of AMS. Besides, the suspended data of monsoon season have been analyzed by using basic statistical techniques such as mean, coefficient of variation, time series plots and correlation. The results of sediment concentrations and sediment loads for the Mataji, Paderdi Badi and Khanpur sites on the Mahi River were calculated. Further, equations developed by Williams (1983) were applied to coarse sediment data in order to understand the geomorphic effectiveness of floods.

In addition to this, parameters of flood hydraulics and hydrodynamics such as boundary shear stress, stream power per unit boundary area, Froude number, and Reynolds number were computed. Simple ratios between effectiveness parameters of moderate-magnitude floods, the floods, large floods and maximum floods were computed to evaluate the impact of floods.

(III) Flood Hydrometeorology

The daily rainfall data were obtained from the India Meteorology Department (IMD), Pune. Besides, data regarding the tracks of the low pressure systems have been obtained from storm track eAtlas software. The isohyetal map and values of depth-area-duration (DAD) of the major rainstorm of the year 1927, 1973 and 2006 have been obtained from PMP Atlas of Narmada, Tapi, Mahi and other adjoining river basins which were jointly prepared by Central Water Commission and India Meteorological Department, Government of India. Further, sea surface temperature (SST) data of the central and eastern Pacific Ocean for the period (1901-1982) have been obtained from Wright (1989) and for 1983 onwards from Climate Prediction Centre (CPC) of National Oceanic and Atmospheric Administration (NOAA).

The daily and annual rainfall data of the selected seven stations such as Sardarpur, Sailana, Banswara, Kushalgarh, Kherwara, Sagwara and Godhra have been analyzed by applying basic statistical methods such as mean, standard deviation, skewness, coefficient of variation, etc. to understand spatio-temporal characteristics of the rainfall in the Mahi Basin. In order to understand the flood generating meteorological situations, the analyses of synoptic conditions associated with floods in the Mahi Basin was carried out. Further, the relation between long term fluctuations in the rainfall, global teleconnections and floods in the Mahi Basin have been studied with the help of Normalized Accumulated Departure from Mean (NADM), Mann Kendall test, student t-test and index of El Niño and Southern Oscillation (ENSO).

(IV) Palaeoflood Hydrology

The palaeoflood discharge data were obtained with the help of palaeostage indicators. These palaeostage indicators were observed during field survey on the Mahi River at Kothada in the Dhar district and Mahudi ka Mal in the Ratlam district of the Madhya Pradesh. The data of slack water deposits (SWD) were collected from palaeoflood site on the Mahi River near Bhungda village of the Banswara district in the Rajasthan. A cross sectional data have been obtained with reference to palaeostage indicators such as shrub line, scour line and SWD. Besides, boulder dimensions were measured to calculate the stream power of the palaeoflood discharges.

A channel survey was conducted in bed rock reaches of the Mahi River to find out palaeostage indicators for the study of palaeoflood hydrology of the Mahi River. Besides, 17 sediment samples were collected from 37 flood units of the slackwater deposits (SWD) to understand the textural characteristics of the sediments. Accordingly, basic statistical techniques such as mean, median, skewness, kurtosis and sorting index have been applied for sediment samples. The graphic sediment log also has been generated for the palaeoflood site of Bhungda. Moreover, Palaeoflood magnitudes have been derived with reference to PSI. Finally, water surface profiles have been generated by using U.S.

Army Corps of Engineers River Analysis System computer programme HEC-RAS (Hydrologic Engineering Center, 1995).

7) Major findings of the study

The major findings and contributions that have emerged from this study are as follows;

1) The Mahi River exhibits all the hydrological, geomorphological and meteorological characteristics of a flood-dominated river. Large floods are common and frequently occurring events at the decadal interval. Interventions of man, mainly due to construction of dams, have made the recent floods more destructive, for instance 2006 flood.
2) The channel perimeter lithology has played significant role in determining efficacy of the floods on the Mahi River. The channel of the river is mainly confined into bedrock particularly in the upper reaches. The channel in middle reaches is comprised of thick Quaternary alluvium with bedrock exposures on the bed and banks. The perimeter in the lower reaches is characterized thick Quaternary alluvium with sandy bed. Since the bank resistance is high, only infrequent large magnitude floods that occur at the interval of several decades or century, are capable to erode the banks and determine size and shape of the cannel of the Mahi River. Thus, the channel morphological characteristics of the bedrock as well as the alluvial reaches of the Mahi River are maintained by infrequent but large magnitude extreme floods such as the 1927, 1973 and 2006 flood events that occur at an interval of several decades or hundreds of years. Apart from transporting the fine-grained sediments in suspension or moving sandy/pebbly bedload or modifying the channel bedforms, the frequently-occurring moderate flows have little effect on the mobility of coarse sediments and on the morphology of the channels.
3) Floods on the Mahi River are not randomly spaced, but follow a pattern dictated by long-term changes in the monsoon rainfall over the basin. Thus, the temporal distribution of geomorphologically effective floods is strongly influenced by long-term changes in the monsoon conditions and the rainfall regime. Examination of the synoptic conditions associated with the flood-generating low pressure systems

reveals that majority of floods are the result of either Bay of Bengal or adjoining land depressions.

The present study sharply contrasts with numerous studies, primarily of humid region, which indicate that frequent, moderate flow events are more important in the transportation of maximum suspended sediment load and in maintaining the stream morphology (Wolman and Miller, 1960). The conclusions of this study are more in agreement with the inferences drawn by Pickup and Warner (1976) for semi-arid regions, and by Gupta (1995a) and Hire (2000) for tropical/monsoonal environments, that a series of flows rather than a single flow determine the channel characteristics. The low or moderate magnitude flows transport most of the fine-grained sediment such as clay, silt and sand and modify the channel bedforms to some extent. However, the channel size and shape is maintained by large magnitude floods, such as the 1927, 1973 and 2006 floods that occur at long intervals.

Investigations of hydrological, geomorphological and meteorological characteristics of floods on the Mahi River have facilitated us to understand the distinctiveness of monsoonal rivers that are categorized by frequent floods of high magnitude. This study has revealed that monsoonal rivers preserve numerous prerequisites for disastrous flood responses.

The inferences regarding the hydrological, geomorphological and meteorological significance of floods accomplished in the present investigation have been discussed only for one medium-sized basin. Nevertheless, the geology, topography, climate and tectonic setup within the monsoonal/tropical region are varied, the conclusions cannot be applied directly to all the basins within the monsoonal/tropical region. Nonetheless, such studies are beginning to provide a database and discuss the significance of the infrequent large magnitude floods in monsoonal environments.

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Introduction

1.1 Rationale and significance of the study

The monsoon dominated rivers of India are characterized by the foremost annual flood events. These events have great significance in the field of fluvial and flood geomorphology, flood hydrology, flood hydrometeorology and hydraulic engineering. Therefore, analysis of the palaeofloods, historical floods and modern floods is an integral part in order to understand the hydrological, geomorphological and meteorological characteristics of rivers. Nevertheless, palaeofloods, historical and modern flood records provides base for the design of the hydraulic structures such as bridges and dams. The estimation of the design flood and its return period is indispensible in the field of hydraulic engineering. Besides, the southwest monsoon is a fundamental source of water for the Indian agriculture, but due to variability of the monsoon some parts of the country facing problems of the flood and some parts drought. In order to solve these problems hydrometeorological and hydrological studies at river basin scale is most crucial aspect in India. Further, flood caused several damages to properties and loss of lives every year in India. Therefore, flood studies also have importance in disaster managent. Yet, flood studies on the Indian rivers are surprisingly limited.

Some of the large rivers of India such as the Brahmaputra, Kosi, Ganga, Teesta, Mahanadi, Narmada, Tapi, Godavari and Kaveri have received greater attentions of the geomorphologists, hydrologist, meteorologist and engineers from India and abroad (Gupta, 1998; Kale, 1998; Hire, 2000). The Mahi River from Western India is notable for its large and flashy discharges during the monsoon season. The extraordinarily large floods have been experienced by the river. However, very little information is available regarding the causes and effects of large floods on the Mahi River. Hence, the present study was undertaken to understand the hydrological, geomorphological, meteorological aspects of floods on the Mahi River.

1.2 Flood: An introduction

Normally, Flood is considered as natural disaster which causes great damages to settlements, agriculture, loss of cattles, industries, and loss of human lives. Every year, floods occur in different parts of the worlds. Evidences of floods in some parts of the world have been documented in historic records. Such as, flood level of the Nile River in Egypt traced back to 3000 to 3500 BC (Biswas, 1970). Like-wise, the period of the first recorded flood event on the Hwang Ho River goes back to 2297 BC (Biswas, 1970). Most of the South Asian countries experienced flood during monsoon season. The major rivers of India such as the Ganga, Brahmaputra, Indus, Narmada, Tapi, Mahi, Godavari, Krishna and Kaveri had overtopped banks due to heavy monsoon rainfall. Therefore, it is essential to understand the concept of flood before the study of flood hydrological, flood geomorphological and flood hydrometeorological characteristics of the Mahi Basin. Some of the notable definitions of the flood are as follows;

(I) Definition(s) of flood

A flood is any relatively high discharge in the river measured by using gauge level at a station whenever the stream channel overflows the usual channel boundaries (Jarvis, 1925; Chow, 1956). According to Rostvedt (1968) flood is significant increase in level of river discharge that flows over the banks of a stream channel. Furthermore, Ward (1978) states that a flood is a rising stream discharge that overflow stream channel. In India, Ramaswamy (1985) define term flood as extraordinary highest water level at least 2 m above the danger level at a station. Besides, Hire (2000) has defined floods and large floods as follows;

(i) Floods (Qf): all annual maximum peak flows above mean annual peak discharges (Qm), but below mean plus one standard deviation ($Qm<Qm+1\sigma$).

(ii) Large floods (Qlf): all annual peak discharges above mean plus one standard deviation ($>Qm+1\sigma$).

(iii) Peak on record (Qmax): highest annual peak flood discharge on record during gauge period. This is the highest Qlf.

(iv) Moderate flows: all flows that are lower than average annual peak flows (Qm) but higher the lowest annual peak discharge recorded at a site.

1.3 Introduction to the study area

1.3.1 Geomorphic setting

The Mahi River is the third largest interstate west flowing river of the Indian peninsula that flows in western India (Figure 1.1). The source of the Mahi River is near Minda village of the Sardarpur tehsil in the Dhar district (Madhya Pradesh). The Mahi River originates at an altitude of 500 m above mean sea level (MSL) on the Malwa Plateau (Figure 1.2). The Mahi River flows for a length of 583 km and meets the Gulf of Khambhat in the Gujarat. The average channel gradient of the Mahi River is 0.00086. After its origin, the Mahi River flows in the north direction through districts of Dhar and Jhabua then flows in northwest direction through Ratlam district. The total length of the Mahi River in Madhya Pradesh is about 167 km.

The Mahi River enters in southeastern parts of the Rajasthan which is known as the Vagad region. It is the major river in the Vagad region with a length of 174 km. Therefore, it is said to be the lifeline of the Vagad. The Mahi River forms boundary between Banswara and Pratapgarh as well as Banswara and Dungarpur districts. Before entering in the Gujarat, the river makes a ‘U’ shaped loop in Rajasthan. The Mahi River crosses the Tropic of Cancer twice in the Banswara district. The Mahi River flows in southwest direction from the village Sarondiya which is located north of the Banswara. The Mahi River flows in the Gujarat through districts of Mahisagar, Panchmahal, Kheda and Vadodara for a length of 242 km and drains into Gulf of Khambhat in the Gujarat.

The Mahi Basin is mainly located in the western part of India. It extends between 22°30' to 24°20' N latitudes and 73°00' to 74°20' E longitudes. It is bounded by the Vindhya Ranges in the south, the Aravali Ranges in the north and northwest, the Malwa Plateau in the east and the Sabarmati Basin in the west. The drainage area of the Mahi River is 34842 km^2. It covers 6695 km^2 (19.22%) area of the Dhar, Ratlam and Jhabua districts in the Madhya Pradesh, 16453 km^2 (47.22%) area in the Banswara, Pratapgarh, Dungarpur and Udaipur districts of the Rajasthan and 11694 km^2 (33.56%) area in the Mahisagar, Panchmahal, Kheda and Vadodara districts of the Gujarat. The Som River, the Jakham River, the Anas River and the Panam River are the major tributaries of the Mahi River. The Som Basin and Anas Basin comprises individually 25% and 16% of the total area of the Mahi Basin. However, the Eru River, the Chap River, the Moran River, the Goma are the small tributaries of the Mahi River.

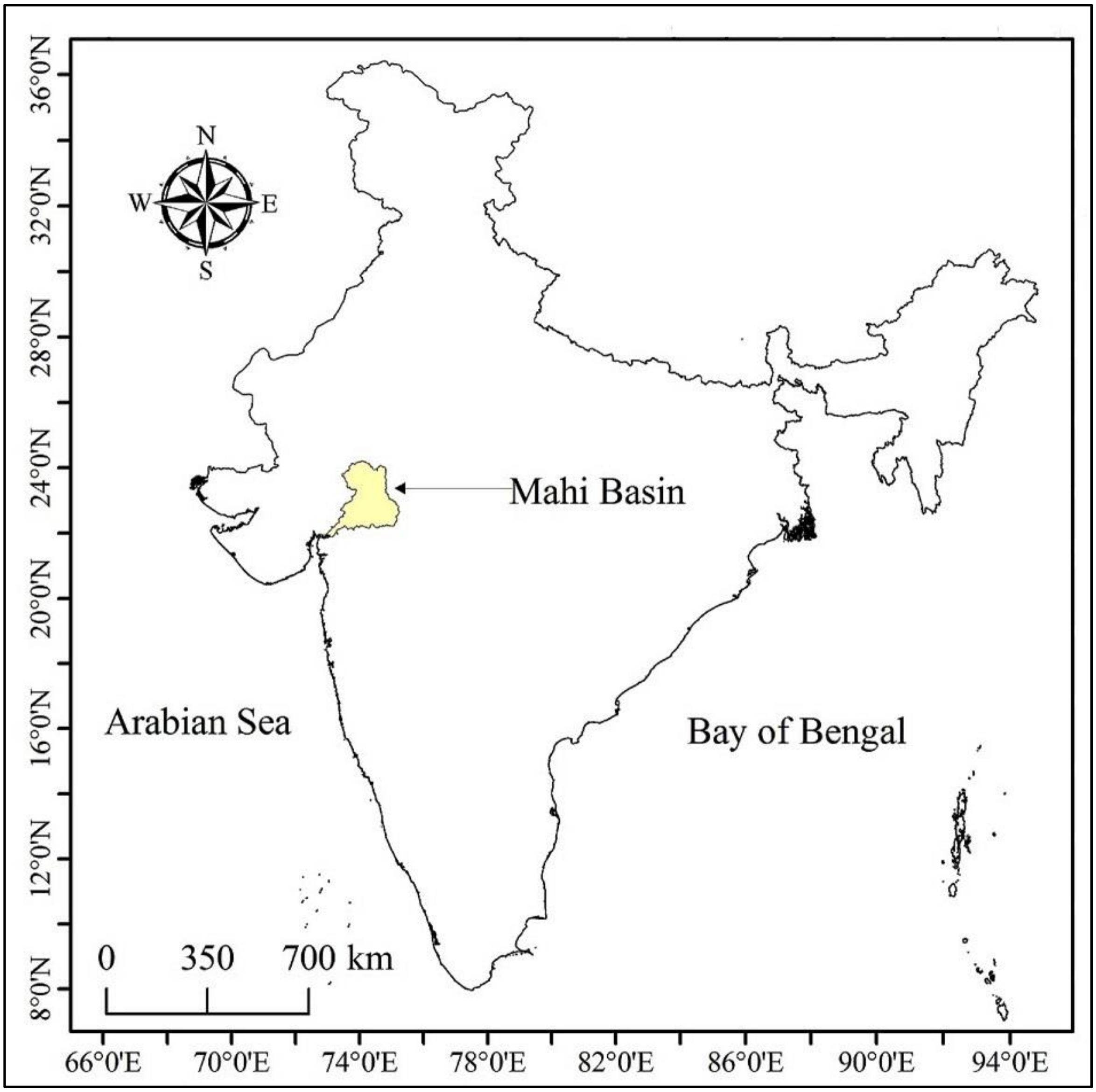


Figure 1.1: Location of the Mahi Basin

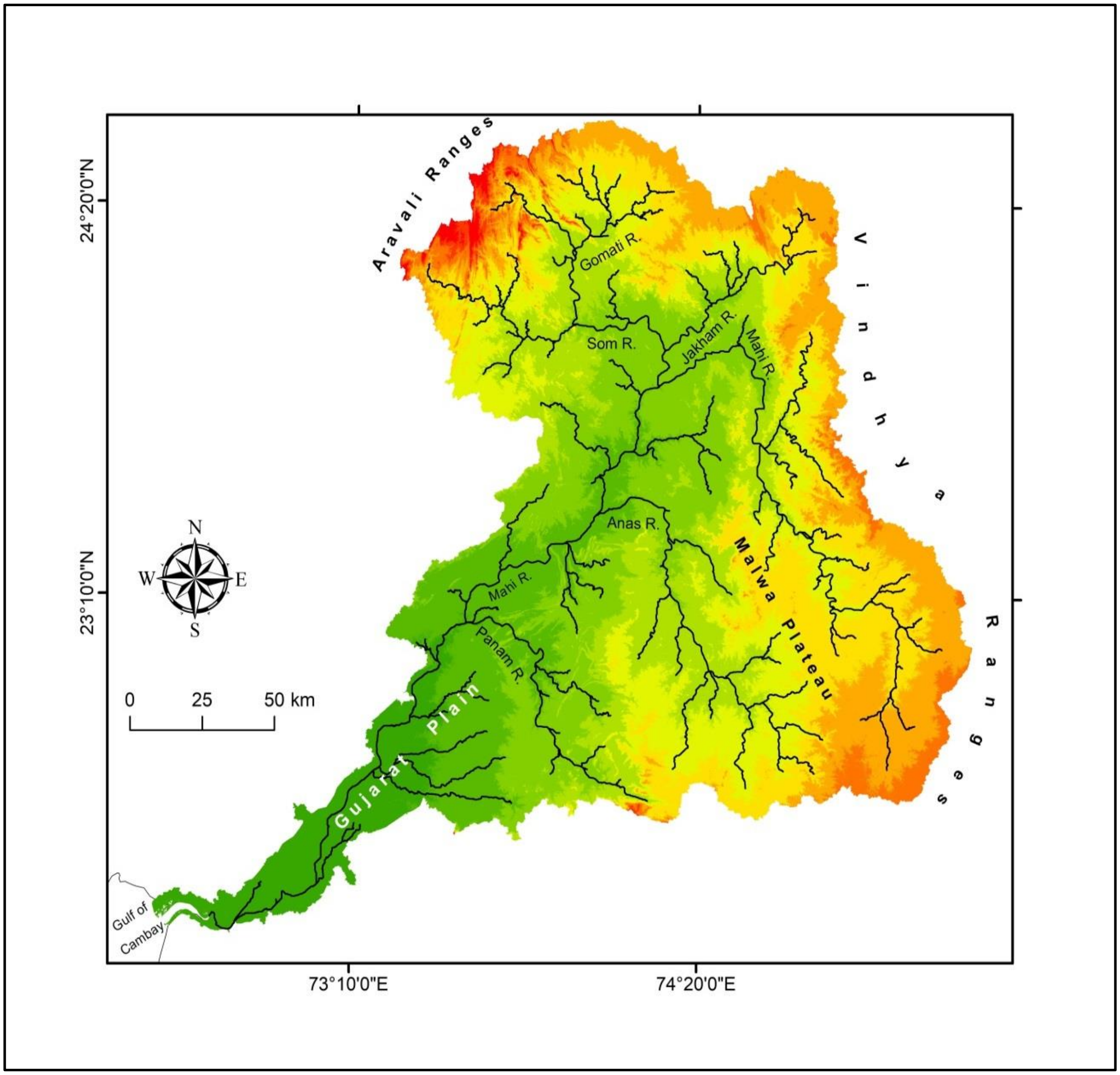


Figure 1.2: Geomorphic setting of the Mahi Basin

1.3.2 Climate

The Mahi River and its tributaries are intensely fed by rainfall of the Indian summer monsoon. Therefore, the Mahi Basin is significantly controlled by southwest monsoon (June-October). The basin contains two climatic regions, the northern part of the basin comprises sub-tropical wet climate in the upper reaches and tropical wet climate in the lower reaches. However, major part of basin comes under tropical wet climate, caused mainly due to existence of Vindhyas.

The annual average rainfall of the Mahi Basin is 889 mm. More than 97% of the annual rainfall occurs during monsoon season (June-October). July (33%) is the rainiest month throughout the Basin followed by August (32%). The months of July and August account nearly 65% of the total annual rainfall of the Mahi Basin (Figure 1.3). Rainfall of the Mahi Basin is significantly influenced by the low pressures systems (LPSs) that forms over Bay of Bengal and adjoining land and moves west and northwest directions. These LPS(s) are accountable to boost rainfall of the Mahi Basin.

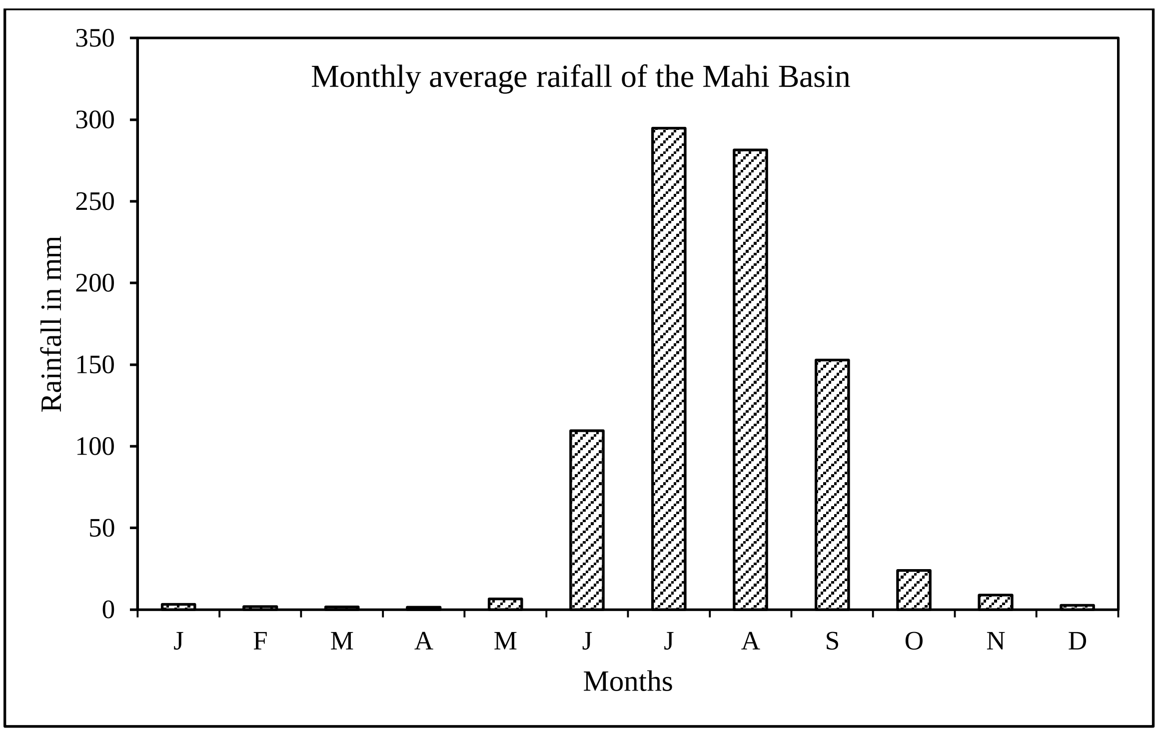


Figure 1.3: Monthly average rainfall of the Mahi Basin

The Mahi Basin shows remarkable spatial variations in the distribution of the rainfall (Figure 1.4). The annual average rainfall is significantly high at middle part of the Basin, particularly at Banswara (1013 mm) and Kushalgarh (1011 mm) rainfall is high due to influence of the low pressure systems and orographic effect of the Vindhya Ranges. The Godhra receives annual average rainfall of 957 mm. The annual average rainfall decreases (Kherwara, 649 mm) towards the western part of the basin (Figure 1.4). The annual average rainfall of the basin ranges between 649 mm (Kherwara) and 1013 mm (Banswara).

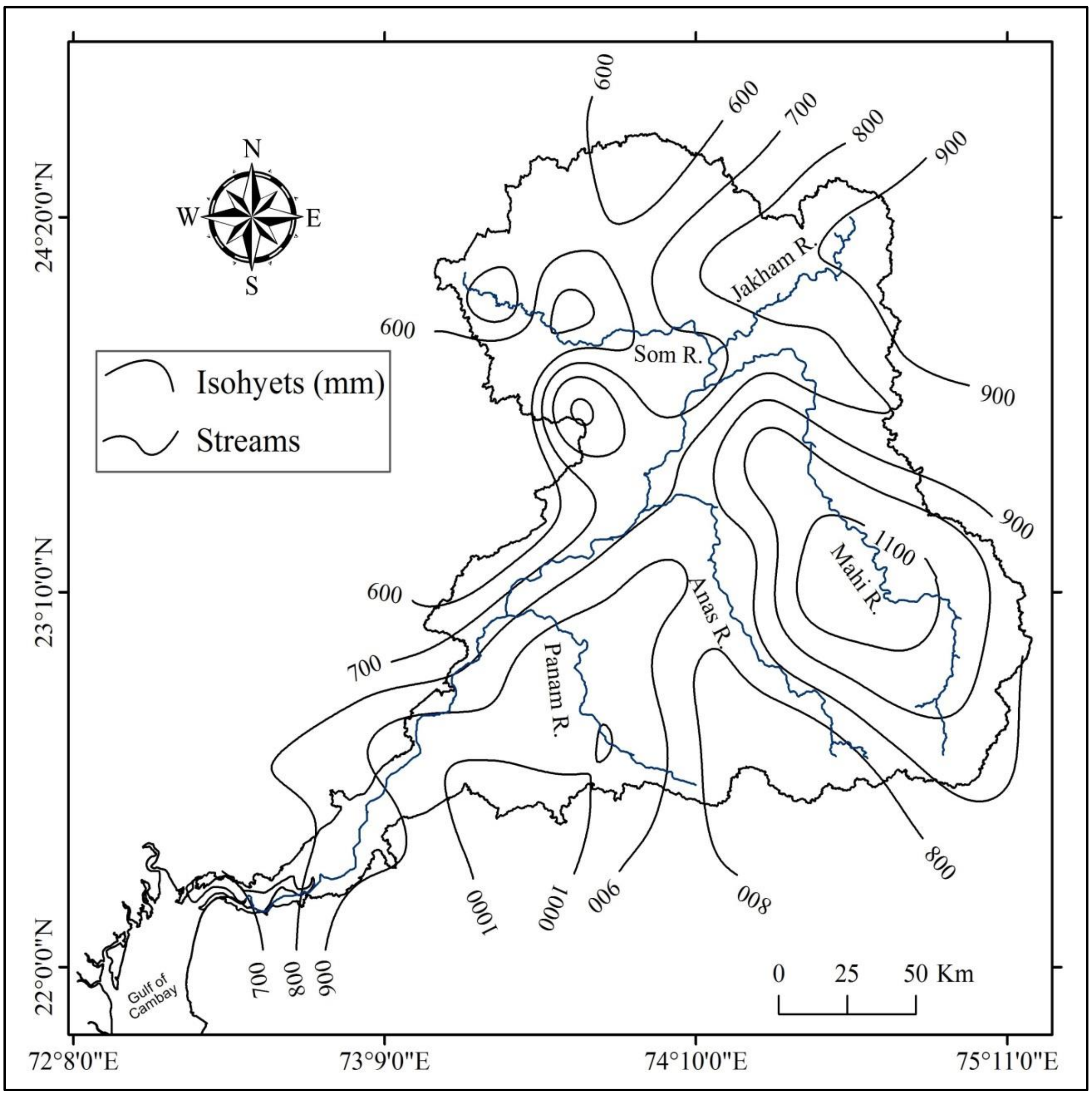


Figure 1.4: Isohyets of the Mahi Basin

1.3.3 Drainage basin and network characteristics

Several researchers have mentioned that the drainage basin and network characteristics are significantly affect the hydrological characteristics of a river (Schumm, 1956; Morisawa, 1962; Leopold et al., 1964). Therefore, basic drainage basin characteristics such as shape, size, basin relief and drainage density have been studied in order to understand their role in the floods of the Mahi Basin. Table 1.1 indicate some of the primary geomorphic and hydrologic characteristics of the Mahi Basin. Besides, morphometric properties of the major tributaries of the Mahi River have been summarized in Table 1.2.

Table 1.1 Morphometric properties of the Mahi Basin

Morphometric parameters	Values
Basin area	34842 km^2
Basin relief	500 m
River length	583 km
Average channel slope	0.00086
Elongation ratio	0.81
Form factor	0.10
Peak on record (Year)	40663 m^3/s (1973)
Unit discharge	0.63-3.89 $m^3/s/km^2$

Table 1.2 Morphometric characteristics of the major tributaries of the Mahi River

Name of the tributary	Elevation of the source in m	Length in km	Area in km^2	Average Slope	Bank
Som	600	156	8707	0.00385	Right
Anas	500	155	5604	0.00322	Left
Panam	300	127	2470	0.00236	Left
Jakham	476	93	2318	0.00511	Right

See Figure 1.5 for location of tributaries

(I) Som River

The Som River is the largest tributary of the Mahi River which joins the Mahi River on it's right bank in the Banswara district of the Rajasthan. It has its source in the hills of the Aravali near the Som village at an elevation of 600 m. It flows for a distance of 156 km through hilly region of the Dungarpur district and joins the Mahi River near Beneshwar village. The catchment area of the Som River spreads in the Udaipur, Dungarpur and Pratapgarh districts of the Rajasthan. The total catchment area of the Som River is 8707 km^2 which is 25% of the total area of the Mahi Basin. The Jakham and Gomati are major tributaries of the Som River.

(II) Jakham River

The Jakham River is the tributary of the Som River which originate near village Jakhamia. It flows through hilly region of the Pratapgarh and Udaipur districts for a length of 93 km and joins the Som River near Biloora village. The total catchment area of the Jakham sub-basin is 2318 km^2. The Karmai and Sukli are major tributaries of the Jakham River.

(III) Anas River

The Anas River has its source in the northern slopes of the Vindhya Range at an elevation of 500 m near Kalmora village of Jhabua district in Madhya Pradesh. It flows in northwest direction for length of 155 km. It enters in Rajasthan near Mehndi khera village and joins the Mahi River. The catchment area of the Anas River is 5604 km^2 which is 16% of the total drainage basin area of the Mahi Basin. The Hiran River is major tributary of the Anas River that originates at an elevation 400 m ASL. It has 1441 km^2 catchment area. It joins the Anas River near Bankaner village of the Banswara district.

(IV) Panam River

The Panam River is a left bank tributary of the Mahi River originates near Bhadra village in Jhabua district of the Madhya Pradesh at an elevation of about 300 m ASL. It flows for a length of 127 km and joins the Mahi River southwest of Lunawada in Panchmahal district of the Gujarat. It has 2470 Km^2 drainage basin area.

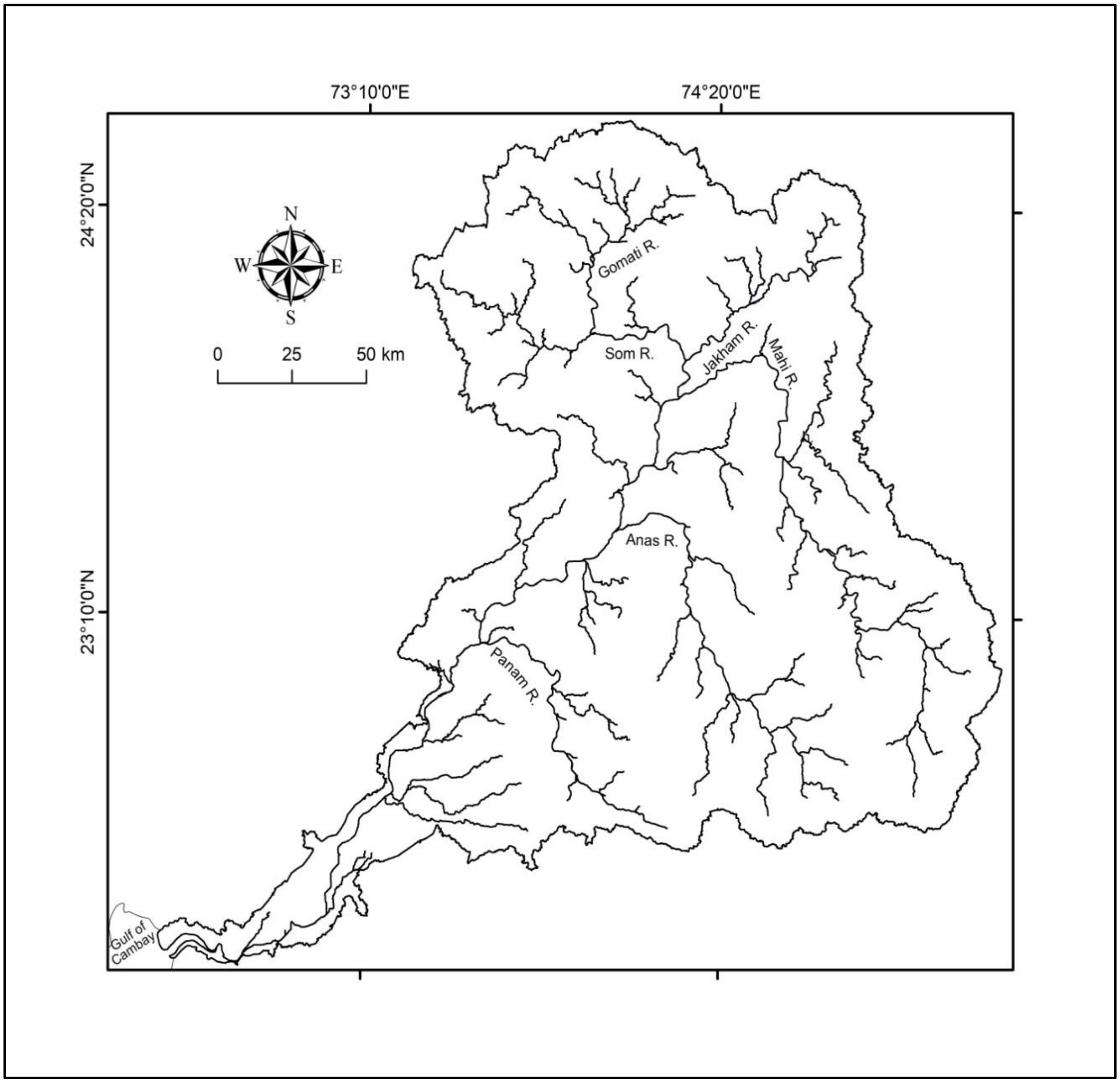


Figure 1.5: Drainage network of the Mahi River

1.3.4 Geology

The geologic sequences of the Mahi Basin are highly varied and complex. It shows rocks of different periods from Precambrian to Quaternary. In the upper parts of the Mahi Basin rocks belong to lower Vindhya, Lunawada group and Godhra granite, Aravali Supergroup, Bhilwara Supergroup, sandstone of Cretaceous and Deccan trap. The middle and lower parts of the basin is covered by deposits of the Quaternary sediment and alluvial tract of the Gujarat plain (Figure 1.6; Table 1.3).

(I) Deccan Trap

The Deccan trap has mostly occupied the upper Mahi Basin in the districts of Dhar, Ratlam and Jhabua. Besides, in the areas of Banswara and Pratapgarh districts the Mahi Basin is characterized by the north-south trending Deccan Traps plateau with prominent scarp on the west. The Deccan Traps superimpose on the rocks of the lower Vindhya in the north and northeast. However, towards the west and south they overlie the rocks of the Mangalwar Group and the Aravali Supergroup. A dark gray basalt of the Deccan Traps which covers extensive area of the eastern margin of the Banswara district, namely Peepalkunt, Kushalgarh, Dungra, Danpur, areas of Ghatol, Choti Sarwan. Besides, the areas of the Meghnagar, Thandla, Petlawad, Rama block and Sondwa part are also occupied by basalt. Intra-trappeans are not common but occasionally a thin layer of reddish clayey material, known as "redbol" occurs between two flows. The basalt is dark grey to olive green in colour and is usually weathered. At several locations, basalt is well jointed with typical columnar joints.

The Deccan Trap outcrops are also found in the lower Mahi Basin covering areas of the Panchmahal, Mahisagar and Vadodara districts in Gujarat. However, in the lower Mahi Basin Deccan Trap outcrops are found in scattered patches, cropping out from alluvial tracts of Gujarat near Wanakbori, Kalol and Timba in the Kheda and Panchmahal districts of the Gujarat (Figure 1.6).

(II) Vindhyan Supergroup

The Vindhyan Supergroup is composed mostly of low dipping formations of sandstone, shale and carbonate, with a few conglomerate and volcani-clastic beds, separated by a major regional and several local unconformities (Bhattacharyya, 1996). According to Sony et al (1978) and Bhattacharya (1996), the Vindhyan Supergroup is classified into four major groups such as the Semri, Kaimur, Rewa and Bhander. However, the Semri Group rocks are belonging to Lower Vindhyan which is found in the northern part of the Mahi Basin (Figure 1.6) covering parts of the Pratapgarh district in the Rajasthan.

(III) Aravali Supergroup

The Aravalli Supergroup is characterized by metamorphosed and complexly folded clastic sediments. This supergroup is bounded by the Bhilwara Supergroup in the east, to the west these are overlain by the rocks of the Delhi Supergroup and towards southeast it is covered by the Deccan Traps and alluvium. The Aravali Supergroup is a massive creation which mostly includes quartzite, shale, conglomerates, composite gneiss and slate.

(i) Lunawada Group

The Lunawada Group is the second youngest group of the Aravalli Supergroup (Gupta et al., 1980, 1992, 1995). The rocks of the Lunawada Group in the Mahi Basin occupies areas of the Mahisagar, Dahod and Panchmahal districts of Gujarat and Dungarpur and Banswara districts of Rajasthan. Lunawada group has been divided into six formations namely, Kalinjara, Bagidora, Bhawanpura, Chandanwara, Bhukia and Kadana. Among these formations only Kadana formation falls in Gujarat while other formations occupy areas of southern Rajasthan (Iqbaluddin, 1989). Lunawada Group occupies maximum areas of the Lunawada tehsil of Mahisagar district and Devgad Baria and Santrampur tehsils of the Panchmahal district. The sequence of the Lunawada Group rock is terminated by Godhra Granite and in southeast by Deccan Trap (Figure 1.6). Quartzite, phyllite, mica schist and bands of dolomitic limestone are major rocks of this group.

(ii) Champaner Group

The rocks of Champaner Group are exposed in the lower Mahi Basin in Gujarat (Figure1.6). It occupies northeast of the Vadodara, parts of Chota Udaipur, Shivrajpur and Jambughoda. Mica, schist, limestone and manganiferous phyllite are major rock types of this group.

(iii) Jharol Group and Ultramafic

The rocks of the Rakhabdev and Jharol belts belong to the Palaeoprotozoic Aravali Supergroup in the northwestern part of the Indian Shield (Roy et al., 1988). The most extensive outcrops of the ultramafic rock occur around Kherwara and Rakhabdev in western part of the Mahi Basin (Figure 1.6).

(iv) Debari Group

The Debari Group is a sequence of conglomerate, quartzite, phyllite, mica-schist, basic meta-volcanics with associated pyroclastic, calcareous quartzite, dolomitic limestone, dolomite, calcitic marble, ferruginous chert, algal phosphatic dolomite and chert, and carbonaceous and manganiferous phyllite. These rocks are found in the northern part of the Mahi Basin. It is located between rocks of the Delwara Group and Jharol Group (Figure 1.6).

(v) Delwara Group

The rocks of the Delwara Group are fond along the eastern margin of the Aravalli Supergroup discontinuously (Figure 1.6). The rocks from the Delwara Group are conglomerate, quartzite, carbonate, basic volcanics, chlorite phyllite and schist. These rocks are mostly found in the areas of Jaisamand, Salumbar, Ghatol and Talwara occupied by the Mahi Basin.

(IV) Bhilwara Supergroup

The rocks of the Bhilwara Supergroup belonging to the green schist, amphibolite and granulite facies and designated as Hindoli Group, Mangalwar Group and Sandmata Complex respectively by Gupta et al. (1980). Each of these major lithostratigraphic units has been further subdivided into several formations by Gupta et al. (1980, 1997). The rocks belonging to the Hindoli Group and Mangalwar Group are mainly found in the northern part of the Mahi Basin (Figure 1.6).

(i) Hindoli Group

The rocks belonging to Hindoli Group are low grade metamorphic volcano-sedimentary rocks, sandwiched between Mangalwar Group and Delwara Group of the Aravali Supergroup. Metavolcanics with shale, slate, phyllite, mica, schist, quartzite, dolomite and limestone are major rocks of the Hindoli Group. These rocks are mainly found in the northern part of the Mahi Basin which includes southern and western areas of the Pratapgarh district of Rajasthan (Figure 1.6).

(ii) Mangalwar Group

The Mangalwar Group is named after Mangalwar village which is located about 55 km southwest of Chittaurgarh. The group extending from Peepalkunt to Mangalwar for over 350 km and showing a width of 12 to 48 km. It is overlain by the Aravalli Supergroup with an erosional unconformity. The western boundary of the group is marked by the rocks of Hindoli Group and in the south the Deccan Traps overlie the Mangalwar rocks (Figure 1.6). Gneiss, schist, quartz-feldspar gneiss, impure marble and migmatites are the major rocks of this group observed in the Mahi Basin.

(V) Alluvium

The Quaternary sediments in the Gujarat alluvial plains in the Mahi Basin represent marine, aeolian and fluvial deposits of the sediments (Merh, 1993). According to Sridhar (2007a) the channel of the Mahi River is deeply incised in the alluvial zone of Pleistocene and Holocene sediments**,** forming alluvial cliffs as high as 40 m along both banks. The youngest alluvium consists of multilayers of sand, silt, clay, kankar, and gravels. In the lower Mahi Basin alluvium is found along the channel of the Mahi River and Panam River in Mahisagar, Panchmahal, Kheda and Vadodara districts of the Gujarat (Figure 1.6). Besides, Quaternary sediment was also observed in parts of the Banswara and Dungarpur districts on both the banks of the Mahi River in discontinuous isolated patches.

(VI Godhra Granites

The Godhra granites are found in the lower Mahi Basin covering areas of the Panchmahal district of the Gujarat (Figure 1.6). These granitic domes have been observed in the eastern part of the Godhra, Santrampur, Chota Udaipur and Devagrh Baria during field survey. A broad belt from Devgad Baria tehsil to Lunawada tehsil, trending SE-NW is occupied by granites around Godhra in Panchmahal district; this extends further across the Mahi River in Balasinor tehsil in the west, and Kalol tehsil in the south. The Godhra granite has been dated as 955±20 Ma by Rb/Sr method (Gopalan et al., 1979).

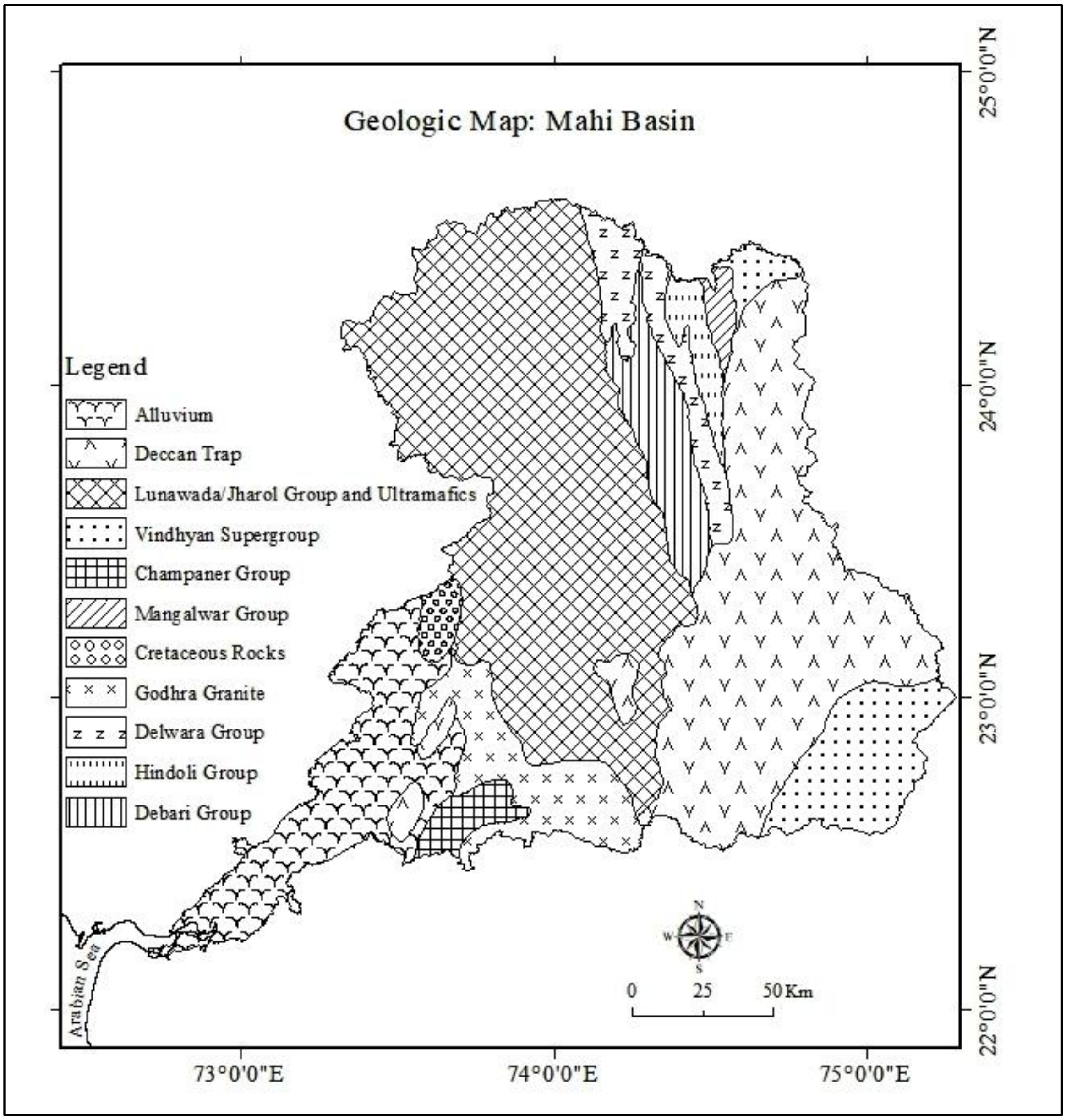


Figure 1.6: Geology of the Mahi Basin; modified after Sharma et al., 2013

Table 1.3: Stratigraphy of the Mahi Basin

Geologic Age	Supergroup	Group	Formation	Lithology
Quaternary		Alluvium, Marine and Aeolian	Singrot, Shihora, Rayaka	Sand, Silt, Clay, Kankar, Gravels, Pebbles and Mud
Cretaceous - Eocene		Deccan Traps		Basalt
Upper Precambrian	Vindhyan	Lower Vindhyan	Semri	Sandstone, Grits and basic lava flows
Upper Proterozoic	Post-Delhi	Godhra Granites		Granite
Lower Proterozoic	Aravali	Champaner		Mica schist, Dolomite Limestone and Manganiferous Phyllite
		Lunawada	Kalinjara, Bagidora, Bhawanpura, Chandanwara Bhukia, Kadana	Phyllites, Mica schist, Meta-subgreywacke, Quartzite and Dolomite
		Jharol		Chlorite, Phyllite, Quartzite and Mica schist
		Debari		Metavolcanics, Quartzite and Phyllite
		Delwara		Conglomerate, Quartzite, Carbonate, Basic volcanics, Chlorite phyllite and Schist
Archaean	Bhilwara	Hindoli		Shales, Slate, Phyllite, Limestone, Dolomitic marbles, Quartzite and Mica schist
		Mangalwar		Gneiss, Schist, Impure marble and Migmatites

Source: Geology and Mineral Resources of Rajasthan; District Groundwater Information Booklet, Jhabua; Groundwater Information, Dungarpur; District Groundwater Brochure: Dahod, Banswara and Vadodara; Hydrogeological Atlas of Rajasthan; Mahi Basin; Hydrogeological Atlas of Rajasthan, Pratapgarh; The Quaternary Geology of the Gujarat Alluvial Plains.

1.4 Research questions

The research work has attempted in order to find out the answers of the following questions based on the field surveys, available secondary data and appropriate research techniques.

- Which are the hydrological characteristics of the flood on the Mahi River and its major tributaries?
- How the fluvial and flood geomorphic characteristics of the Mahi River and its tributaries change with respect to discharges?
- What are flood hydrometeorological characteristics of the Mahi Basin? and how synoptic conditions define the flood characteristics of the Mahi River and its tributaries?
- What are the palaeoflood characteristics of the Mahi River?

1.5 Hypothesis

The present study has been based on a hypothesis which has given the direction to the work. Following hypothesis is formulated for the present research work.

- Fluctuations in the monsoon rainfall during the last century show significant variations in the flood hydrological, flood geomorphological and flood hydrometeorological characteristics of the Mahi Basin.

1.6 Main objectives of the study

The primary objective of the present study is to analyze the hydrological, geomorphological and meteorological data of the Mahi River and its tributaries to understand the characteristics of floods. The subsidiary objectives are;

- To understand the hydrological characteristics of floods on the Mahi River and its major tributaries in terms of magnitude, frequency and distribution.
- To evaluate the geomorphic impact of floods on the river in terms of sediment transport, hydraulic characteristics and effects.
- To examine the meteorological aspects associated with large floods in the Mahi Basin.

- To integrate the modern, historical and palaeoflood data to establish the long-term fluctuations in the flood magnitude and frequency.

1.7 Arrangement of the text

The research work is classified into five chapters. The introduction of the research topic and study area, research questions, hypothesis and main objectives of the study have comprised in the first chapter. The second chapter contains review of previous research work done in the field of flood hydrology, flood geomorphology, flood hydrometeorology and palaeoflood. The third chapter covers data and research methodology. The fourth chapter is of analysis and interpretation. The fifth deals with major conclusions of the study.

Chapter 2

Review of Literature

2.1 Introduction

Flood geomorphology can be defined as the scientific study of the floods and their role in landscape modification. It also involves the analysis of flood causes, flood processes and changes in the river processes and forms through space and time. The origin of the modern flood geomorphology is found in the studies of process geomorphology by G. K. Gilbert in 1870s. However, the scientific knowledge and understanding of flood processes progressively developed in this century, mostly after the formative paper by Harlen Bertz in 1920s on catastrophic Missoula floods in northwest USA (Baker et al., 1988). The Flood geomorphology was not considered as a sub-discipline of fluvial geomorphology until 1950s and 1960s because of overwhelming supremacy of the concept of uniformitarianism and cycle of erosion proposed by William Morris Davis in 1884. Nevertheless, 1950s and 1960s was the period significant changes in the field of flood geomorphology. During this period, several rivers of world has experienced great flood (Probst and Tardy, 1987; Burn and Arnell, 1993; Kale, 1996b), these events received the attention of geomorphologists to study the causes and effects of floods.

Several empirical and experimental research works have done by Leopold, Wolman and Miller on the floods in the 1950s. As a result, a book on "Fluvial Processes in Geomorphology" was published in the year 1964, which established fluvial geomorphology as scientific sub-discipline and provided scientific base for flood studies. Now, many geomorphologists accept significance of floods in shaping the landscape. In the 1980s Mayer and Nash, Baker et al. and Beven Carling had made great contributions to the field of flood science by publishing two volumes on flood hydrology and geomorphology. These include "Catastrophic Flooding" by Mayer and Nash (1987) and "Flood Geomorphology" by Baker et al. (1988) and "Flood: Hydrological, sedimentological and Geomorphic Implications" by Beven Carling (1989).

The last three to four decades, described as the recent period in flood research which have included main four themes. These are; 1) Flood Hydrology 2) Flood Geomorphology

3) Flood Hydrometeorology 4) Palaeoflood Hydrology. The studies in above mentioned themes have been discussed in detailed in the following section of the literature review.

2.2 Studies in Flood Hydrology

The history and development of hydrology as a multi-disciplinary subject have been discussed by Biswas (1969a, 1970), Benson (1962) and Chow (1962). Mutreja (1995) has defined hydrology as the science of water and deals with origin, movement and distribution of the waters of the earth. In the last century, Flood Hydrology and Paleoflood Hydrology have gained recognition as an applied hydrologic science. Flood hydrology is mainly associated with the quantitative analyses of hydrologic processes and estimation of floods. Flood hydrology has gone through the phases of observation, quantification and present phase of development and application of methods for flood forecast (Chow, 1964; Backer, 1994). As stated by Ward (1978) and Zawada (1997) deterministic, probabilistic and empirical are the three main techniques which have been applied in flood hydrology. These techniques are illustrated in short in the following sub-sections.

2.2.1 Deterministic techniques: It comprises the estimation of the extreme or maximum flood discharges in relation to the features of the drainage basin. Dickens calculate discharge ($Q = cA^k$) for Bengal region in 1965 (Mutreja, 1995). Several attempts have been made to refine Dickens formula of discharge by estimating the constant (i.e. c and k) for various regions (Alexander, 1972; Ward, 1978) and developing a more elegant experiential relationship connecting different aspects such as basin relief, rainfall, vegetation cover, etc. (Ward, 1978; Garde and Kothyari, 1990). A brief review of this association for Indian region has given by Garde (1998). Probable maximum flood (PMF) is another most frequently used statistical method in hydrology in relation to probable maximum precipitation (PMP). In order to convert probable maximum precipitation values into probable maximum flood, unit hydrograph technique and catchment features are taken in to consideration (Ward, 1978).

The concept of unit hydrograph was first introduced by Sherman (1932) and he suggested that the unit hydrograph should be applied for watersheds of 5000 km^2 or less. The Unit Hydrograph is the hydrograph of direct runoff resulting from one unit (1 cm) of constant intensity rainfall uniformly distributed over the entire catchment area (Chow et al., 1988). The first synthetic unit hydrograph on the basis of investigations of 20 watersheds in the Appalachian Mountains was proposed by Snyder (1938). Furthermore, Snyder (1955) and Eagleson et al. (1966) have developed least squares and matrix inversion methods to estimate the unit hydrograph. Chow et al. (1988) deliberated unit hydrograph and its linear systems theory. In addition, the history and procedure for various methods of unit hydrographs was presented by Viessman et al., 1989; Wanielista, 1990 and Husain, 2015. The linearity and superposition are essential assumptions in the development of the unit hydrograph technique (Ponce, 1985).

The probable maximum flood (PMF) determined on the probable maximum precipitation (PMP), which is defined as "theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of the year" (Hansen, et al., 1982). Win (1993) discussed the meteorological and hydrological aspects that affect probable maximum flood (PMF) determinations. Bowles et al. (1992) stated that values used for constant rates in probable maximum flood (PMF) analysis are mainly based on suggested range of values for each soil type in the watershed. Shiravand (2004) calculated the Golestan dam basin's probable maximum flood by applying probable maximum precipitation with the help of synoptic analysis of the severe storm occurred in the catchment area. Rakhecha and Clark (2002) studied the probable maximum flood at the Ukai dam (Tapi River) and Lakhwar dam (Yamuna River) sites by using methods of estimation of probable maximum precipitation (PMP), Unit hydrograph (UH) and rational method. Since, several incidence of catastrophic dam failure have taken place in India, it is necessary to robust estimates of probable maximum flood (PMP) more acute (Rakhecha and Mandal, 1983; CBIP, 1993).

2.2.2 Probabilistic techniques: This approach mainly related with the probability of the occurrence of the flood events. Fuller (1914) introduced concept of magnitude-frequency and first empirical equation for frequency analysis of maximum daily discharge. The estimated discharges by using Fuller formulas show higher magnitudes ratio as compared to observed quantities (Fill and Steiner, 2003). Nevertheless, flood events are assumed to follow some type probability distribution (Ward, 1978). The most commonly used probability distributions are Gumbel extreme value type I (GEVI), Log Pearson type III (LP-III), Lognormal and Gamma. Foster (1924) and Gumbel (1941) introduced the Log Pearson type III (LP-III) and Extreme value type I (EVI) probability distributions for describing the flood data. The United State Water Resources Council (USWRC) in 1967 has recommended Log Pearson type III (LP-III) probability distribution and the Institute of Engineers Australia (1987) also recommended that LP-III distribution is best fit to annual peak discharge data by using mean, standard deviation and coefficient of skewness of the logarithms of flow data (Pilgrim, 1987; Kottegoda and Rosso, 1997; Koutrouvelis and Canavos, 2000). Accordingly, Srikanthan and McMahon (1981) and McMahon and Srikanthan (1981) examined the applicability of LP-III distribution to Australian rivers. Flood frequency analysis at site can be studied by flood frequency curves concerning either discharge, stage or volume parameters (Dalrymple, 1960).

The main objective of magnitude frequency analysis is fitting together magnitude of extreme events and their frequency of occurrence by applying probability distributions (Chow et al., 1988). Several studies on the flood frequency analysis by applying various probability distributions have been made in last four to five decades in India. Sakthivadivel and Raghupathy (1978), Goswami (1988), Garde and Kothyari (1990), Hire (2000), Patil (2017), Hire and Patil (2018) and Pandey et al., (2018) have stated that Gumbel Extreme Value type I (GEVI) and Log Pearson type III (LP-III) probability distributions are more suitable for the annual maximum series (AMS) data of the Indian rivers.

Hydrologists have often applied regional flood frequency analysis (RFFA) technique in situations either long series flood data are not available or ungauged drainage basin for the prediction of magnitude of flood and return period (Ward, 1978; Singh, 1987). The regional flood frequency analysis (RFFA) method considers extreme events at various sites in a region which may have analogous statistical characteristics (Cunnane, 1989). In the view of superiority of regional flood frequency analysis (RFFA) over flood frequency analysis (Enzel et al., 1993) and usefulness for ungauged watershed, RFFA has been widely used in India (Garde, 1998). The concept of L-moment for regional frequency analysis was introduced by Hosking (1990). Accordingly, Kumar and Chatterjee (2005) used L-moments for regional flood frequency studies of the north Brahmaputra region of

India. The reliability of flood estimates has been questioned by several workers (Linsley, 1986; Baker, 1994) due to the fact that predications are based on unverified suppositions and predications are also not verifiable and untestable.

2.2.3 Empirical techniques: The empirical approach assumed that the maximum discharge per unit catchment area in one basin is to be expected in adjacent basin which has analogous hydroclimatic controls (Mutreja, 1986). The unavailability of continuous and long series flood data affects the accuracy of flood prediction. Therefore, several empirical techniques have been suggested by Ward (1978), Enzel et al., (1993) and Baker, (1994). Flood envelope curve is one of the alternative techniques which show the empirical relationship between the maximum peak discharge and catchment area or region. Jarvis (1925) was an inventor of envelope curve, he framing the maximum flood envelope curve from the examination of 888 fluviometric stations in the United States. An envelope curves have often played a significant role in the prediction of floods (Creager, 1939; Crippen and Bue, 1977; Georgiadi, 1979; Crippen, 1982; Wolman and Costa, 1984; Dooge, 1986). In view of Enzel et al. (1993) regional envelope curves demarcate upper limit to flood magnitude in a specified hydroclimatic region. Therefore, regional envelope curves are more useful and reliable to estimate maximum possible magnitude of floods for different sizes of drainage basin area (Ward, 1978).

Several attempts have been made to develop envelope curves for various regions in different regions of the world. Some of the prominent examples comprises envelope curve developed for United States by Matthai (1969), Crippen (1982) and Costa (1987) and for World Rivers by Baker (1995). An envelope curve for different river basins in Turkey has been developed by Bayazit and Onoz (2004). Likewise, Marcellini et al. (2015) applied flood series record of the principle hydrographic basins in Brazil to estimate the curves developed by Creager et al. (1945). According to Mimikou (1984), estimated discharges with the help of envelope curve for ungauged basin can be used in hydraulic designs. Ahsan et al. (2016) used the envelope curves for the Indus and Jhelum rivers, in Pakistan. Kanwar Sain & Karpov have determined the two enveloping curves for the rivers of Southern India and Rivers of the Central and Northern India respectively in 1967 (CWC, 1983). Hire (2000) specified that rivers of the Deccan such as the Tapi River produce comparatively smaller flood peak discharges than some of the drainage basins with comparable basin areas in the other parts of the world. However, Patil (2017) compared the Par Basin envelope curve with the world envelope curve (Baker, 1995) and quantified that Par Basin has produced maximum discharges than other world basins of comparable basin areas.

Now a days, historical and Palaeoflood data for magnitude frequency analysis have been strongly advocated as a means of extending the available short term data for improving the accuracy in flood estimation (Costa, 1978; Hosking and Wallis, 1986c; Frances et al., 1994; Baker, 1994). Flood hydrologists have applied several techniques other than mentioned above such as hydrograph analysis, time series analysis, flood frequency magnitude index (FFMI), flow duration curve (FDC) in order to understand the characteristics of the floods. Time series analysis based on daily, monthly and annual maximum series provides best understanding about temporal variations, flood magnitude and frequency. In addition, FFMI values (Beard, 1975) illustrates the flashiness of the flood. Moreover, plotting of the flow duration curve (FDC) is useful in determining availability and variability of sustained flows (Viessman et al., 1989).

2.3 Studies in Flood Geomorphology

In recent times, flood geomorphology has developed as a main sub-discipline of fluvial geomorphology. Flood geomorphology can be defined as “the study of the role of floods in shaping the landscape, including the analysis of flood causes, flood processes, resistance factor to flood induced landscape change, and change in flood related processes and forms through time” (Baker et al., 1988). Flood geomorphology principally concerned with the geomorphic effectiveness of floods. Wolman and Gerson (1978) have discussed the concept of geomorphic effectiveness. Further, Wolman and Leopold, (1957) specified that bankfull discharges which have mean return period of one or two years are certainly the "effective" discharges. Wolman and Miller (1960) stated that maximum geomorphic work is accomplished by moderate floods than infrequent catastrophic flood events. In contradictory, while discussing about the bedrock channel, Baker (1988), Wohl (1992b), Baker and Kale (1998) and Patil (2017) have mentioned that only infrequent, high magnitude floods contribute to shaping the morphology of the bedrock river. Therefore, the crucial question is whether infrequent, high magnitude flood events are more significant than the regular floods.

Geomorphic effectiveness is the ability of flood to shape the landscape (Wolman and Gerson, 1978). The efficiency of flood is evaluated through the magnitude and frequency of flows and the quantity of suspended sediment they transport (Wolman and Miller, 1960). Several researchers have suggested that geomorphic effectiveness is not related to magnitude and frequency of flood, but linked with shear stress and stream power per unit boundary area corresponding to the available resistance (Baker and Costa, 1987; Wohl, 1993; Baker and Kale, 1998; Hire, 2000; Kale and Hire, 2004; Hire and Kale, 2006; Kale and Hire, 2007; Patil, 2017). Rhoads (1987) defined "stream power as a measure of geomorphic effectiveness of flood, as it quantifies river energy, dissipation in alluvial system". In view of Knighton (1984), Stream power could be a better indicator of steam energy than discharge alone.

Schumm (1977) quantified significant variation in the geomorphic response of stream channels to flood, while studying bedload transport during floods. Furthermore, flood magnitude, sediment load, valley gradient and composition of stream bank and bed are the determinants of the channel morphology (Leopold and Maddock, 1953; Leopold et al., 1964). Therefore, while studying the fluvial and flood processes and its influence on the river, a basic difference has been made between alluvial rivers and bedrock rivers with more resistant channel boundaries (Baker, 1998). Numerous studies in the past have suggested that channel of the alluvial river readily modify to moderate magnitude floods, but shape and morphology of the bedrock channels are only transformed during the infrequent and high magnitude floods (Baker, 1988; Wohl, 1992b; Baker and Kale, 1998). Although lithology is a critical factor, the effects of flood depend on the hydraulic characteristics of flood flows.

Several studies have been determined empirically differences in the hydraulic variables during floods, beginning with the research on hydraulic geometry (Leopold et al., 1964).
Leopold and Maddock (1953) expressed the hydraulic geometry relationships in the form of power functions of discharge. However, depth and velocity are the function of bed roughness and the rate of change in roughness in not uniform, the power function model

will not show the precise nature of hydraulic (Richards, 1973, 1976). Knighton (1974, 1975, 1977a) examined at a station and downstream variations in width-discharge and its implication for hydraulic geometry. Leopold and Wolman (1957) and Knighton (1972) explored modifications in a reach morphology and hydraulic geometry. Leopold and Maddock (1953) have revealed that large magnitude floods that transport enormous quantities of sediment have almost constant downstream velocity. In bedrock channels maximum change in the velocity and flow depth are associated with large floods (Baker and Kale, 1998). Rhodes (1977, 1987) has used the exponents of the hydraulic geometry equation to classify river cross sections relating to hydrologic and morphologic responses to variations in discharge.

The unit stream power and shear stress exerted by large floods play significant role in producing major changes in the river channel and movement of cobbles and boulders (Baker and Costa, 1987). According to Govers (1990) shear stress could be used to calculate sediment transport capacity under erodible conditions. However, Abraham et al. (2001) and Zhang et al. (2009) have suggested that sediment transport capacity can be effectively predicted by shear stress under non-erodible conditions. In view of Govers and Rauws (1986), unit stream power could sufficiently predict sediment transport capacity. Bagnold (1977, 1980) has defined concept of specific stream power (ω) which has been applied by several researchers (e.g. Costa, 1983; Williams, 1983; Hassan et al., 1992; Gintz et al., 1996; Petit et al., 2005) as a simple indicator of river dynamics. Gintz et al. (1996) also revealed that hydraulic jumps and supercritical flow, produced by steps or large particles, increase the bed roughness and thereby decrease in the efficacy and degree of sediment transport. Wohl (2000) also brought out the same conclusion that as the river depth increases and as the part of the contact layer in the whole water column decreases, the grain resistance tends to be weaker.

Since, there is not a unique threshold of sediment transport, critical threshold is considered as the minimum limit from which motion of a particle of a given size could occur (Williams, 1983). However, thresholds for bedload transportation significantly differ from river to river because of variations in channel gradient, bed material and magnitude of discharge (Lamb et al., 2008). The transportation of bedload is not possible to measure directly during large floods. Therefore, estimation of the transportation of coarse sediment mostly depends on theoretical and empirical equations (Komar, 1988). The equations developed by Williams (1983) and Costa (1983) are widely used in boulder transport calculations. Baker and Kochel (1988) have recognized geomorphic effects of floods with different magnitude and recurrence time in terms of channel erosion and sediment transport. Several instigations have mainly concentrated on flood induced modifications in stream channel morphologic features and erosional as well as depositional properties (Leopold et al., 1964; Gupta and Fox, 1974; Pickup and Warner, 1976; Goswami, 1985; Kochel, 1988; Wohl, 1992a and b; Kale et al., 1994; Gupta, 1995a; Baker and Kale, 1998).

One of the foremost outcomes of these investigations is that significant variations in the effects of floods in the allied hydro-geomorphic environment (Kochel, 1988; Miller, 1990). Wolman and Miller (1960) have validated the overwhelming importance of low magnitude floods occurring frequently, research in arid regions and seasonal tropics suggest that extreme floods are geomorphologically more effective (Baker, 1977; Patton and Baker, 1977; Wolman and Gerson, 1978; Wohl, 1992b; Kale et al., 1994; Gupta, 1995a; Hire, 2000). However, duration and sequence of flood events (Wolman and Gerson, 1978; Kochel, 1988), hydraulic characteristics of floods (Costa and O'Connor, 1995), the availability of sediments (Magilligan et al., 1998) and role of river basin and channel (Kochel, 1988) are important factors producing geomorphologically effective flows.

2.3.1 Flood Geomorphology studies in India

The Indian rivers are monsoon dominated. As a result, most of the geomorphic work has been completed by the rivers during the monsoon season (June-October). Therefore, the rivers show all usual characteristics of the seasonal rivers in terms of streamflow, sediment transport and channel morphology (Kale, 2005). Numerous studies have signified the dominant role of seasonality of the flows and occurrence of large magnitude floods in the channel form and processes (Goswami, 1985; Gupta, 1995a; Kale et al., 1997a; Gupta et al., 1999; Hire, 2000). The geomorphic effects of floods are most remarkable in the Himalaya, the Thar Desert, and the Indus-Ganga-Brahmaputra Plains.

Several examples of flood induced modification in the channel dimensions, position and patterns are observed in these areas (Kale, 2003).

Several investigations of the hydrologic and geomorphic characteristics of the Himalayan and Peninsular rivers have shown that there are significant variations between two river systems in terms of streamflow, sediment transport and channel morphology (Kale, 2005). Coleman (1969) identified the continuous alteration of thalweg of the Brahmaputra River from one place to another within the bank lines of the river. In relation to this, Phukan et al. (2010) stated that the complex flow pattern of Brahmaputra River results in erosion and shifting of thalweg. Besides, Goswami (1985) have studied the sediment characteristics of the Brahmaputra River and quantified that the finer sediments denote vertical accretion from overbank flows and the coarser sediments likely to signify channel bars and islands accreted laterally through meandering of the channel. Further, Goswami (1998) also have specified that flash floods are most common in case of the north bank tributaries of the Brahmaputra River due to shallow, braided channels with steep gradient which carry heavy silt.

As compared to Brahmaputra Basin, flood geomorphologic studies of Ganga River are very limited. However, Singh (1996) have studied the sedimentation and solution load of the Ganga River. In addition to this, Chakrapani and Saini (2009) also have discussed spatio-temporal variations in discharge and sediment load in the Alaknanda River and Bhagirathi River by considering influence of monsoon, location and human impact in the catchment region. However, several researchers have discussed about the immensely dynamic channel of the Kosi River and its flood frequency (Gole and Chitale, 1966; Wells and Dorr, 1987; Sinha and Jain, 1998; Chakraborty et al., 2010). Recent studies also have been emphasized that the problem of the Kosi River channel instability and flooding have been intensified in recent years (Dixit, 2009; Sinha, 2009 a, b; Sinha et al., 2013, 2014). The volume change in the Kosi River bed is associated with the aggradation process as described in flood memorandums on floods in the Bihar (Agrawal and Narain, 1996). Moreover, Basu et al. (1996) stated that significant modifications in the Hugli River channel have occurred during 1973–1993.

Sinha and Friend (1994) discussed about the drainage systems of the northern Bihar and sediment flux. Besides, Jain and Sinha (2004) stated that anabranching reaches of the Baghmati River are characterized by gentle channel slope, medium to high sinuosity, low form ratio and frequent overbank flooding with variable peak discharge and sediment load. According to Kale (1998), the mountain-fed rivers emerging onto the plains experience a rapid downstream decrease in unit stream power and shear stress and hence are highly unstable. Several case studies of the Indian rivers specifies that widening of channel, erosion of bars, deposition of coarse gravel within channel and floodplain, scouring of floodplain are the most commonly observed effects of floods (Gupta, 1988). However, the response of alluvial channels and the bedrock channels significantly vary to comparable flood magnitudes. As compare to the Himalayan Rivers, the rivers of Indian peninsula are generally incised in rock or alluvium and have stable channels and changes in the channel position in reaction to floods are exceptional (Kale, 2003).

The Multi-date channel cross section studies of the Tapi River and some other rivers of Deccan Trap region indicate notable modifications in the channel bed forms, but minimal changes in the total channel morphology (Deodhar and Kale, 1999; Hire, 2000). The Narmada River is predominantly flood controlled river (Rajaguru et al., 1995) and stream flow effects are reflected in sediment transportation but not in channel form. The Narmada River flows through bedrock and alluvial reaches. Therefore, the erosion, sediment transport and channel maintenance operate differently between bedrock and alluvial reach (Gupta et al., 1999). The quantifiable changes did not observe in the Narmada River channel near Jabalpur after large flood of 1991 (Rajaguru et al., 1995). Likewise, Mujumdar et al. (1970) also have observed that the geomorphological impact of flood of 1969 on the Godavari River also did not show remarkable changes in the river channel morphology in spite of high velocity, hydraulic radius and stream power per unit area.

Most of the research work on flood geomorphology in India mainly focused on rivers whose drainage basin located in humid seasonal tropics except the Luni River. Monsoon rainfall in the Thar Desert is very less and erratic. As a result, ephemeral drainage system experienced catastrophic floods due to heavy to very heavy rainfall associated with low pressure systems. For example, In July 1979, the Luni River catastrophically flooded due to heavy rainfall. This catastrophic flood caused significant changes in the channel morphology. The channel width increased from the pre flood 40-700m to 500-1360m after the floods (Dhir et al., 1982; Sharma et al., 1982). The Luni River is known to transport large amount of sediment during high flows. According to Dhir et al. (1982) in July 1979 flood, flood water spread upto a distance of 3 km on either side of the Luni River at Sindari.

2.4 Studies in Flood Hydrometeorology

Floods are result of meteorological circumstances and events that produced heavy to very heavy precipitation to a drainage basin than that can be readily stored or absorbed in the basin (Hirschboeck, 1991). Therefore, analysis and investigation of flood producing meteorological conditions have great significance in the field of flood and fluvial geomorphology, flood hydrology and flood hydrometeorology. Hayden (1988) prepared a map of flood climate regions of the world and classified atmosphere as baroclinic and barotropic. According to him, baroclinic atmosphere is associated with weather phenomena and modest rainfall at higher and middle latitudes. Whereas, barotropic atmosphere is associated with meteorological events of low latitude region of tropics which produce heavy to very heavy rainfall. In view of Gupta (1988), tropical cyclones, monsoon system winds and easterly waves are the foremost flood generating phenomena in the barotropic atmosphere which produces heavy to very heavy rainfall associated with high magnitude floods in humid and seasonal tropics. Baker (1977) and Wolman and Gerson (1978) stated that high rainfall variability has greater potential to produce large magnitude floods in the arid and semi-arid tropics.

Several researchers have studied meteorological conditions responsible for generating floods in the monsoon dominated rivers of India. Prominent among them are Parthsarathy (1955), Bose (1958), Dhar (1959), Dhar and Changrani (1966), Jagannathan (1970) and Dhar et al. (1975, 1980, 1981d, 1986, 1990, 1991, 1992, 1993 and 1994). Ramaswamy (1987) has prepared a comprehensive monograph of meteorological aspects of severe floods in India during the period 1923 to 1979. Likewise, Abbi and Jain (1971) and Ramaswamy (1987), have mentioned that most of the floods were produced by the heavy to very heavy rainfall associated with the one or combination of several synoptic systems. These systems are;

i. Tropical disturbances (monsoon depressions and cyclonic storms) passing through the country from either Bay of Bengal or Arabian Sea,
ii. Track of low pressure system LPS(s) or monsoon lows,
iii. Breaks in the monsoon generally during months of July and August,
iv. Active monsoon conditions for several days over a region and off-shore vortices along the west coast,
v. Mid-latitude westerly system moving from west to east,
vi. Mid-tropospheric cyclonic circulations over western region of the India.

During the period of southwest monsoon season, tropical disturbances ranging from lows to cyclones formed over the Bay of Bengal and the Arabian Sea produce widespread, heavy rainfall and severe floods in Indian rivers (Gupta, 1988; Gupta, 1995a; Rakhecha, 2002; Hire, 2000; Gunjal, 2016; Patil, 2017). More or less 80-90% of the annual rain over most parts of the country falls during the summer monsoon rainfall season i.e. June to September.

The weather system and rainfall variability over the India have always been the central theme of monsoon research. Parthasarathy et al. (1994) have discussed inter annual variability of Indian Summer Monsoon Rainfall (ISMR) by using data of 306 rain gauge stations well distributed in India. Furthermore, long term variability in monsoon rainfall is very well understood by Normalized Accumulated Departure from Mean (NADM). NADM is one of the effective and frequently applied quantitative methods and can be resolved successive properties contained by long term data (Riehl et al., 1979; Mooley and Parthasarathy, 1984; Probst and Tardy, 1987; Kale, 1999b). Normally, at decadal scale ISMR shows epochal nature alternating 30 year of dry and wet monsoons. In addition, Joseph (1976, 1978) stated that tropical cyclones of the Bay of Bengal (westward and northwestward movement) and equatorward invasion of the mid-latitude westerly winds of the upper troposphere over south Asia had a significant role in the epochal behavior of the monsoon. Nevertheless, floods are not randomly distributed but there is a propensity for periods of high and low floods to match with periods of high and low rainfall (Burn and Arnell, 1993; Chiew and McMohan, 1993; Kale, 1999b).

Since, El Niño Southern Oscillation (ENSO) phenomenon is the foremost feature of inter-annual variability in the monsoon rainfall and associated floods (Philander, 1990). The ENSO is the large scale oceans atmospheric circulation in the equatorial Pacific (Chiew and McMahan, 2002). The teleconnection between ENSO and Indian monsoon was well recognized by using observational data and general circulation models (Walker, 1924; Khandekar, 1979; Sikka, 1980; Rasmusson and Carpenter, 1983; Shukla and Paolino, 1983; Ropelewski and Halpert, 1987; Kane, 1989; Simpson et al., 1993; Fennessy et al., 1994; Ju and Slingo, 1995; Webster and Yang, 1992; Khole, 2004; Lutgens and Tarbuck, 2007; Ihara et al., 2007). Normally, La Niña associated with flood conditions and El Niño is typically associated with drought conditions in the Indian monsoon region (Krishnan and Sugi, 2003; Saha et al., 2007). According to Kripalani et al. (2003), Panda and Kumar (2014), Panda et al. (2014), Dwivedi et al. (2015), the warm phase (El Niño) is linked with decreasing Indian monsoon rainfall and the length of rainy season, while the cold phase (La Niña) is associated with increasing of the Indian monsoon rainfall and number of rainy days.

Several researchers have studied seasonal and annual rainfall trends and associated floods by employing non-parametric test of Mann-Kendall (e.g. Hollander and Wolfe, 1973; Probst and Tardy, 1987; Chiew and McMahon, 1993; Marengo, 1995; Kale, 1998; Hire, 2000; Douglas et al., 2000; Yue et al., 2003; Burn et al., 2004; Singh et al., 2008a,b). According to investigation by Singh et al. (2005), rainfall over the Indus, Brahmaputra, Ganga, Cauvery and Krishna Basins is increasing and decreasing over Narmada, Tapi, Mahi, Sabarmati, Godavari and Mahanadi Basins. In addition, Jena et al. (2014) examined fluctuations in the heavy rainfall and associated floods over Mahanadi Basin and proposed that there is an increase in extreme rainfall and high floods in the middle reaches of the basin. Therefore, the most important question is whether the future is likely to see the condition of Indian summer monsoon rainfall decreased, unchanged or exacerbated. Although the nature of monsoon is very complex to predict the trend and magnitude of change, it is possible to estimate the percentage change essential in the future data series before it can be considered to be statistically significant (Kale, 1998).

Chiew and McMohan (1993) and Marengo (1995) have been applied Student's t-test to find out the percentage change necessary in the mean of the future rainfall data series before it can be considered to be significantly different from the historical gauge record.

2.5 Studies in Palaeoflood Hydrology

According to Baker (2008), Paleohydrology is the study of past occurrences, distributions, and movements of continental waters. The term Palaeohydrology was first used in relation to ancient hydrologic circumstances associated with the formation of suite of river terraces in Wyoming (Leopold and Miller, 1954). Palaeoflood hydrology studies consist of three approaches such as the regime based palaeoflow estimates, palaeocompetence studies and palaeostage estimates (Baker, 1996). The regime based palaeoflow estimates attempt to show a relationship of mean annual flow and bankfull discharges with palaeochannel gradient, sediment types and palaeochannel dimensions Baker (1991). In view of Kochel and Baker (1982), the thickness and grain size of the slack water deposit (SWD) sediment is directly proportional to the magnitude of flood at mouths of tributary i.e. thicker and/or coarser units denote larger floods with higher streamflow velocities.

Palaeoflood hydrology is the reform of the magnitude and frequency of large floods using geological evidence (Baker et al., 2002) such as flood deposits, silt line and scour line along a river channel, valley walls and terraces. The ideal sites for the deposition and preservation of palaeoflood SWD are tributary mouths, channel margin alcoves, caves and rock shelter (Kochel and Baker, 1982; Baker, 1987; Benito et al., 2003b). Several researchers have applied different methods and techniques of estimating peak flows based on palaeostage indicators in different regions of the USA, Israel, Australia, Europe (Baker et al., 1983a; Pickup et al., 1988; Jarret, 1991; Enzel, 1992, Ely et al., 1993; Woodward et al., 2001; Benito, 2003a; Benito et al., 2003b; Sheffer et al., 2003; Thorndycraft et al., 2003; Ortega and Garzn, 2003). Costa (1978), Baker et al. (1979), and Costa and Baker (1981) have applied paleoflood data for flood frequency analysis.

The magnitudes of the palaeoflood are obtained by linking the levels of palaeostage indicator with water surface profiles produced by step-backwater computer program (O'Connor and Webb, 1988). Slackwater deposits (SWD) are coarse grained sediments that are transported in suspension during extremely energetic flood flows and deposited in areas of flow separation that result in long-term preservation after the flood recession (Baker et al., 1983a). A Palaeocompetence study involves empirically based sediment transport hydraulics in order to reconstruct shear stress, stream power, velocity which is essential for sediment transport (Jarrett, 1991). Several equations have been developed by William (1983) and Costa (1983) to estimate threshold values of stream power, bed shear stress and critical velocity required for transport of boulders.

Indian peninsular rivers flow through bedrock gorges, providing excellent locations for the deposition and preservation of palaeoflood slackwater deposits. According to Kale et al. (1994), most of slackwater deposits indicate multiple units of flood sediment, demarcated by abrupt change in texture, colour and composition. However, the ages of the SWD are determined by radiocarbon dating or optically simulated luminescence (OSL) dating. Palaeoflood sites in monsoon dominated rivers of India have been explored by several geomorphologists and hydrologist (e.g. Baker, 1998; Kale et al., 1994; Ely et al., 1996; Kale et al., 1996; Kale et al., 1997b). Numerous SWD and palaeostage indicator (PSI) sites have been identified in the river basins of the Narmada, Tapi, Luni, Mahi, Godavari, Krishna and Kaveri. Palaeoflood records of the large magnitude floods for the period of early to middle Holocene have been reported from some of the monsoon dominated rivers of India, such as the lower Ganga (Goodbred and Kuehl, 2000), the Narmada and Tapi (Kale et al., 2003) and lower Mahi River (Sridhar, 2007a).

The investigation of palaeoflood in the Narmada reveals oldest record of catastrophic floods before the Last Glacial Maximum (Rajaguru et al., 1995). The floods of late Holocene have been recognized along the main river at Punasa (Kale et al., 1994, Ely et al., 1996) and Sakarghat (Kale et al., 1997b). Palaeoflood investigations in the east flowing Godavari River and Krishna River have discovered evidence of multiple floods during the last two millennia. Furthermore, Sridhar, (2007b) have been attempted to quantify palaeo-discharge and changes in the hydrologic regime of the Mahi River through the mid-late Holocene.

Chapter 3

Research Methodology

3.1 Introduction

Generally, Research methodology is the systematic and theoretical analysis of the methods which are applied in the field of research to solve the research problem. According to Myers (2009), the research method is a strategy of enquiry, which starts from the basic assumptions to research design and data collection. Therefore, detailed account of different research methods used in the present work has been discussed in the following section.

3.2 Flood Hydrology

3.2.1 Hydrological data

Flood is the most outstanding aspect of monsoonal rivers (Kale, 1998). Similar to the other monsoonal rivers of India, Mahi River also shows remarkable variations in flood frequency and magnitude. Thus, it is essential to understand fluvial and flood regime characteristics of the Mahi River and its major tributaries (Figure 3.1). Therefore, daily discharge data (26 to 39 years) for six discharge gauging sites and annual maximum series (AMS) data (26 to 51 years) for seven discharge gauging sites on the Mahi River and its tributary were collected from Central Water Commission (CWC), Gandhinagar (Figure 3.1). In addition, AMS data from 1959 to 2009 (51 years) for Wanakbori site on the Mahi River also have been obtained from CWC (Figure3.1).

3.2.2 Methodology for flood hydrology analysis

(I) Fluvial regime and flow characteristics

The fluvial regime and flow characteristics of the Mahi River and its tributaries have been obtained by analyzing daily and mean monthly discharge data. Since, there are extreme variations in the daily discharges of the Mahi River and its tributaries. Average monthly flows, mean annual flows, mean monsoon flows, percentage of monsoon flows and non-monsoon flows have been calculated to understand average flow characteristics of the Mahi River and its tributaries. Besides, the mean flow characteristic has been shown by mean annual hydrograph. In order to acquire better information about daily variations in the discharges of the Mahi River and its tributaries, the daily streamflow data from June 2006 to May 2006 have been represented by hydrograph.

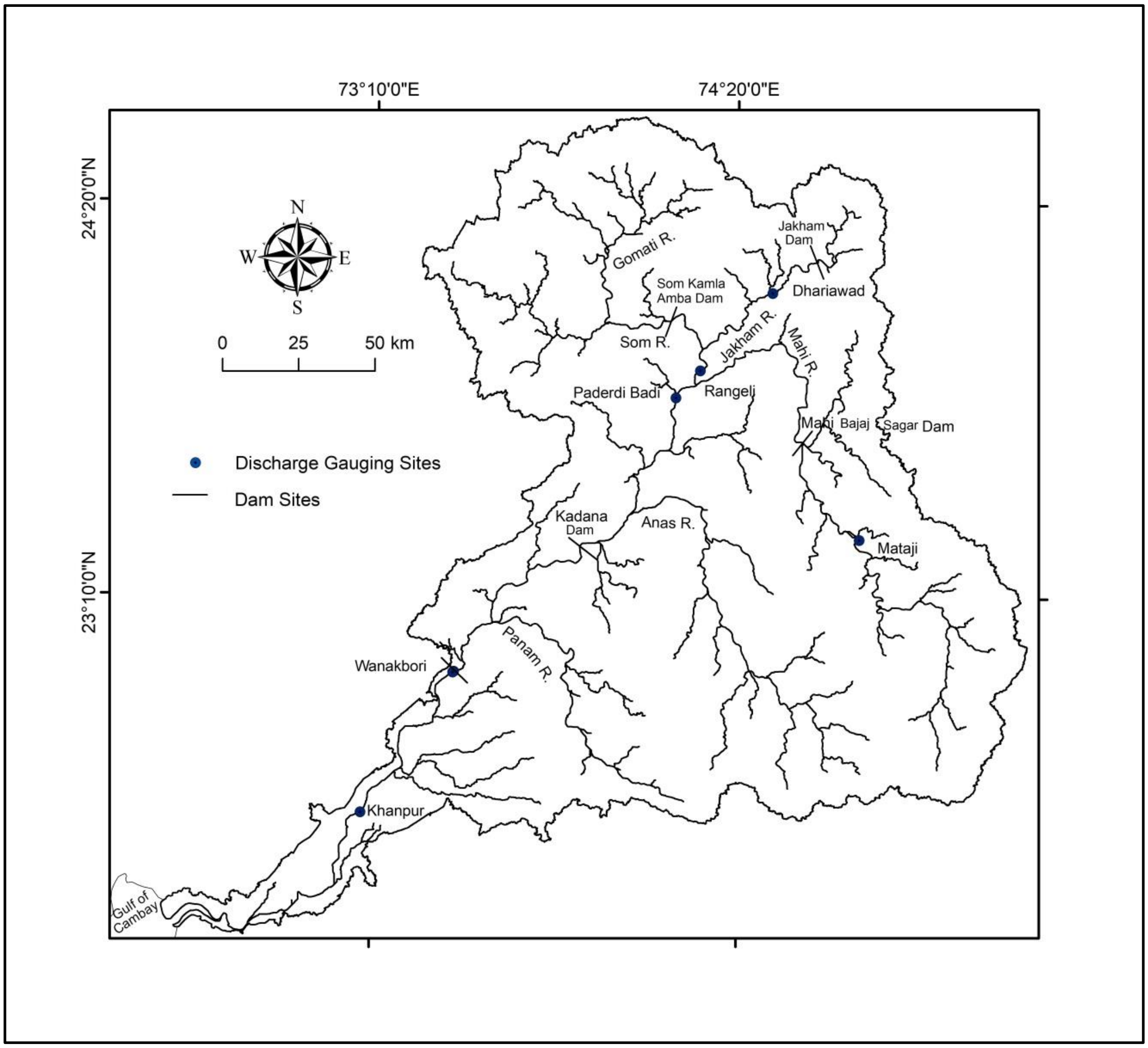


Figure 3.1: Discharge gauging sites on the Mahi River and its tributaries

(II) Flood regime characteristics

Flood regime characteristics can be well understood with the help of AMS data. Therefore, some of the basic quantitative methods such as mean, standard deviation, coefficient of variation, coefficient of skewness and Qmax/Qm ratio (ratio between highest annual peak flood discharge on record during the gauge period (Qmax) and mean annual peak discharge (Qm)) have been applied to AMS data to understand the average magnitude and variability in the peak discharges. In addition, AMS and deviation from mean annual peaks have been shown graphically for all sites of the Mahi River and its tributaries to highlight temporal variation in the annual peak discharges.

Several researchers have evaluated variability of peak floods by using the Beard's (1975) flash flood magnitude index (FFMI). Accordingly, FFMI values are calculated from the standard deviation of logarithms of AMS as given below;

$$\mathrm{FFMI} = \sqrt{\frac{\sum X^2}{N-1}} \qquad \text{......Equation 3.1}$$

where, X = Xm – Qm; Xm = annual maximum event; Qm = mean annual peak discharge; N = number of years of record (X, Xm, and Qm expressed as logarithms to the base of 10)

Since, the AMS data are not normally distributed. Therefore, it is required to find the skewness of the data. Accordingly, the coefficient of skewness (Cs) has been calculated. Besides, unit discharges have been calculated for each site as well as for the Mahi Basin by relating peak discharge (Qmax) and the upstream catchment area (A).

(III) Flood frequency analysis

Flood frequency analysis is most frequently used technique by the hydrologist, geomorphologists and hydraulic engineers. However, availability of the longest flood series data along with the historic pre-instrumental records are required for the higher accuracy in the estimation of discharges for various return periods (Cunnane 1989; Gaal et al., 2010 and Elleder et al., 2013). Although, there are several magnitude frequency probability distribution models such as the generalized extreme value, Gumbel extreme value type 1 (GEVI), Log-Normal and the Log Pearson type III (LP-III) distribution to compute the magnitude and return period of the flood, none of them received complete recognition and unambiguous for a country (Law and Tasker, 2003). Nevertheless, one of the most commonly used probability distributions for Indian rivers namely Gumbel Extreme Value type I (GEVI) is applied to AMS data of the selected sites to estimate flows for a desired recurrence interval such as 2, 5, 10, 25, 50, and 100 years by using the following equation (Shaw, 1988).

$$Q_T = Qm + [K(T) * \sigma Q]$$ ......Equation 3.2

where, Q_T = discharge of required return period; Qm = mean annual peak discharge; σQ = standard deviation of AMS; K(T) = frequency factor and is the function of the return period T. However, K (T) values were obtained from book entitled “Hydrology in Practice” by Shaw (1998).

The recurrence interval of mean annual peak discharge (Qm), large flood (Qlf) and actually observed maximum annual peak discharge during gauge period (Qmax) at each site have been estimated by applying the following equation (Shaw, 1988).

$$\frac{1}{T} = 1 - F(X) = 1 - \exp[-e^{-b(X-a)}]$$ ......Equation 3.3

where, T = recurrence interval for a given discharge; F(X) = probability of an annual maximum $Q \leq X$; a and b are two parameters related to the moments of population of Q values. The parameters a and b were determined by the following equations.

$$a = Qm - \frac{\gamma}{b} \quad (\gamma = 0.5772)$$ ......Equation 3.4

$$b = \frac{\pi}{\sigma Q \sqrt{6}}$$ ......Equation 3.5

where, Qm = mean annual peak discharge; σQ = standard deviation of annual peak discharge.

The observed annual peak discharges have been plotted against the return period or F(X) values (plotting positions) on the Gumbel graph paper, designed for EVI probability distribution. Several formulae have been used to calculate plotting positions. However, Cunnane (1978) and Shaw (1988) suggested that Gringorten (1963) formula is the best because the outliers fall into line better than other plotting positions. Accordingly, the F(X) values have been calculated by using Gringorten formula as follows;

$$P(X) = 1 - F(X) = \frac{r - 0.44}{N + 0.12}$$ ......Equation 3.6

where, r = flood magnitude rank; N = number of years of record.

(IV) Discharge-area envelope curve

The envelope curve for the Mahi Basin has been prepared with the help of annual maximum peak discharge (Qmax) and drainage area (A) either available at gauging sites or estimated based on field surveys. The maximum peak discharge data have been made available for seven sites in the Mahi Basin. Further, for comparative analysis, envelope curve of the Mahi Basin has been plotted on the same figure of world envelope curve prepared by Baker (1995).

(V) Flood hydrographs

A flood hydrograph shows discharge with respect to time. However, the intensity and duration of rainfall, size, shape and orientation of drainage basin and channel network, slope, antecedent moisture and type of landuse determine the shape of the flood hydrograph (Petts and Foster, 1985; Patton, 1988). In order to understand flood characteristic of the Mahi River, daily discharge data have been used for flood hydrograph due to lack of hourly discharge data. Nevertheless, the slope of the rising limb depends on the duration and intensity of rainfall, and the antecedent soil moisture conditions. The crest segment of a flood hydrographs denotes peak discharge from a drainage basin for that event.

3.3 Flood Geomorphology

3.3.1 Geomorphological data

The data regarding nineteen the cross sectional sites were obtained with reference to HFL at a station from field surveys and Central Water Commission (CWC), Gandhinagar (Figure 3.2). However, data about channel slope (S), channel length (L), and catchment area (A) for the sites were obtained from toposheets, CWC and field surveys. Besides, AMS and hydraulic parameters data for at-a-station hydraulic geometry analysis were obtained for the sites from CWC, Gandhinagar.

Geomorphic effectiveness of the floods is also measured in terms of sediment transport. Therefore, suspended sediment data for the Mahi River were obtained from CWC, Gandhinagar. Besides, during field surveys, dimensions of the largest boulders were measured. In order to get an idea about geomorphic effects of floods on river channel, multi-date cross sectional data have been obtained from Central Water Commission, Gandhinagar. Moreover, during field survey data about flood years with HFL and major damages to hydraulic structures were collected to understand the effect of specific flood events in the modern times.

3.3.2 Methodology for flood geomorphology analysis

(I) Channel morphology

The channel morphological dimension (channel width, channel depth, cross sectional area, width-depth ratio, hydraulic radius and wetted perimeter) varies throughout the course of river at different reaches (Morisawa, 1985). Therefore, to identify channel morphological properties of the Mahi River and its major tributaries such as the Anas, the Panam, the Som and the Jakham, cross sectional surveys have been conducted.

Further, channel morphological variables have been used to define the channel morphology of the Mahi River and its tributaries in terms of shape, size and efficiency (Petts and Foster, 1985). Further, the cross sectional data of the Mahi River and its tributaries have been analysed by applying these variables. Nevertheless, channel cross section parameters have been derived relating to maximum annual peak discharge (Qmax) observed at each cross section.

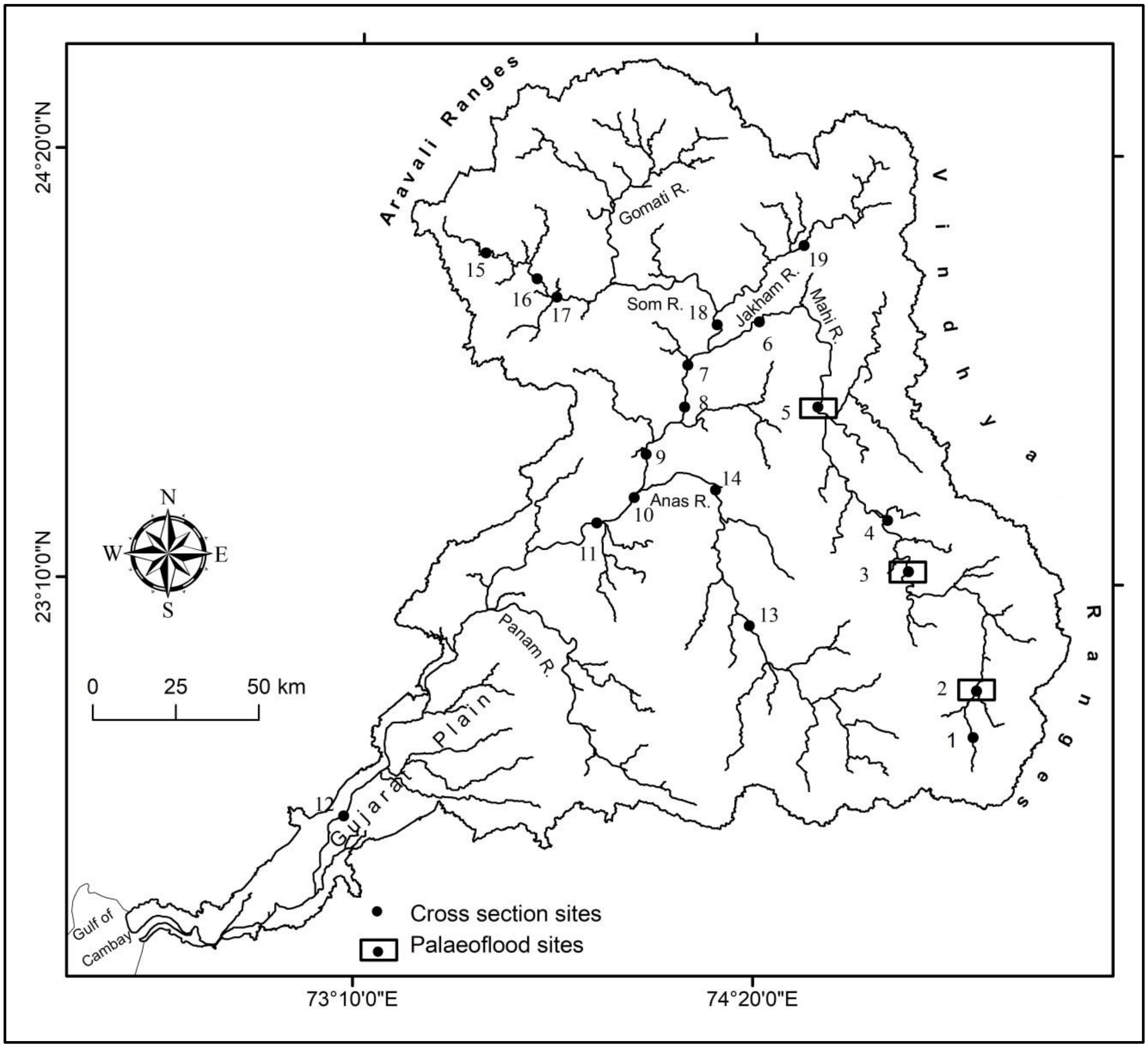


Figure 3.2: Cross section sites on the Mahi River and its tributaries and palaeoflood sites on the Mahi River

1 = Rupakheda; 2 = Kothada; 3 = Mahudi ka Maal; 4 = Mataji; 5 = Bhungda; 6 = Jagpura; 7 = Paderdi Badi; 8 = Kailashpuri; 9 = Galiyakot; 10 = Chikhali; 11 = Kadana; 12 = Khanpur; 13 = Chakaliya; 14 = Thapra; 15 = Saroli; 16 = Masaron ki Obri; 17 = Depur; 18 = Rangeli; 19 = Dhariawad

(II) Hydraulic geometry

Hydraulic geometry illustrates how the dynamic properties of stream channel (width, mean depth and mean velocity) adjust to change in discharge (Leopold, et al., 1964). Accordingly, hydraulic geometry equations have been derived for six gauging sites on the Mahi River and its tributaries by applying hydraulic parameters. These functions are;

$$w = aQ^b \qquad \text{....Equation 3.7}$$

$$d = cQ^f \qquad \text{....Equation 3.8}$$

$$\bar{v} = kQ^m \qquad \text{....Equation 3.9}$$

where, w = width; d = mean depth; $\bar{v}$ = mean velocity; Q = water discharge in cubic meter per second (m^2/s); a, c, k, b, f and m are numerical constants.

Besides, width, depth, and velocity are plotted on logarithmic scales against discharge. In addition, exponents of hydraulic geometry (b, f, and m) of the gauging stations on the Mahi River and its tributaries were plotted on Rhodes (1977) ternary diagram. In order to understand the nature of changes in flood hydraulics in connection to flood discharge of various magnitudes width-depth ratios of accompanying floods have been analyzed.

(III) Sediment transport

(i) Suspended sediment transport

The quantity of sediment transported in suspension by a river is considered as the suspended load. Suspended load is the product of suspended sediment concentration (g/1) and discharge, the proportion of sediment transported by a river close to the river bed is termed as the bedload (Woodward and Foster, 1997). However, suspended sediment carried by flows is considered as one of the significant measures of geomorphic effectiveness. Therefore, the suspended data of monsoon season have been analyzed by using basic statistical techniques such as mean, coefficient of variation, time series plots and correlation. The results of sediment concentrations and sediment loads for the Mataji, Paderdi Badi and Khanpur sites on the Mahi River were calculated. To get an idea about the temporal variations in discharge and suspended sediment concentration, time series plots have been obtained for each site. Further, a best-fit relation between river discharge and suspended sediment concentration was derived through linear regression (Terrio, 1996). Since, the relationship between concentration of suspended sediment and discharge may be more complex during a flood period. Therefore, a flood event has been selected for each station and represented by flood hydrographs and sediment concentration.

(ii) Coarse sediment transport

In view of several researchers, infrequent and large magnitude floods that occur at an interval of several decades are associated with much higher stream power than normal floods which result movement of coarse sediments (Baker and Kale, 1998; Kale, 2003; Hire and Kale, 2006). Therefore, to evaluate geomorphic effectiveness of floods in terms of coarse sediment transport, the equations developed by Williams (1983) were applied. The approximate minimum critical values of bed shear stress (τ), unit stream power (ϖ), and mean velocity ($\bar{v}$) that could initiate coarse sediment movement were estimated with the help of following formulae;

$$\varpi = 0.079\ dg^{1.27} \quad \text{.....Equation 3.10}$$

$$\tau = 0.17\ dg \quad \text{.....Equation 3.11}$$

$$\bar{v} = 0.065\ dg^{0.5} \quad \text{.....Equation 3.12}$$

where, dg = intermediate diameter of the grain in mm.

(IV) Flood hydraulics and hydrodynamics

The geomorphic efficacy of a flood is usually interconnected to flood power and the degree of turbulence (Wolman and Gerson, 1978). Therefore, parameters of flood hydraulics and hydrodynamics such as boundary shear stress, unit stream power per unit boundary area, Froude number, Reynolds number were computed (Leopold et al., 1964; Baker and Costa, 1987) to examine consequences of infrequent and large magnitude floods in the Mahi Basin for the known rare flood events. The values of the hydraulic parameters have been obtained by using following equations;

(i) Shear stress (τ)

Shear stress is defined as the component of stress co-planner with a material cross section. Shear stress is represented by the Greek letter τ (tau). Shear stress increases with flow depth and channel steepness. It is calculated as;

$$\tau = \gamma RS \qquad \text{……Equation 3.13}$$

where, τ (tau) = boundary shear stress expressed in Newton per square meter (N/m^2); γ (gamma) = specific weight of clear water (9800 N/m^3); R = hydraulic radius or mean depth of water in m; S = channel slope.

(ii) Unit stream power (ϖ)

Unit stream power (ϖ) is the capacity of a given flow to transport sediment. Unit stream power is calculated as;

$$\varpi = \gamma QS/w \qquad \text{…..Equation 3.14}$$

where, ϖ (lower-case omega) = unit stream power expressed in watts per square meter (W/m^2); Q = discharge in m^3/s; w = water surface width in m.

(iii) Froude number (Fr)

Froude number (Fr) is the ratio between inertial and gravitational forces. It is calculated as;

$$Fr = \bar{v} / (gR)^{0.5} \qquad \text{…..Equation 3.15}$$

where, Fr = Froude number; $\bar{v}$ = mean flow velocity in m/s; g = acceleration due to gravity (9.8 m/s^2); R = hydraulic radius or mean depth of water in m.

According to the range of Froude number values three possibilities of flow exist;

(a) If Froude number is less than one ($Fr < 1$), the flow is said to be subcritical and gravitational force dominates.

(b) If value of Froude number is greater than one ($Fr > 1$), the flow is supercritical and inertial forces govern the flow.

(c) The value of Froude number is equal or close to one (Fr = 1), in such case the flow is critical or transitional.

(iv) Reynolds number (Re)

In order to measures the degree of turbulence or random changes in flow direction and/or velocity superimposed on the main downstream movement of water of the Mahi River, Reynolds numbers (Re) were calculated.

$$Re = \bar{v} R / \nu \qquad \text{.....Equation 3.16}$$

where, Re = Reynolds number; $\bar{v}$ = mean flow velocity in m/s; R = hydraulic radius or mean depth of water in m; ν (Greek small letter Nu) = kinematic viscosity (1×10^{-7} m^2/s for water temperature of $20^{o}c$) (Leopold et al., 1964; Petts and Foster, 1985).

(V) Geomorphic effectiveness

In order to understand geomorphic effectiveness of floods, multi-date cross sections were plotted for the Mahi River and its tributaries. Historical information about damages due to floods of the year 1973, 1991 and 2006 was used for analysis. Further, to evaluate the impact of floods, simple ratios between parameters of moderate-magnitude floods, the floods, large floods and maximum floods were computed.

3.4 Flood Hydrometeorology

3.4.1 Hydrometeorological data

The analysis of spatio-temporal variations in the monsoon rainfall distribution over the Mahi Basin and its effect on the magnitude and frequency of the floods is one of the objectives of the research work. Accordingly, to understand the rainfall regime characteristics of the Mahi Basin and its association with floods, daily rainfall data have been obtained from India Meteorological Department (IMD), Pune. Seven raingauge stations namely Sardarpur, Sailana, Banswara, Kushalgarh, Kherwara, Sagwara and Godhra were selected on the basis of longest record length and their well distributed locations in the Mahi Basin (Figure 3.3). Heavy to very heavy rainfall from low pressure systems during the monsoon season is one of the root causes of large and extreme floods on the Indian rivers (Ramaswamy 1987; Dhar and Nandargi 2003; Panchawagh and Vaidya 2011). Therefore, data regarding the tracks of the LPS(s) were obtained from storm track eAtlas software. The isohyetal map and values of depth-area-duration (DAD) of the major rainstorm 1927, 1973 and 2006 have been obtained from PMP Atlas of Narmada, Tapi and other adjoining river basins prepared jointly by Central Water Commission and India Meteorological Department, Government of India.

In order to understand relation between the long-term annual rainfall and floods in the Mahi Basin, AMS data (from 1959 to 2009) of the Wanakbori site have been obtained from CWC, Gandhinagar. Moreover, El Niño and Southern Oscillation (ENSO) is the most important influencing force of Indian monsoon (Ropelewski and Halpert, 1987; Webster and Yang, 1992; Krishna Kumar et al., 1999; Lau and Nath, 2000; Wang et al., 2003). Therefore, sea surface temperature (SST) data of the central and eastern Pacific Ocean for the period (1901-1982) have been obtained from article of the Wright (1989). Further, SST data from 1983 to 2011 have been procured from the National Oceanic and Atmospheric Administration (NOAA).

3.4.2 Methodology for flood hydrometeorological analysis

(I) Rainfall regime analysis

The floods in the Mahi Basin are significantly associated with the spatio-temporal characteristics of the rainfall regime. Therefore, basic statistical methods such as mean, standard deviation, skewness, coefficient of variation etc. have been applied to understand spatio-temporal and interannual variability of monsoon rainfall in the Mahi basin. Besides, spatio-temporal and interannual variability of selected raingauge stations have been shown by the simple bar graphs and time series graphs respectively. In addition, percent departures from mean rainfall of the Mahi Basin and its association with floods also have been represented by graphically.

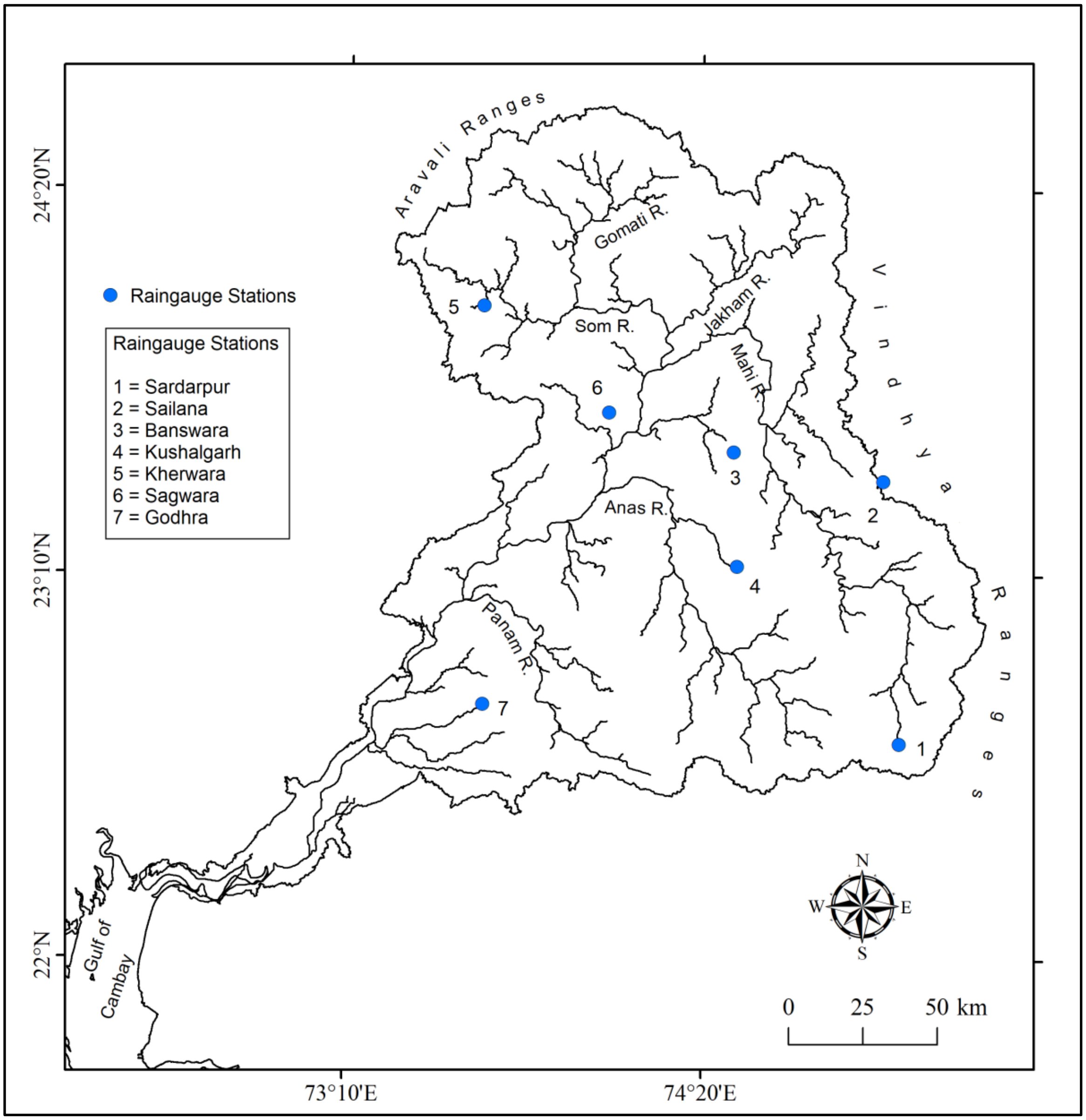


Figure 3.3: Raingauge stations in the Mahi Basin

(II) Flood generating meteorological conditions

Extraordinary synoptic conditions caused by heavy rainfalls over river basin are fundamental cause of river floods within the catchment (Hirscheboeck, 1991). Therefore, it is essential examine the association of synoptic conditions with the floods in the Mahi Basin. The Mahi Basin is located in the west part of the India which frequently influenced by the LPS(s) originated either in Bay of Bengal or Arabian Sea. According to Rao (1976) and others, heavy rainfall occurs over a belt of 400 km wide and to the left of track (i.e. southwestern sector) for a length of 500 km from the center of rainstorm. Therefore, a buffer of 500 km from the Mahi Basin has been demarcated and LPS(s) that pass through the buffer have been identified. Similar methodology has been applied by Hire (2000) and Patil (2017), who have prepared mean track of the LPS(s) for the Tapi Basin and Par Basin respectively. Accordingly, tracks of LPS(s) have been identified and a map of major LPS tracks that caused heavy rainfall and floods in the Mahi Basin has been prepared. In view of Mooley and Shukla (1987), latitudinal and longitudinal locations of such LPS(s) were taken into consideration for each day of their life span. By using these data, average latitudinal and longitudinal locations were computed on the basis of eAtlas data regarding LPS(s) from year 1891 to 2007. In addition, mean track of the LPS(s) was prepared by using software eAtlas (procured from IMD, Chennai) and ArcGIS 10.1. Besides, synoptic conditions associated with major floods in the Mahi Basin have been examined.

Moreover, return period of highest 24-hr rainfall has been calculated by Webull's method. The daily rainfall values used to estimate the recurrence interval that is the time span after which an event of similar or greater magnitude as observed event likely to occur by using following formula;

$$RI = (N+1)/r \qquad \text{.....Equation 3.17}$$

where, RI = recurrence interval in years; N = number of years; r = rank.

The return period of daily rainfall associated with major floods for Sardarpur, Sailana, Banswara, Kushalgarh, Kherwara, Sagwara and Godhra stations have been computed and represented graphically. In addition, Depth-area-duration (DAD) curves have been prepared for large flood generating LPS(s) of the year 1927, 1973 and 2006 based on 1 to 3 days duration of rainstorm and rainfall depth produced by rainstorm.

(III) Relationship between annual rainfall totals and flood occurrences

Since, there is a great probability of event of large floods during higher than average annual rainfall years. Therefore, an attempt has been made to establish the association between total annual rainfall and floods in the Mahi Basin. Accordingly, the annual rainfall data of the Mahi Basin and flood series data of the Wanakbori site (representing lower reaches of the Mahi River) for the period (1959-2009) have been shown by the plot discharge verses rainfall departure from mean.

(IV) Normalized accumulated departure from mean (NADM)

Normalized accumulated departure from mean (NADM) plotting method has been applied to understand association between long-term fluctuation in the monsoon rainfall and peak flows in the Mahi Basin. Further, long-term annual rainfall data of the Mahi Basin and annual peak flows data of Wanakbori site have been compared.

(V) El Niño and Southern Oscillation (ENSO)

An index of El Niño and Southern Oscillation (ENSO) have been calculated to understand relation between the annual average rainfall of the Mahi Basin (1901-2011) and the sea surface temperature (SST) anomalies of the eastern and central equatorial Pacific Ocean (-0.5^{o} C and +0.5^{o} C). According to the ENSO index values have been classified into cold, warm and normal conditions (Eltahir, 1996). Further, floods in the Mahi Basin associated with ENSO were identified.

(VI) Detection of changes in the annual rainfall

The rainfall data of the Mahi Basin (1901-2011) have been analyzed by using the non-parametric Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975) for rainfall trend analysis. The Mann-Kendall's Tau (τ) has been obtained by following equation;

$$\tau = \frac{\text{Actual total Scores (ATS)}}{\text{Maximum possible total}} \qquad \text{.... Equation 3.18}$$

where, ATS is the total of all sum(s) as calculated by the method adopted by Gunjal, (2016).

The maximum possible total has been acquired with the following equation;

$$\text{Maximum possible total} = N\,(N-1)/2 \qquad \text{.....Equation 3.19}$$

where, N = number of observations

The result of the rainfall trend over the Mahi Basin derived by Mann-Kendall test has been tested by testing the significance of Tau (τ). Therefore, value of τ has been transformed into a normal standard deviate as follows.

$$z = \frac{\tau}{\sqrt{2(2N+5)/9N(N-1)}} \qquad \text{.....Equation 3.20}$$

The z value can be achieved while replacing the computed value of Tau (τ). When the numbers of observations are greater than 30, Z value should be more than 2.32 at 0.01 confidence levels and 1.64 at 0.05 confidence level for the sample to be statistically significant.

(VII) Detection of future changes in the rainfall

The Student's t-test has been applied in order to find out the required percent change in the future rainfall of the Mahi Basin (Chiew and McMohan, 1993; Marengo, 1995). The percentage change can be estimated as;

$$t = \sigma * t\alpha\sqrt{\left(\frac{1}{nh} + \frac{1}{nf}\right)} \qquad \text{..... Equation 3.21}$$

$$\%\ \text{Change} = (t / AAR) * 100 \qquad \text{.....Equation 3.22}$$

Where,
t = Student's t value
σ = standard deviation of the historical gauge data
nh = length of historical rainfall series
nf = length of future rainfall data
tα = critical value of the t-statistics at 95% level of significance and
AAR = average annual rainfall

3.5 Palaeoflood Hydrology

3.5.1 Palaeoflood hydrology data

The data regarding palaeofloods were obtained with reference to SWD at a small right bank tributary of the Mahi River near Bhungda village of the Banswara district in Rajasthan (Figure 3.2). Accordingly, cross sectional survey was conducted to calculate the palaeodischarges. Information about channel slope (S), length (L), and catchment area (A) for the site was obtained through field surveys. Sediment samples were collected to understand the textural characteristics of the sediments. Information about palaeostage indicators (PSI) have been obtained by field surveys on the Mahi River near Kothada, Mahudi ka Maal in Dhar and Ratlam districts of the Madhya Pradesh (Figure 3.2). Cross sectional data have been obtained with reference to palaeostage indicators such as shrub line, scour line and SWD. Besides, boulder dimensions were measured to calculate stream power of the palaeoflood discharges.

3.5.2 Methodology for palaeoflood hydrology analysis

In order to understand palaeoflood hydrology several palaeostage indicators (PSI) are used such as scour lines, silt lines, large flood-transported boulders, tree lines, flood debris, slackwater flood deposits, flood-scarred trees are used (Baker, 1987; Kochel and Baker, 1982). Bedrock rivers offer the most appropriate locations for reconstructing the palaeoflood record (Baker et al., 1983a). Accordingly, a channel surveys were conducted in bed rock reaches of the Mahi River to find out palaeostage indicators. As expected, vertically stacked sequences of SWD were identified at the mouth of a small left bank tributary of the Mahi River which joins the river at 198 km from the source near Bhungda village located downstream of the Mahi Reservoir situated in Banswara district of Rajasthan State. The individual flood units were identified on the basis of abrupt changes in texture, colour and compositions. In order to get idea about the palaeoflood time 14 samples were collected for the OSL dating. Besides, to understand the textural characteristics of the sediments, out of 37 flood units of the slackwater deposits 17 soil samples were collected for sedimentological analysis. Some of the basic statistical techniques such as mean, median, skewness, kurtosis and sorting index have been applied to understand sediment characteristics of SWD. Sedlog graph has been prepared for the palaeoflood site of Bhungda.

Besides, cross sectional surveys conducted to calculate the palaeodischarges at Bhungda and Mahudi ka Mal. In addition to this, hydraulic modeling of the palaeodischarges was carried out by using the cross sectional data the elevations of the slackwater deposits. Palaeoflood magnitudes are determined by comparing the elevations of palaeostage indicators with the water surface profiles generated by slope-area method or HEC-RAS computer model is employed to estimate the discharges and the associated hydraulic parameters (O'Connor and Webb, 1988; Benito et al., 2004a). The discharge at a cross section is determined by using the slope-area method, which is based on Manning's equation;

$$Q = 1/n * A * R^{2/3} * S^{1/2} \qquad \text{.....Equation 3.23}$$

where, Q = discharge in m^3/s; A = channel area in m^2; R = hydraulic radius in m; S = energy slope; n = Manning's roughness

Chapter 4

Analysis and Interpretation

4.1 Flood Hydrology

The fluvial processes of erosion and sediment transfer are mostly confined to fluvial and flood regime characteristics of the river (Leopold et al., 1964; Schumm, 1977). Langbein and Schumm (1956) accentuated significant control of climate on fluvial and flood regime, erosion and sediment production. River regimes are seasonal fluctuations of discharges associated with meteorological circumstances at regional as well as river basin scale (Beckinsale, 1969). According to Gupta (1995a) the seasonal variations in the streamflows and peak flood discharges during monsoon season significantly control the river processes. The monsoon dominated rivers of the tropics experienced greatly inter-seasonal and inter-annual variability in the flood and fluvial regimes that significantly controlled by the intense rainfall, monsoon trough passage and associated LPS(s). Therefore, an attempt has been made to examine the fluvial and the flood regime characteristics of the monsoon dominated Mahi Basin through the analysis of daily streamflow data.

4.1.1 Fluvial regime characteristics of the Mahi Basin

I) Mean annual streamflow pattern

The mean annual streamflow pattern in the Mahi Basin has been studied by mean annual hydrographs of the Mahi River and its tributaries (Figure 4.1). The result significantly indicates that mean annual flow pattern in basin follows seasonal rhythm of the Indian summer monsoon over the basin. Mean annual streamflow shows simple fluvial regime pattern in the monsoon season. Moreover, the river flow drops or rivers remain dry in the non-monsoon season (November to May).

The graph (Figure 4.1) also reveals that discharges starts increasing from July and the highest peak occurs in mid of the August. Since, maximum rainfall occurs in the month of July over the Mahi Basin. All the hydrological losses are completed upto the month of the August and maximum surface runoff is joining to the river channel. Besides, all the gauging sites on the Mahi River and its tributaries have their location at downstream of the major dams (Figure 3.1) Consequently, when water is released from the dam, flash floods occur in downstream channel of the rivers which is notably reflected in the mean annual hydrographs. The stream flows steadily declining from mid of October. Subsequently, either streams having low flows or they become dry.

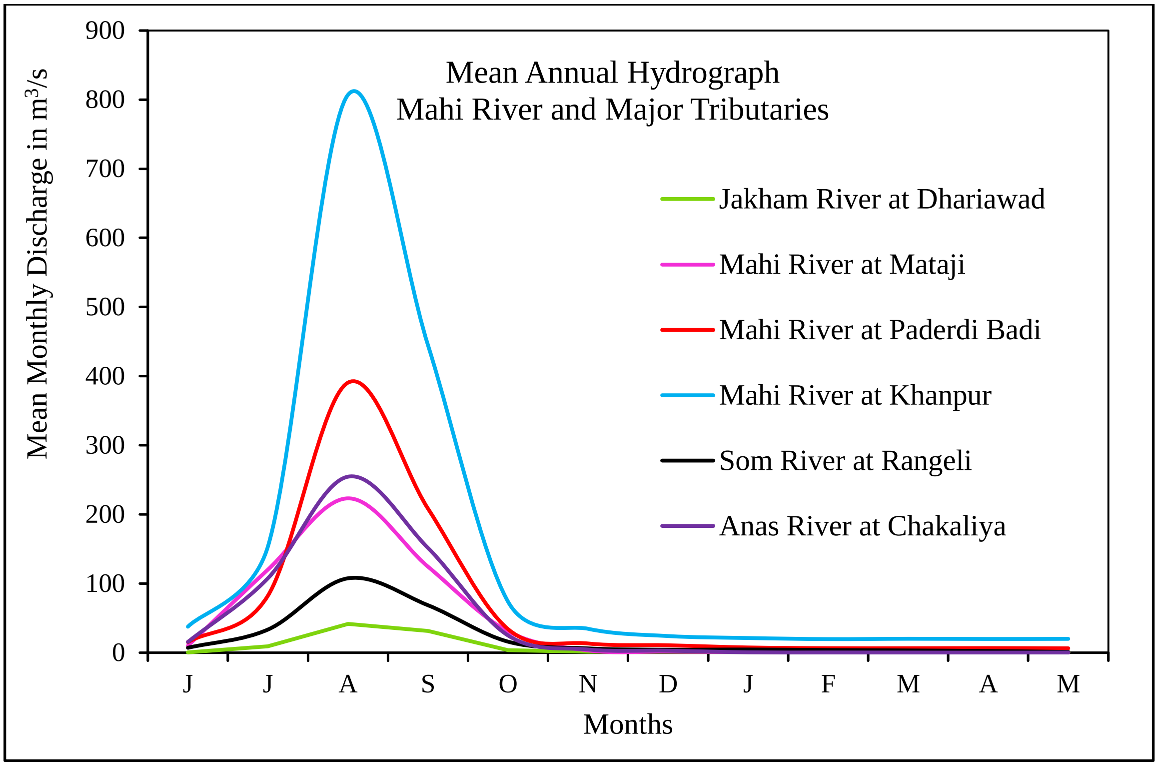


Figure 4.1 Mean annual hydrograph of the Mahi River and major tributaries

The average flow characteristics of the Mahi River and its major tributaries are given in Table 4.1. Table 4.1 shows that that above 93% of the flows are recorded in the monsoon months and the flows are insignificant throughout non-monsoon months. All rivers in the Mahi Basin experience average maximum discharges in the month of August. It shows that maximum geomorphic work of erosion and transportation is restrained in the monsoon season and the most of the geomorphic processes are accomplished in the month of August. Moreover, the annual hydrographs of the flood year 2006 (Figure 4.2a to Figure 4.2f) shows short, sharp and multiple peaks, with respect to hydrometeorological conditions prevailed over the Mahi Basin. Daily discharges of the Mahi River fluctuate between 15000 m^3/s (at Mataji) and 31000 m^3/s (at Khanpur).

Table 4.1 Flow characteristics of the Mahi River and its major tributaries
[Averages of the monthly mean discharges m^3/s (1978-2016)].

Water year	Mahi River Mataji	Mahi River Paderdi Badi	Mahi River Khanpur	Anas River Chakaliya	Som River Rangeli	Jakham River Dhariawad
Record Length	1982-2016	1978-2016	1979-2016	1991-2016	1979-2016	1990-2016
June	9.97	15.16	37.520	15.50	7.04	0.39
July	120.14	82.42	153.587	107.64	33.39	9.35
August	223.19	390.59	806.903	254.56	107.55	41.79
September	124.34	208.31	444.727	151.45	68.57	31.45
October	30.73	34.01	73.700	24.86	15.86	3.62
November	3.24	13.24	34.515	4.56	6.13	1.06
December	1.58	10.65	24.003	2.88	4.27	1.28
January	0.91	7.49	21.164	0.52	4.55	1.43
February	0.69	6.49	19.602	0.28	3.79	1.46
March	0.33	6.45	20.073	0.15	3.17	0.97
April	0.04	6.61	19.789	0.05	2.39	0.28
May	0.09	6.31	19.944	0.18	1.05	0.15
Mean annual flow m^3/s	42.94	65.65	139.63	46.89	21.48	7.77
Mean monsoon flow m^3/s (Jun-Oct)	101.67	146.1	303.29	110.80	46.48	17.32
% of monsoon flow (Jun-Oct)	99.00	94.70	93.03	98.90	92.77	94.81
% of non-monsoon flow (Nov-May)	1.00	5.30	6.97	1.10	7.23	5.19

Source: CWC; See figure 3.1 for location of sites

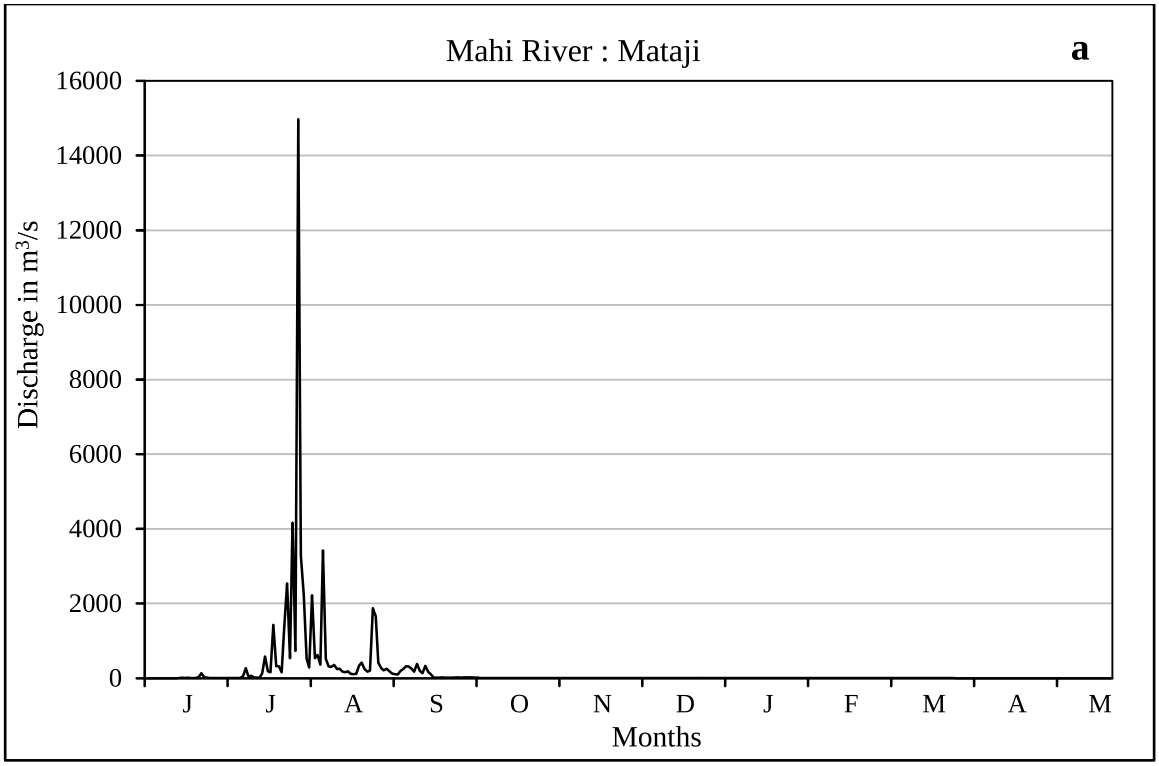


Figure 4.2a: Annual hydrograph of the Mahi River: Mataji; Water year 2006-2007

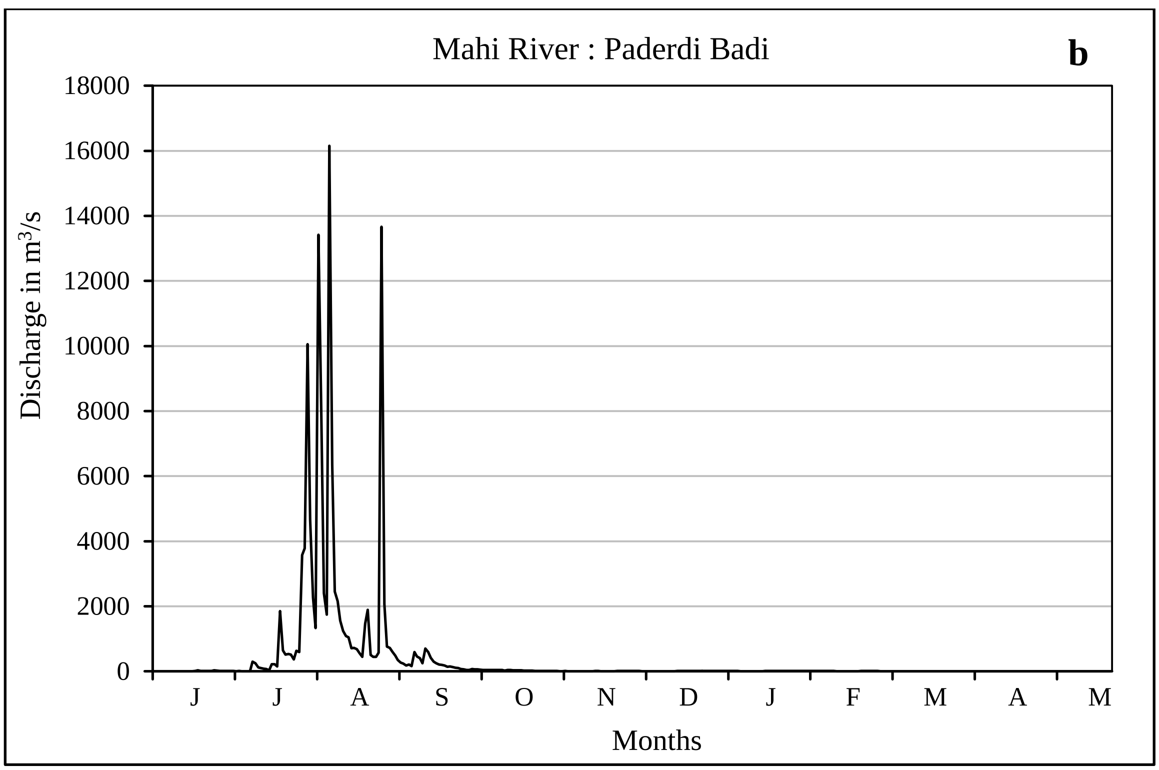


Figure 4.2b: Annual hydrograph of the Mahi River: Paderdi Badi; Water year 2006-2007

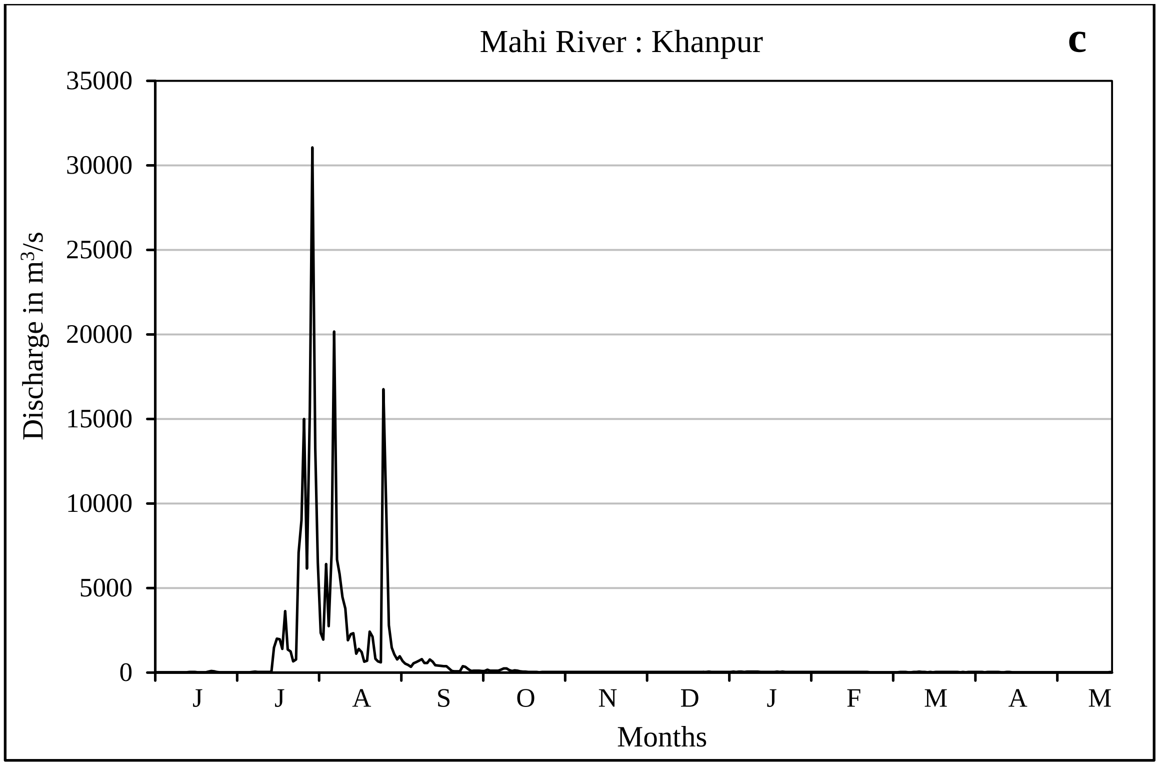


Figure 4.2c: Annual hydrograph of the Mahi River: Khanpur; Water year 2006-2007

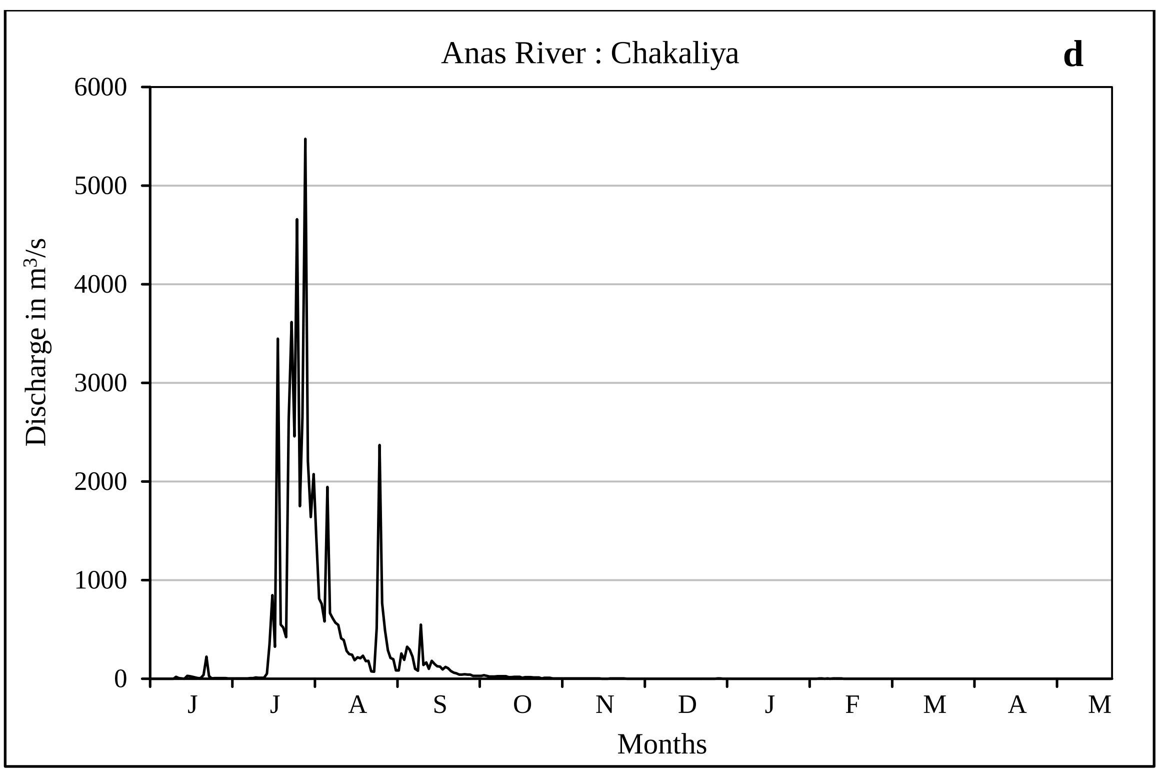


Figure 4.2d: Annual hydrograph of the Anas River: Chakaliya; Water year 2006-2007

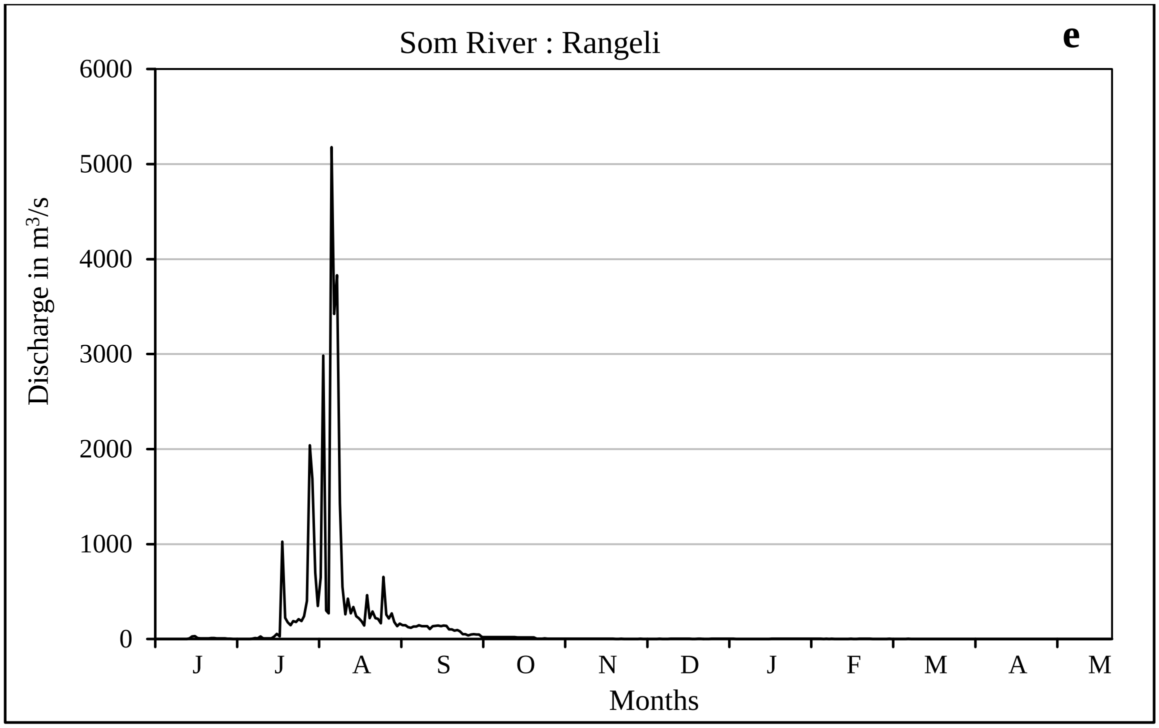


Figure 4.2e: Annual hydrograph of the Som River: Rangeli; Water year 2006-2007

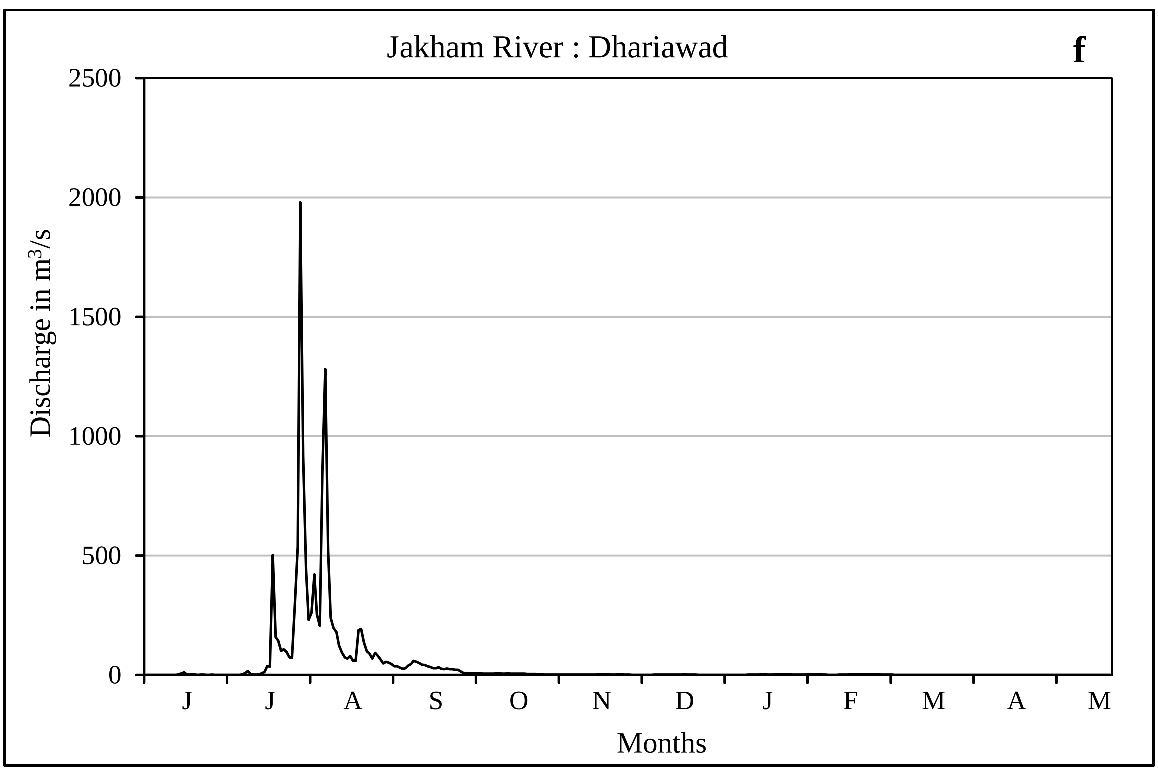


Figure 4.2f: Annual hydrograph of the Jakham River: Dhariawad; Water year 2006-2007

4.1.2 Flood regime characteristics of the Mahi Basin

I) Interannual variability in annual peak discharges

The Figures 4.3a to 4.3g indicate that Mahi River and its tributaries show significantly year to year variations in the annual peak discharges. However, interannual variability is high for all sites in the Mahi Basin. The 1973 flood was the highest flood with a discharge of 40662 m^3/s magnitude at Wanakbori. Besides, floods of the year 1994 and 2006 were the highest floods after 1973. These floods were associated with heavy rainfall and release of large volume of water from the Mahi Bajaj Sagar Dam and Kadana Dam on the Mahi River, Som-Kamla-Amba Dam on the Som River and Jakham Dam on the Jakham River. These infrequent extreme flood events have a great significance in point of view of geomorphic processes as large proportion of geomorphic work had accomplished by these events.

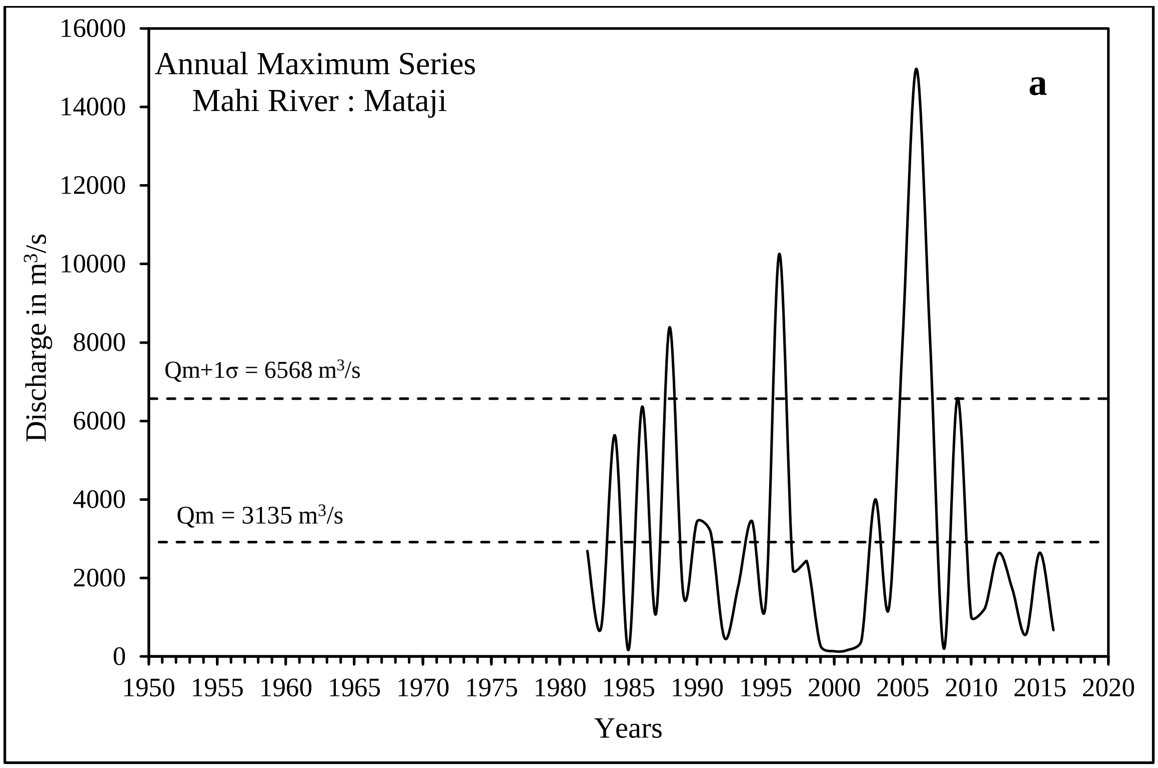


Figure 4.3a: Annual maximum series plot of the Mahi River: Mataji; Qm = mean annual peak discharge; σ = standard deviation

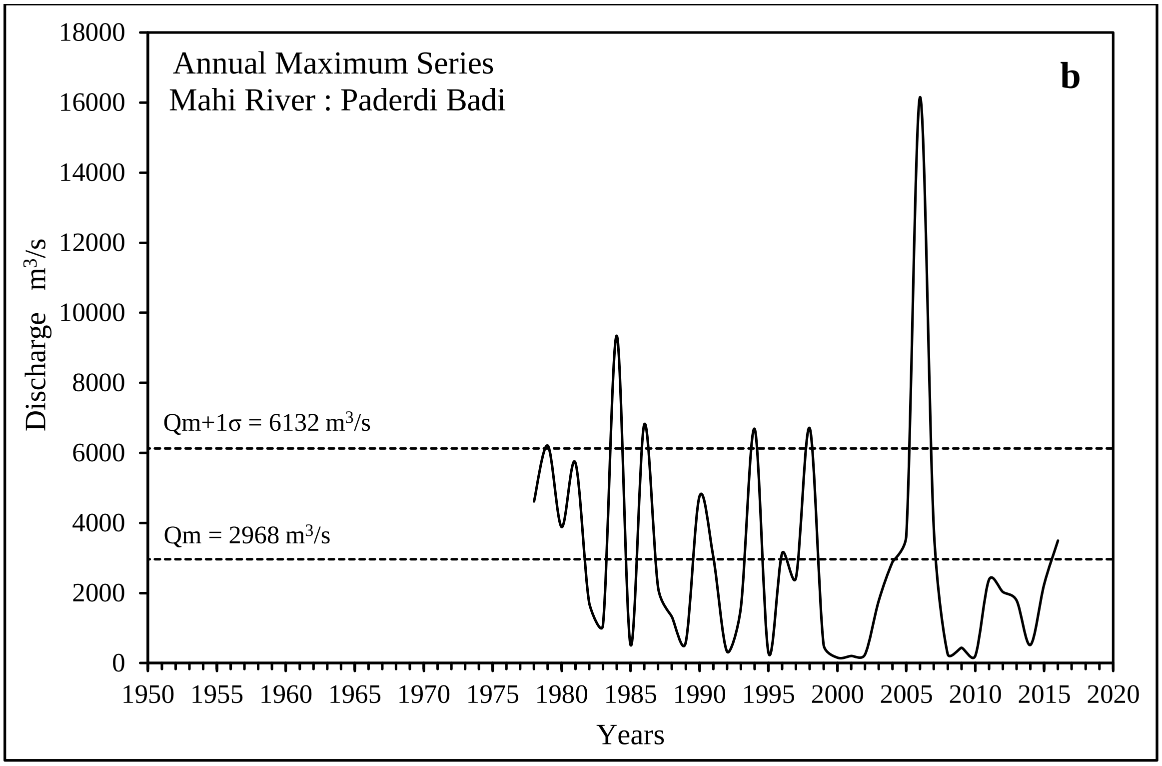


Figure 4.3b: Annual maximum series plot of the Mahi River: Paderdi Badi; Qm = mean annual peak discharge; σ = standard deviation

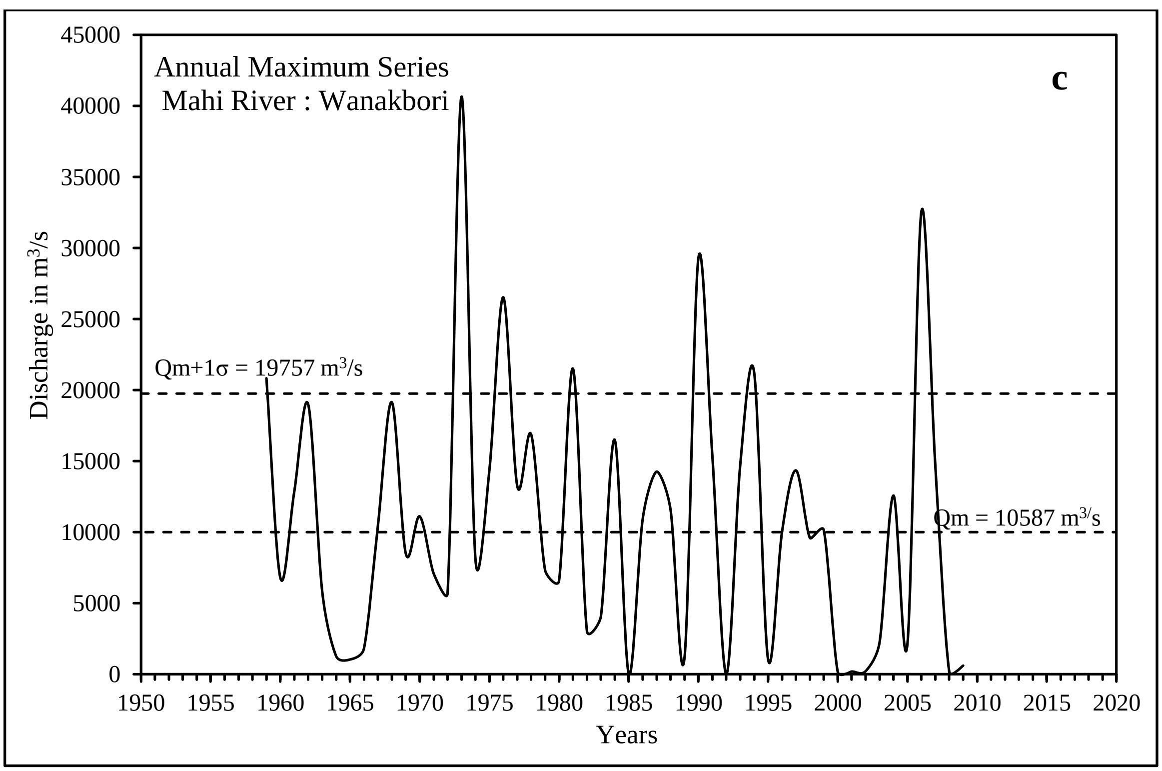


Figure 4.3c: Annual maximum series plot of the Mahi River: Wanakbori; Qm = mean annual peak discharge; σ = standard deviation

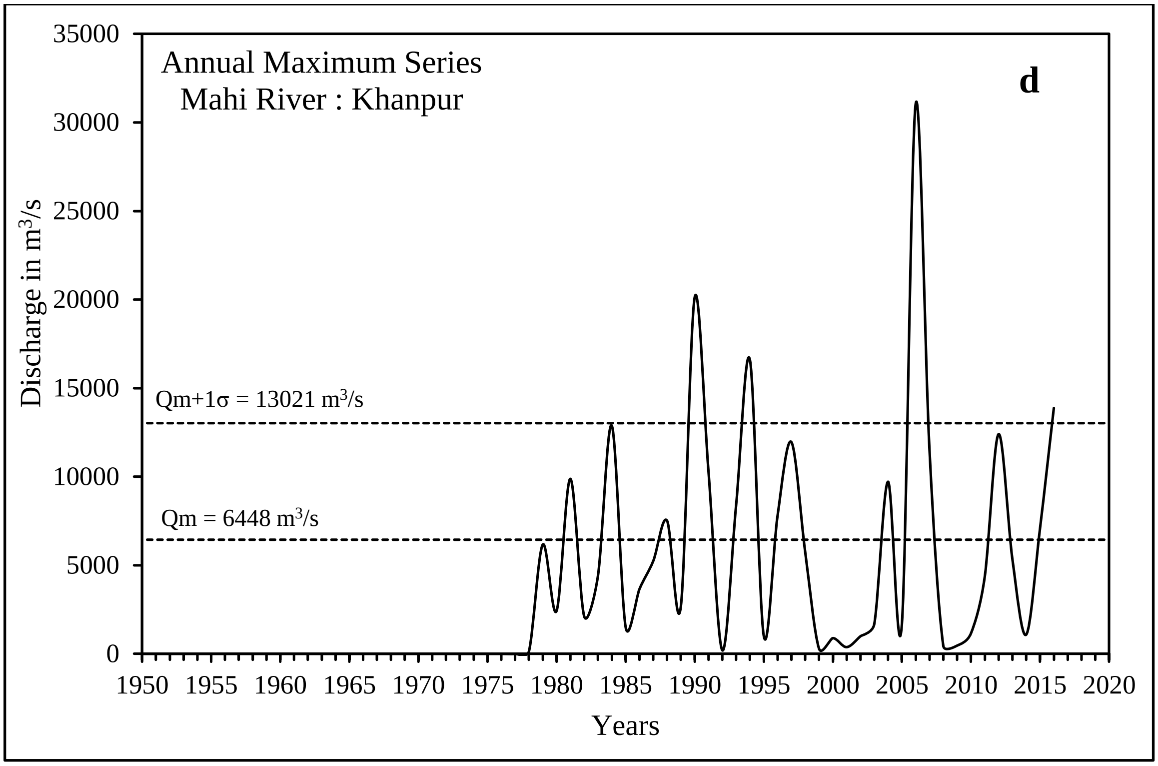


Figure 4.3d: Annual maximum series plot of the Mahi River: Khanpur; Qm = mean annual peak discharge; σ = standard deviation

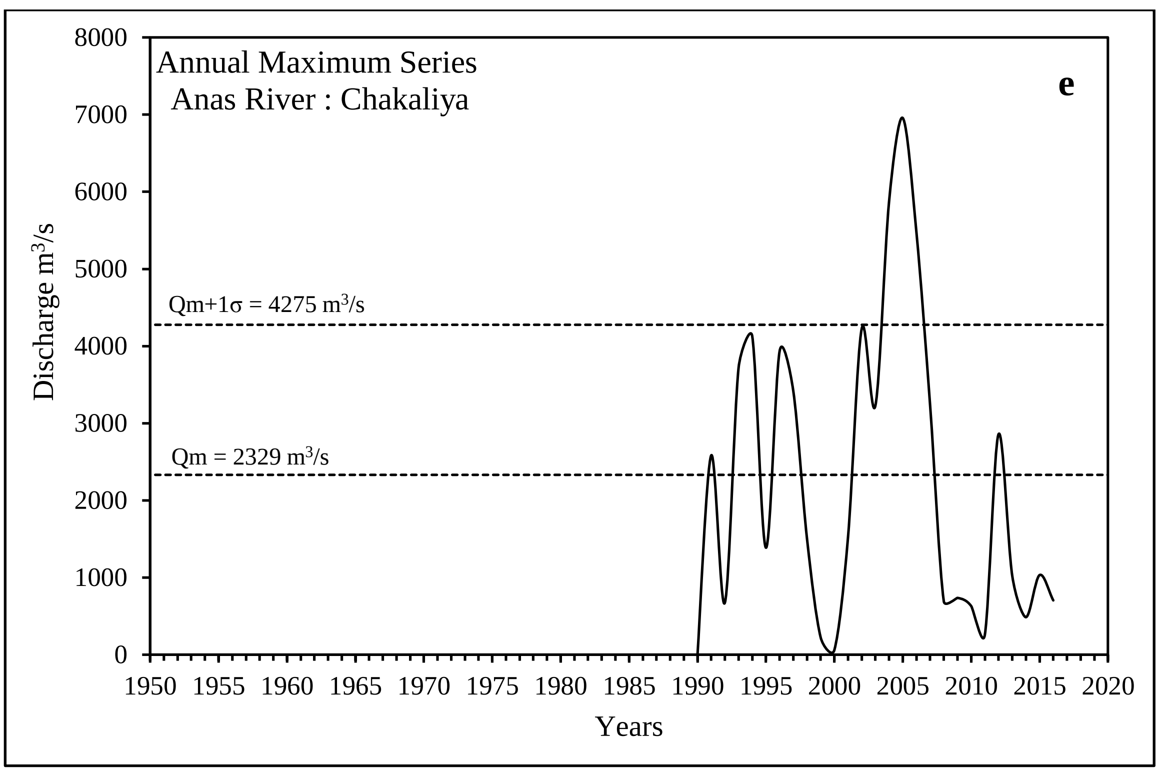


Figure 4.3e: Annual maximum series plot of the Anas River: Chakaliya; Qm = mean annual peak discharge; σ = standard deviation

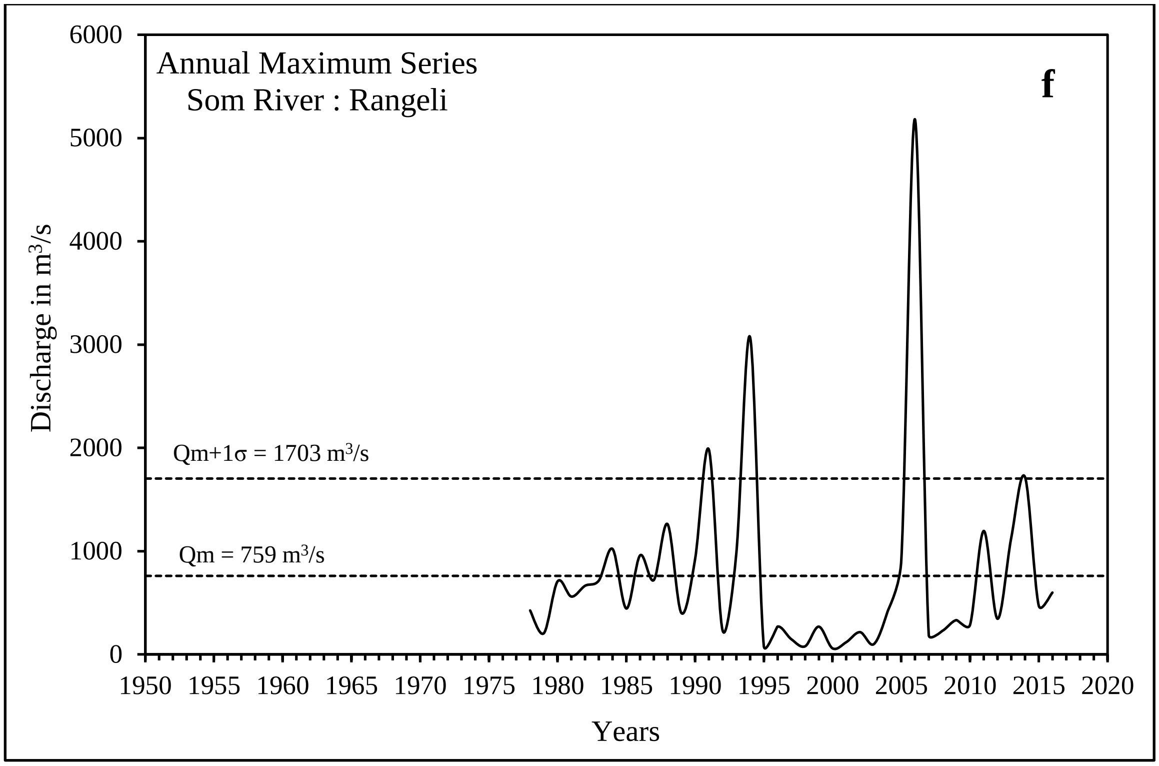


Figure 4.3f: Annual maximum series plot of the Som River: Rangeli; Qm = mean annual peak discharge; σ = standard deviation

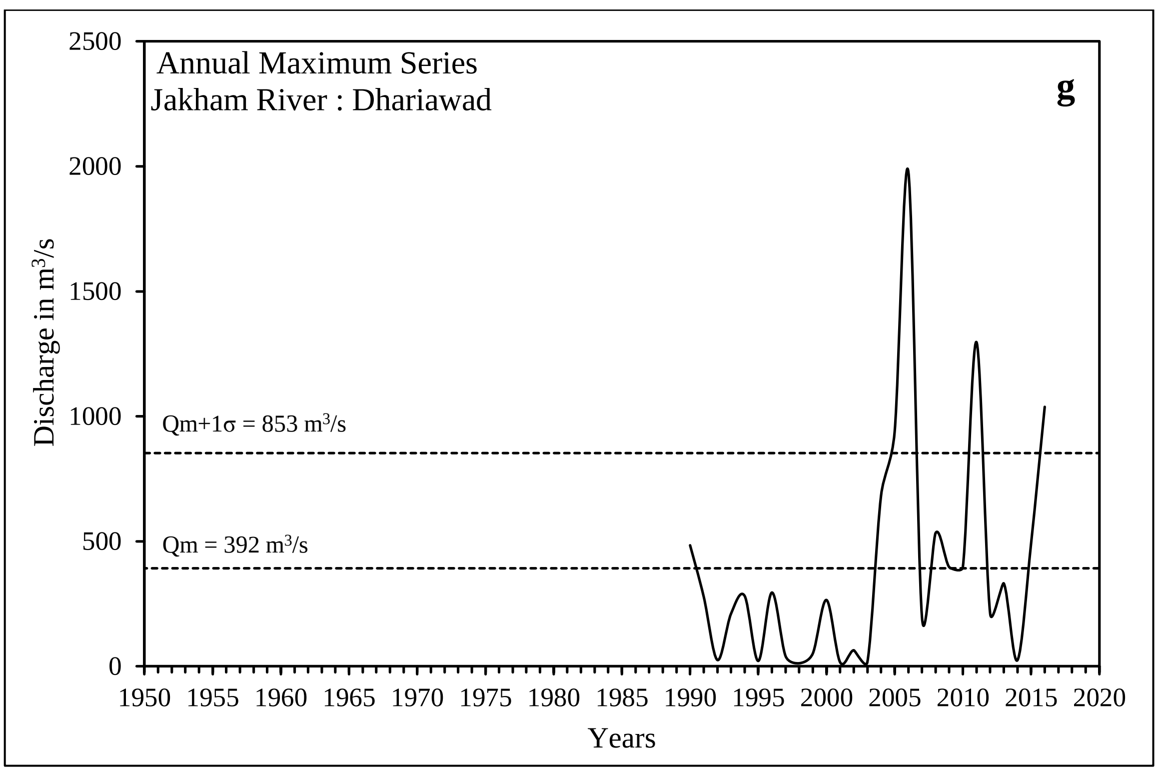


Figure 4.3g: Annual maximum series plot of the Jakham River: Dhariawad; Qm = mean annual peak discharge; σ = standard deviation

II) Average magnitude and variability

Normally, at-a-station range in discharge increases from mean discharge. Moreover, at the downstream sites not only the discharges can fluctuate to a significant degree but variability also increases. Table 4.2 reveals that mean (Qm) discharge of the Mahi River at downstream (Khanpur site) has significantly increased. However, the maximum Qmax/Qm ratio is observed for the Rangeli site on the Som River and lowest for the Chakaliya site on the Anas River. These ratios vary between 3 and 7 respectively. Therefore, it shows that Qmax are 3 to 7 time greater than Qm. Besides, Table 4.3 also indicates that the coefficient of variation range between 0.84 and 1.24 (or 84 to 124%). The value of the Cv is very high in case of the Som River at Rangeli (1.24 or 124%) as compared to other sites. The result of analysis reveals high variability. Moreover, Table 4.4 reveals that the variability in peak flows in the Mahi Basin is in fact higher than some of the large rivers of the India. The Figures 4.4a to Figure 4.4g also reveal high variability in the annual maximum streamflows in the Mahi Basin.

Table 4.2: Flood flow characteristics of the Mahi River and its major tributaries

SN	River	Site	A km^2	Record Length	Qmin m^3/s	Qmax m^3/s	Qm m^3/s	Flood range	Qmax / Qm
1	Mahi	Mataji	3880	35	134	14972	3135	14838	4.78
2	Mahi	Paderdi Badi	16247	39	158	16153	2968	15995	5.44
3	Mahi	Wanakbori	30665	51	029	40663	10587	40634	3.84
4	Mahi	Khanpur	32510	38	200	31062	6448	30862	4.82
5	Anas	Chakaliya	3121	26	060	6956	2329	6896	2.99
6	Som	Rangeli	8329	39	059	5179	759	5120	6.82
7	Jakham	Dhariawad	1510	27	012	1980	392	1968	5.05

Source: CWC; Qmin = Minimum annual peak discharge; Qmax = Maximum annual peak discharge; Qm = Mean annual peak discharge; A = Catchment area; See Figure 3.1 for location of sites

Table 4.3 Discharge characteristics of the Mahi River and its major tributaries

SN	River	Site	Record length	Qmax m^3/s	Qm m^3/s	σ	Cv	C_s	C_s/Cv
1	Mahi	Mataji	35	14972	3135	3433	1.09	1.72	1.58
2	Mahi	Paderdi Badi	39	16153	2968	3164	1.07	2.23	2.08
3	Mahi	Wanakbori	51	40663	10587	9170	0.87	1.00	1.15
4	Mahi	Khanpur	38	31062	6448	6574	1.02	2.00	1.96
5	Anas	Chakaliya	26	6956	2329	1946	0.84	0.80	0.95
6	Som	Rangeli	39	5179	759	944	1.24	3.2	2.58
7	Jakham	Dhariawad	27	1980	392	461	1.18	2.0	1.69

Source: CWC; Qmax = Maximum annual peak discharge; Qm = Mean annual peak discharge; σ = Standard deviation; Cv = Coefficient of variation; C_s = Coefficient of skewness; See Figure 3.1 for location of sites.

Table 4.4: Discharge characteristics of some large Indian rivers

SN	River	Site	Qmin m^3/s	Qmax m^3/s	Qm m^3/s	σ	Cv	C_s	C_s/Cv
1	Ganga	Farakka	39413	72915	55776	7979	0.14	0.04	0.26
2	Mahanadi	Naraj	11157	42334	29269	8731	0.30	-0.39	-1.31
3	Narmada	Garudeshwar	741	69400	23935	14623	0.61	1.21	1.98
4	Godavari	Dowleshwarm	11490	79990	29207	12378	0.42	1.93	4.54
5	Krishna	Vijaywada	7187	30040	14775	4516	0.31	2.06	6.65
6	Tapi	Kathore	3270	41700	9698	5883	0.61	1.40	2.30
7	Mahi	Wanakbori	29	40663	10587	9170	0.87	1.00	1.15

See table 4.2 and 4.3 for notation

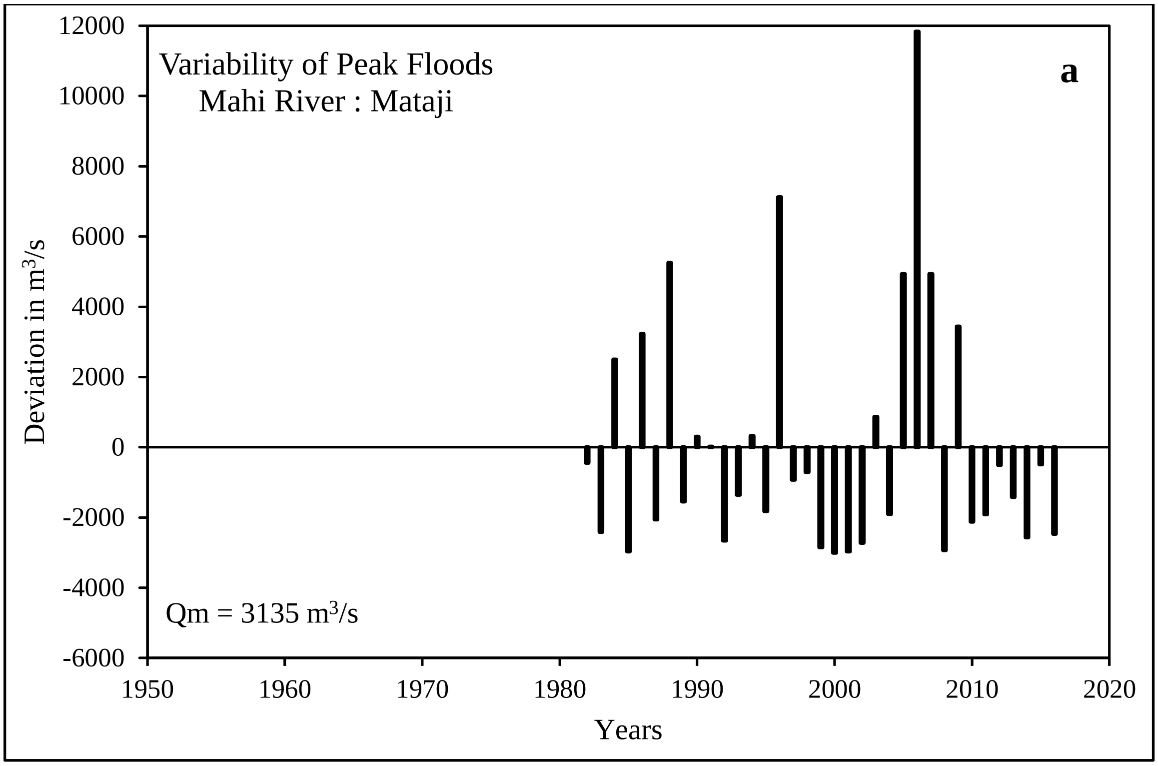


Figure 4.4a: Variability of peak floods in the Mahi River: Mataji

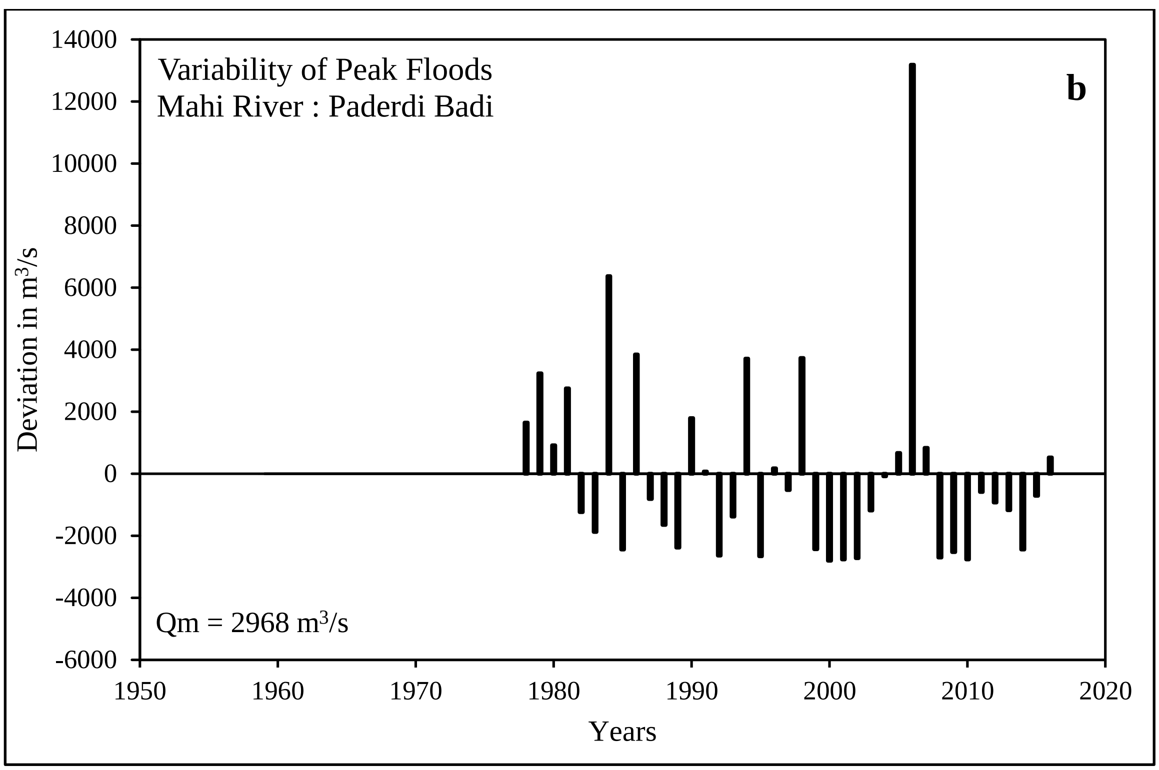


Figure 4.4b: Variability of peak floods in the Mahi River: Paderdi Badi

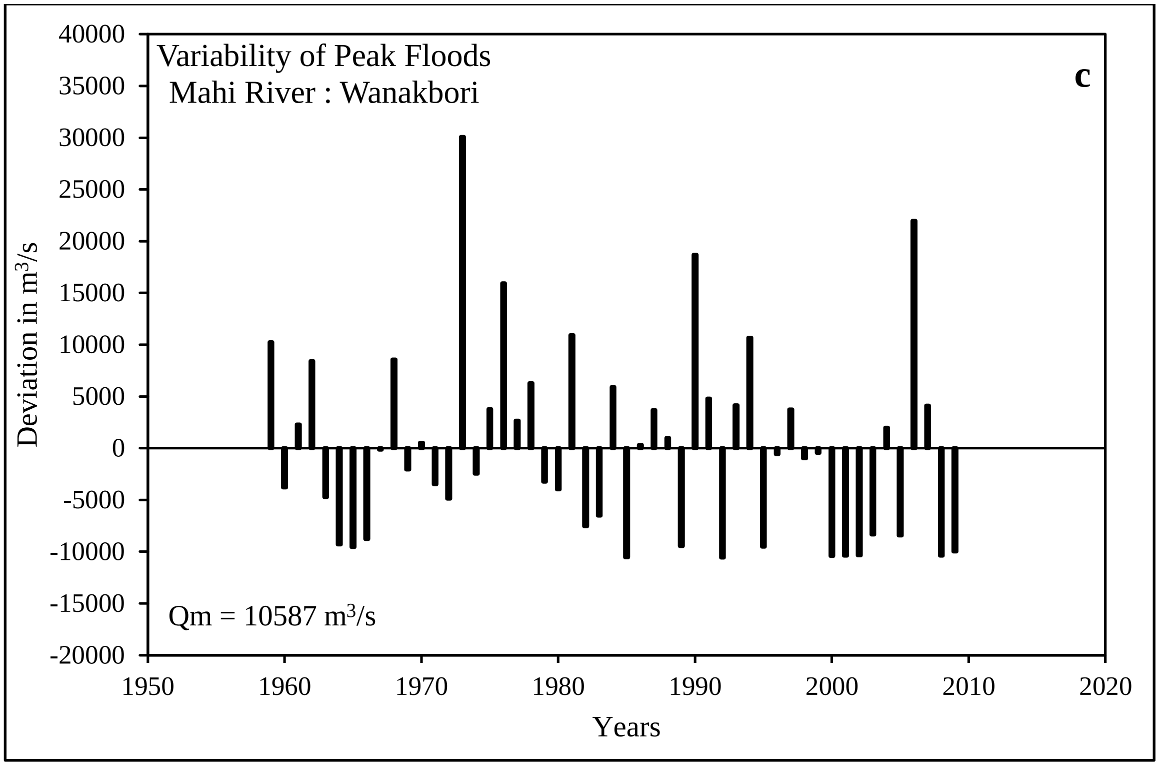


Figure 4.4c: Variability of peak floods in the Mahi River: Wanakbori

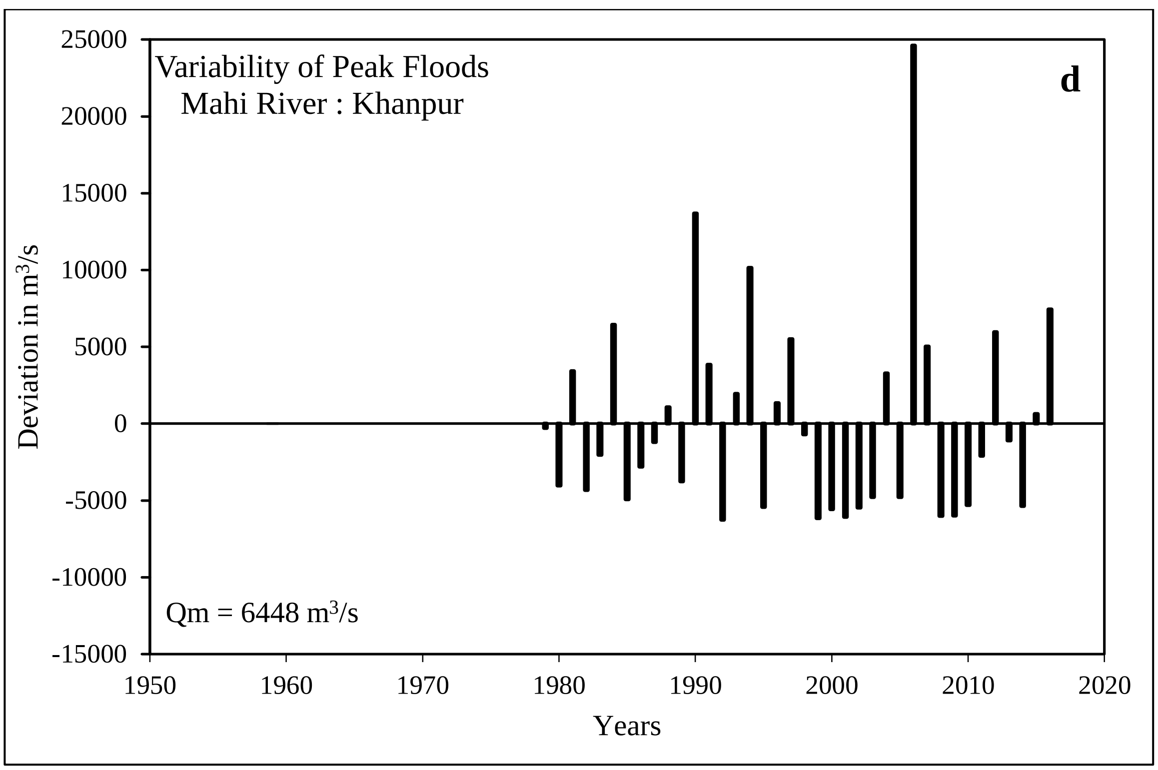


Figure 4.4d: Variability of peak floods in the Mahi River: Khanpur

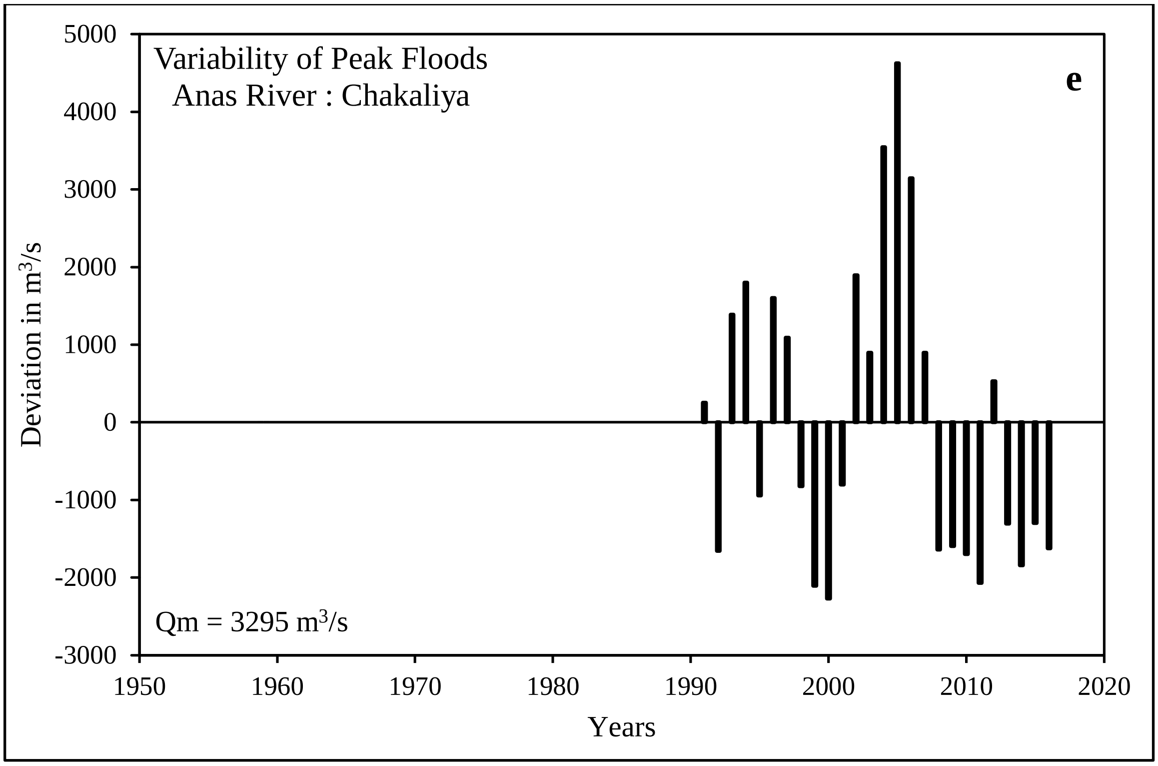


Figure 4.4e: Variability of peak floods in the Anas River: Chakaliya

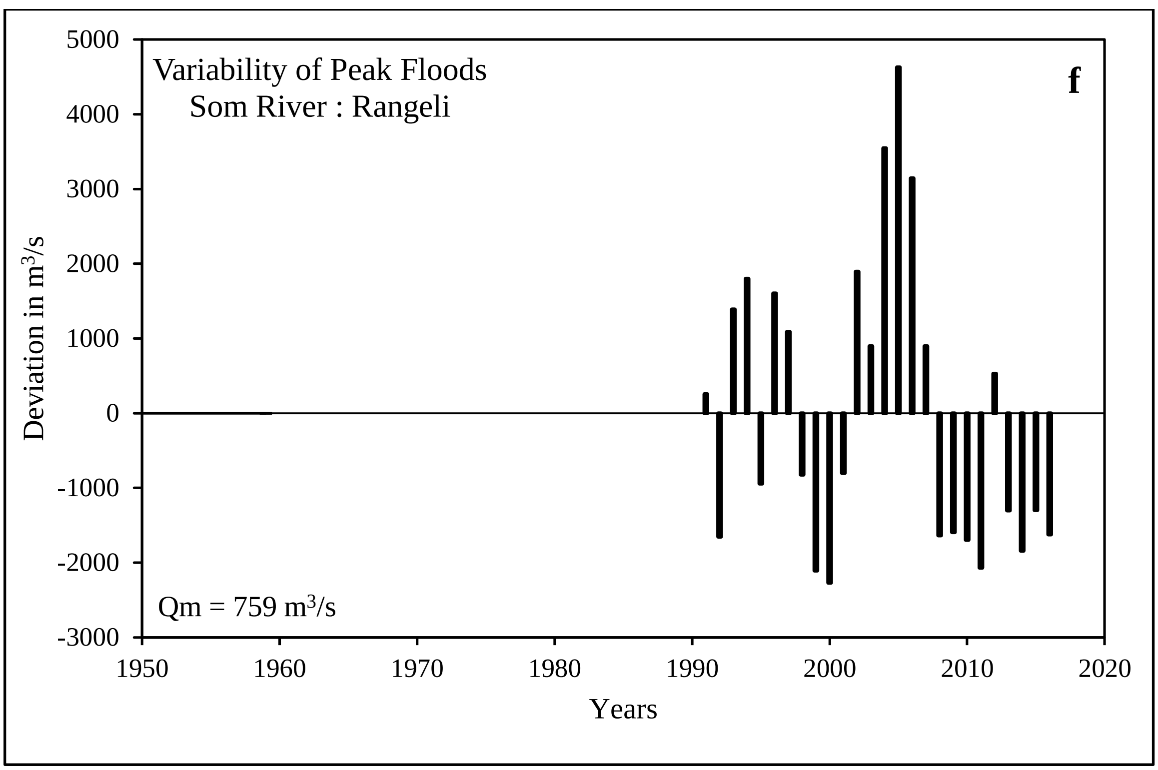


Figure 4.4f: Variability of peak floods in the Som River: Rangeli

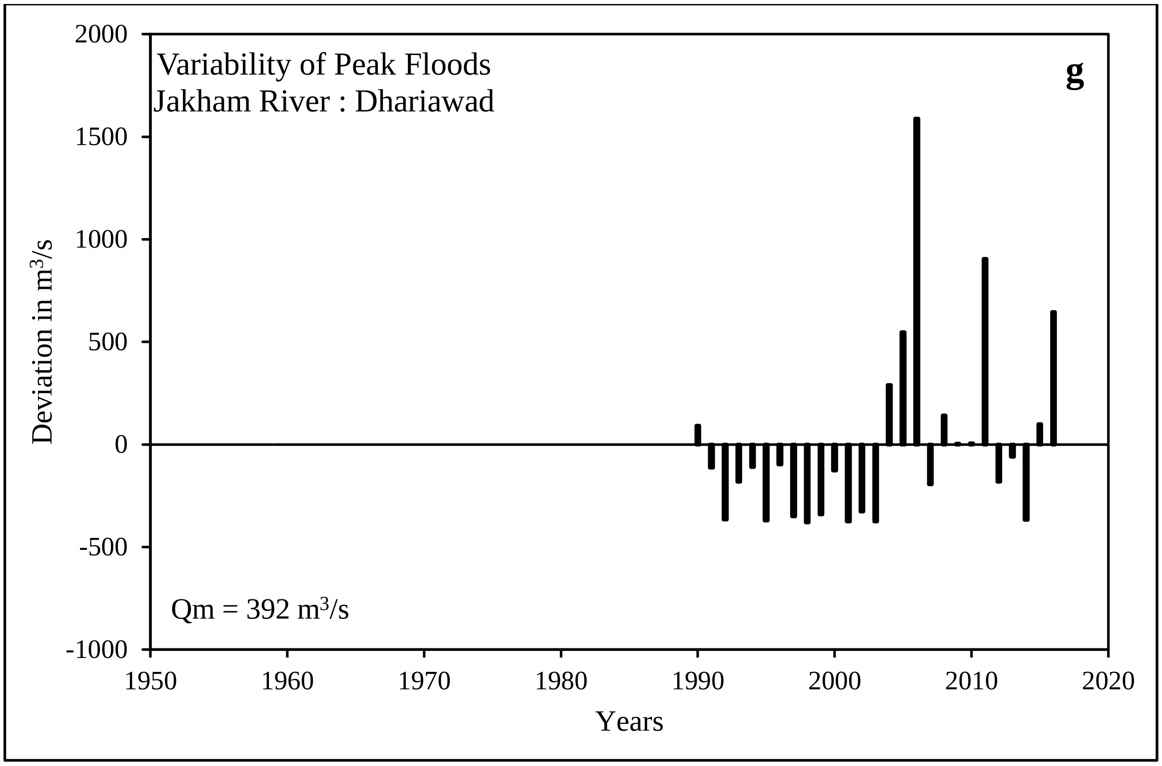


Figure 4.4g: Variability of peak floods in the Jakham River: Dhariawad

Table 4.5 shows that FFMI of the Mahi River range between 0.53 and 0.56. However, the highest FFMI is (0.65) observed on the Jakham River at Dhariawad. The mean FFMI value of the Mahi Basin is greater (0.57) than the mean FFMI value of the world, which is 0.28 (McMohan et al., 1992).

Table 4.5: Flash flood magnitude index of the Mahi River and its major tributaries

SN	River	Site	Record length	FFMI
1	Mahi	Mataji	35	0.55
2	Mahi	Paderdi Badi	39	0.53
3	Mahi	Wanakbori	51	0.56
4	Mahi	Khanpur	38	0.56
5	Anas	Chakaliya	26	0.51
6	Som	Rangeli	39	0.44
7	Jakham	Dhariawad	27	0.65
8	**Mahi Basin**	**Mean value**	**-**	**0.57**

Source: CWC; FFMI= Flash flood magnitude index; See Figure 3.1 for location of sites

III) Skewness

The coefficient of skewness is most generally used measure of moments in the studies of flood hydrology and flood geomorphology. The values of C_s for all the stations in the Mahi Basin are positive and ranging between 0.80 and 2.0 except Paderdi Badi and Rangeli. The Paderdi Badi site on the Mahi River and Rangeli site on the Som River show high positive C_s values which are 2.23 and 3.2 respectively.

According to Viessman et al., (1989) when skewness is calculated based on less than 50 years data, the value of skewness will be questionable. As a result, some of the hydrologists have also been used the ratio between skewness and coefficient of variation to further validate the degree of skewness (Shaligram and Lele, 1978). The ratio values are more than 2.0 for most large rivers of India (Shaligram and Lele, 1978). This, therefore, suggests that the distribution of peak discharges is not highly skewed.

IV) Unit discharges

The values of unit discharges calculated for each site on the Mahi River and its tributaries. Table 4.6 shows that minimum unit discharge is 0.62 $m^3/s/km^2$ on the Som River at Rangeli site and maximum unit discharge is 32.76 $m^3/s/km^2$ for the Mahi River at Rupakheda sit. Table 4.6 also reveals that most of the values of the unit discharges are above or close to 1.0. However, Kothada, Mahudi ka Mal, Mataji, Bhungda Thapra, Saroli and Masaron ki Obri sites have much higher unit discharges.

Table 4.6: Unit discharges of the Mahi River and its major tributaries

SN	River	Site	A km^2	Qmax m^3/s	Unit Discharge $m^3/s/km^2$
1	Mahi	Rupakheda	442	14480	32.76
2	Mahi	Kothada	716	7251	10.13
3	Mahi	Mataji	3046	14972	4.92
4	Mahi	Mahudi Ka Mal	3714	14322	3.86
5	Mahi	Bhungda	3803	25049	6.59
6	Mahi	Jagpura	6260	15690	2.51
7	Mahi	Paderdi Badi	16247	16153	0.99
8	Mahi	Kailashpuri	16471	21553	1.31
9	Mahi	Galiyakot	18989	21383	1.13
10	Mahi	Chikhali	24819	27196	1.10
11	Mahi	Kadana	25884	28046	1.08
12	Mahi	Wanakbori	30665	40663	1.33
13	Mahi	Khanpur	32510	31062	0.96
14	Anas	Chakaliya	3121	6956	2.23
15	Anas	Thapra	3549	16792	4.73
16	Som	Saroli	499	2558	5.13
17	Som	Masaron ki Obri	1216	4750	3.91
18	Som	Depur	1806	5033	2.79
19	Som	Rangeli	8329	5179	0.62
20	Jakham	Dhariawad	1510	1980	1.31

Source: CWC; A= Upstream catchment area; Qmax= Maximum annual peak discharg**;** See Figure 3.1 and 3.3 for location sites

4.1.3 Flood frequency analysis

The hydrological and geomorphological significance of the effectiveness of the floods in terms of magnitude and frequency have been revealed in the magnitude-frequency analysis by Chow (1964); Leopold et al. (1964); Morisawa (1968). In addition, Bedient and Huber, (1989) stated that reciprocal of T is the exceedance probability of an events equaled or exceeded in any one year. Since the objective of this analysis is not to find out the most applicable probability distribution(s) for the Mahi Basin, but to estimate the return period of high flows. Therefore, the Gumbel extreme value type I (GEVI) probability distributions which is widely used for Indian rivers have been used in the flood frequency analysis of the Mahi River and major tributaries.

I) Gumbel Extreme Value Type I (GEVI) Distribution

(i) Estimation of discharges for return periods

A designed flood has been mostly determined on the basis of observed Qmax or historic flood. Therefore, the continuous, long and good quality of record of stream discharges is essential for the more accurate appraisal of recurrence interval of the peak flows. Generally, the AMS data have been more recurrently applied for the analyses. Accordingly, discharges have been estimated for different return periods such as 2, 5, 10, 25, 50, and 100 year by using Gumbel extreme value I (GEVI) probability distribution and the estimated discharges are given in Table 4.7.

Table 4.7: Estimated discharges in m^3/s for different return period for different gauging sites on the Mahi River and its tributaries (Based on GEVI distribution)

SN	River	Site	Record length	Estimated Discharges (m^3/s)					
				2 Yr	5 Yr	10 Yr	25 Yr	50 Yr	100 Yr
1	Mahi	Mataji	35	2586	5607	7598	10138	12095	13915
2	Mahi	Paderdi Badi	39	2462	5246	7081	9423	11226	12903
3	Mahi	Wanakbori	51	9120	17189	22508	29294	35421	39381
4	Mahi	Khanpur	38	5396	11181	14994	19859	23606	27090
5	Anas	Chakaliya	26	2018	3730	4859	6299	7408	8439
6	Som	Rangeli	39	608	1439	1986	2685	3223	3723
7	Jakham	Dhariawad	27	318	724	991	1332	1595	1840

See Figure 3.1 for location of sites

The estimation of discharges for the 50 and 100 year recurrence interval have great importance while designing hydraulic structures such as bridges and dams. Therefore, an attempt has been made to estimate discharges for different return period. The highest (47632 m^3/s) estimated discharge of 100 year return period was for the Wanakbori site on the Mahi River in the Gujarat state. The minimum (19861 m^3/s) estimated discharge for 100 year return period was for Paderdi Badi site. However, the peak discharge of 40663 m^3/s magnitude was observed at Wanakbori on the Mahi River in the year 1973 due to heavy to very heavy rainfall associated with the low pressure system. This flood caused serious damages to ongoing construction of the Kadana Dam due to inaccuracy in the estimation of the design flood. The 1927 flood could be larger than 1973, but no record is available about discharge. Therefore, the design flood of Kadana Dam initially was based on the 1959 flood discharge. However, after the flood of 1968 again design flood of the Kadana Dam was changed due to observed discharge of 21820 m^3/s. Furthermore, 1973 flood was the largest flood on record in the Mahi Basin. The observed discharge of the 1973 flood was 32986 m^3/s at Kadana which caused again design flood of the Kadana Dam was changed and finally 46871 m^3/s discharge has been considered as design flood of the Kadana Dam (More, 1986).

(ii) Estimation of return periods

Likewise, estimation of discharge for different return periods, it is also significant to estimate the recurrence interval for various discharges such as mean annual peak discharge, large floods, and actually observed maximum annual peak floods. Therefore, recurrence intervals for all the sites on the Mahi River and its major tributaries were estimated by using GEVI probability distribution and results have shown in Table 4.8. The recurrence intervals of mean annual peak discharges (Qm) and large floods (Qlf) are 2.33 year and 6.93 year respectively. Nevertheless, there are great variations in the return periods of actually observed maximum annual peak floods (Qmax) ranging between 720-yr. on the Som River and 38-yr. on the Anas River. The return period of the highest observed Qmax (40663 m^3/s) at Wanakbori site on the Mahi River is 120-yr.

Table 4.8: Return period of Qm, Qlf and Qmax for different gauging sites on the Mahi River and its tributaries (Based on GEVI distribution)

SN	River	Site	Record length	Q m^3/s	Return period (yr)
					GEVI
1	Mahi	Mataji	35	Qm = 3135	2.33
				Qlf = 6568	6.93
				Qmax = 14972	150.00
2	Mahi	Paderdi Badi	39	Qm = 2968	2.33
				Qlf = 6132	6.93
				Qmax = 16153	373.00
3	Mahi	Wanakbori	51	Qm = 10587	2.33
				Qlf = 19757	6.93
				Qmax = 40663	120.00
4	Mahi	Khanpur	38	Qm = 6448	2.33
				Qlf = 13022	6.93
				Qmax = 31062	217.00
5	Anas	Chakaliya	26	Qm = 2329	2.33
				Qlf = 4275	6.93
				Qmax = 6956	38.00
6	Som	Rangeli	39	Qm = 753	2.33
				Qlf = 1697	6.93
				Qmax = 5179	720.00
7	Jakham	Dhariawad	27	Qm = 392	2.33
				Qlf = 853	6.93
				Qmax = 1980	148.00

Qm = Mean annual peak discharge; Qlf = Large flood; Qmax = Maximum annual peak discharge; See Figure 3.1 for location of sites

(iii) Magnitude frequency curve

In order to understand relation between return period and observed discharges magnitude frequency curve have been prepared for all sites on the Mahi River and its major tributaries. Figures 4.5a to Figure 4.5g show that fitted lines are fairly close to the most of the data points. Therefore, these curves can be reliably and conveniently used to derive flood frequency characteristics of the Mahi River and tributaries. However, extrapolation of the lines to estimate discharges for a higher return period such as 200 years, 500 years or 1000 years based on short record length is not likely to be accurate and reliable.

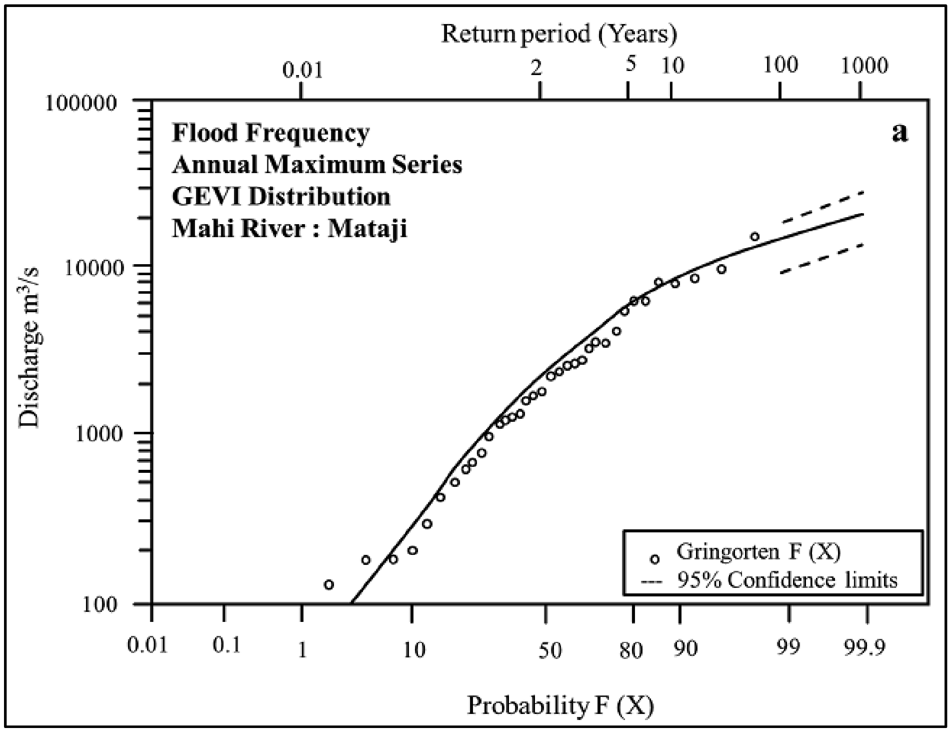


Figure 4.5a: Flood frequency, annual maximum series, GEVI distribution, Mahi River: Mataji

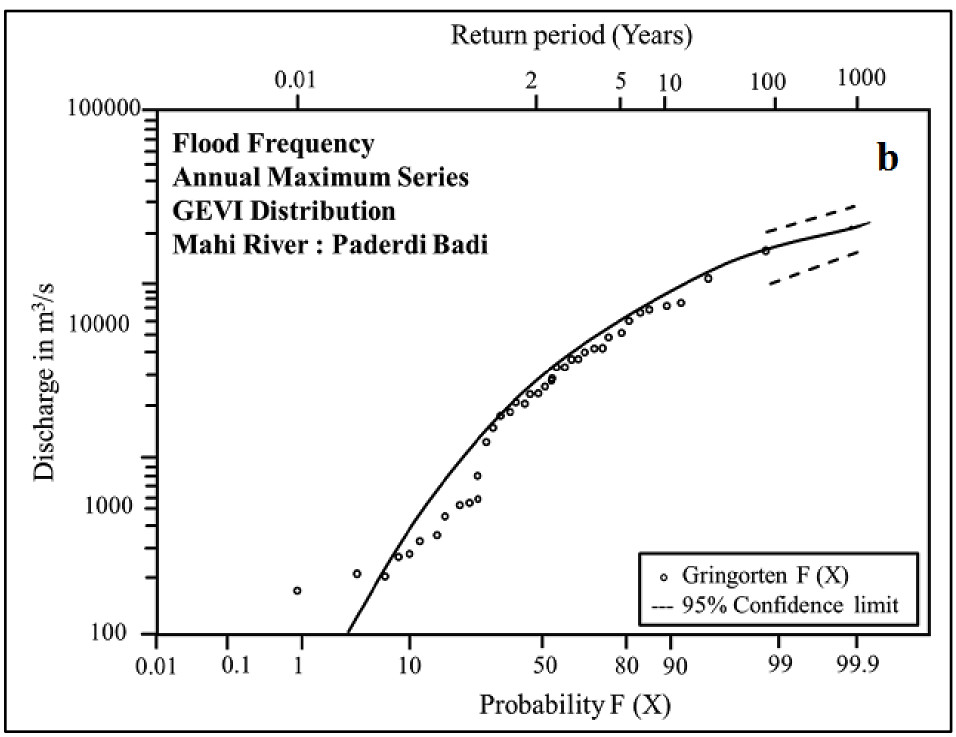


Figure 4.5b: Flood frequency, annual maximum series, GEVI distribution, Mahi River: Paderdi Badi

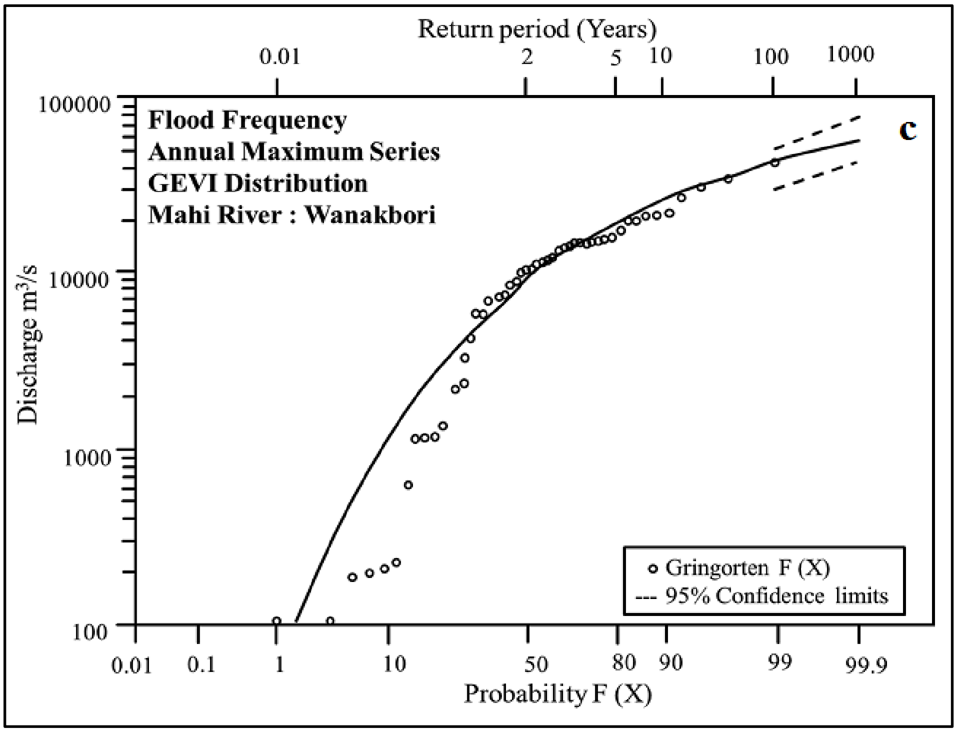


Figure 4.5c: Flood frequency, annual maximum series, GEVI distribution, Mahi River: Wanakbori

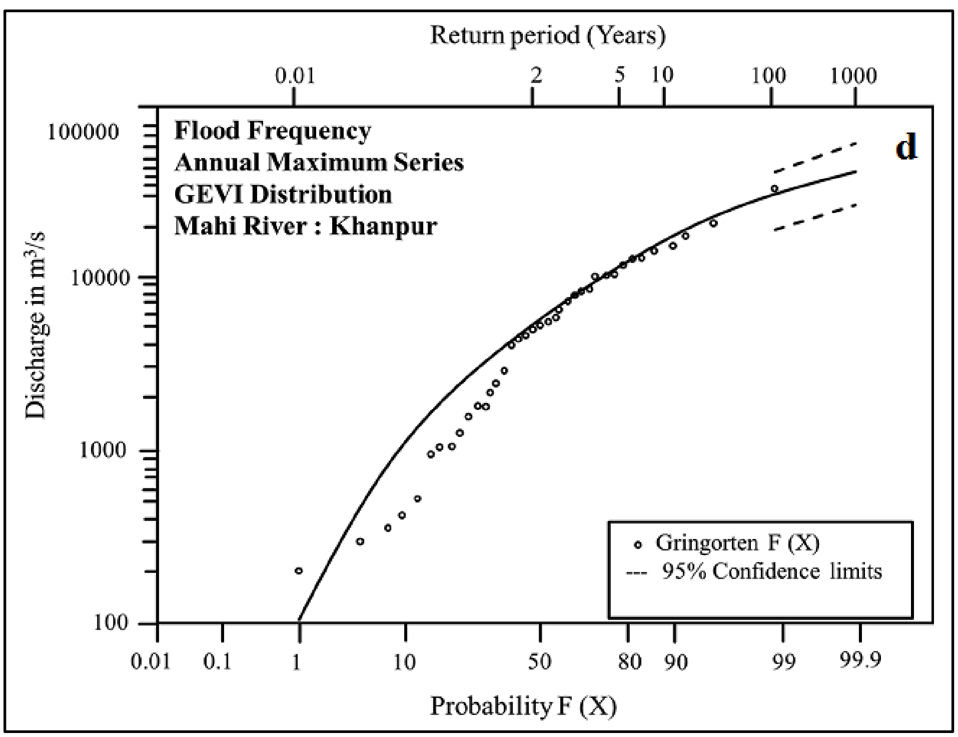


Figure 4.5d: Flood frequency, annual maximum series, GEVI distribution, Mahi River: Khanpur

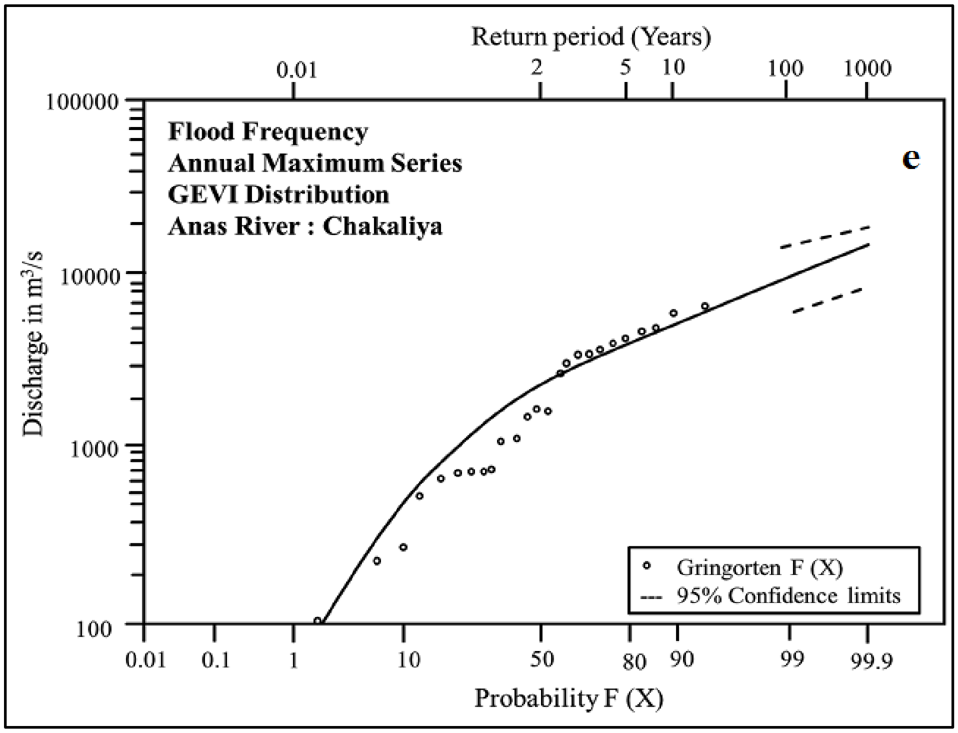


Figure 4.5e: Flood frequency, annual maximum series, GEVI distribution, Anas River: Chakaliya

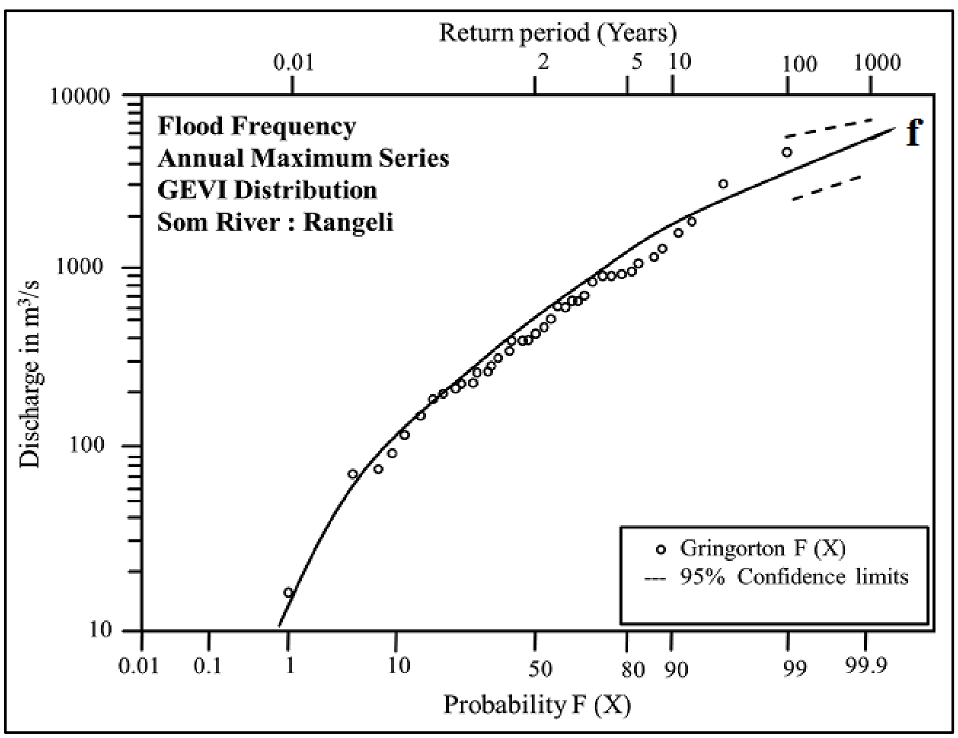


Figure 4.5f: Flood frequency, annual maximum series, GEVI distribution, Som River: Rangeli

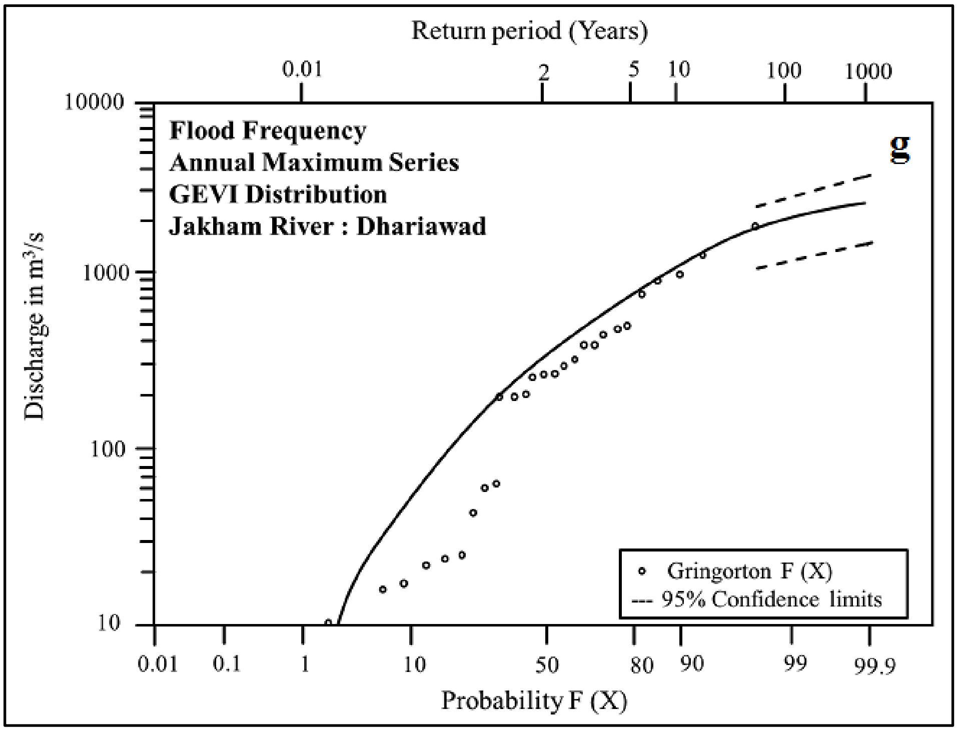


Figure 4.5g: Flood frequency, annual maximum series, GEVI distribution, Jakham River: Dhariawad

4.1.4 Discharge-area envelope curve

The comparative analysis of world envelope curve (Baker, 1995) and the Mahi Basin envelope curve (Figure 4.6) indicates that for drainage areas up to about 10^4 km^2, there is a rapid increase in the maximum possible discharge with an increase in drainage area. Nevertheless, the peak discharge recorded at Wanakbori site (40663 m^3/s) lies below the world envelope curve. However, peak discharges of Rupakheda and Bhungda are above the world envelope curve.

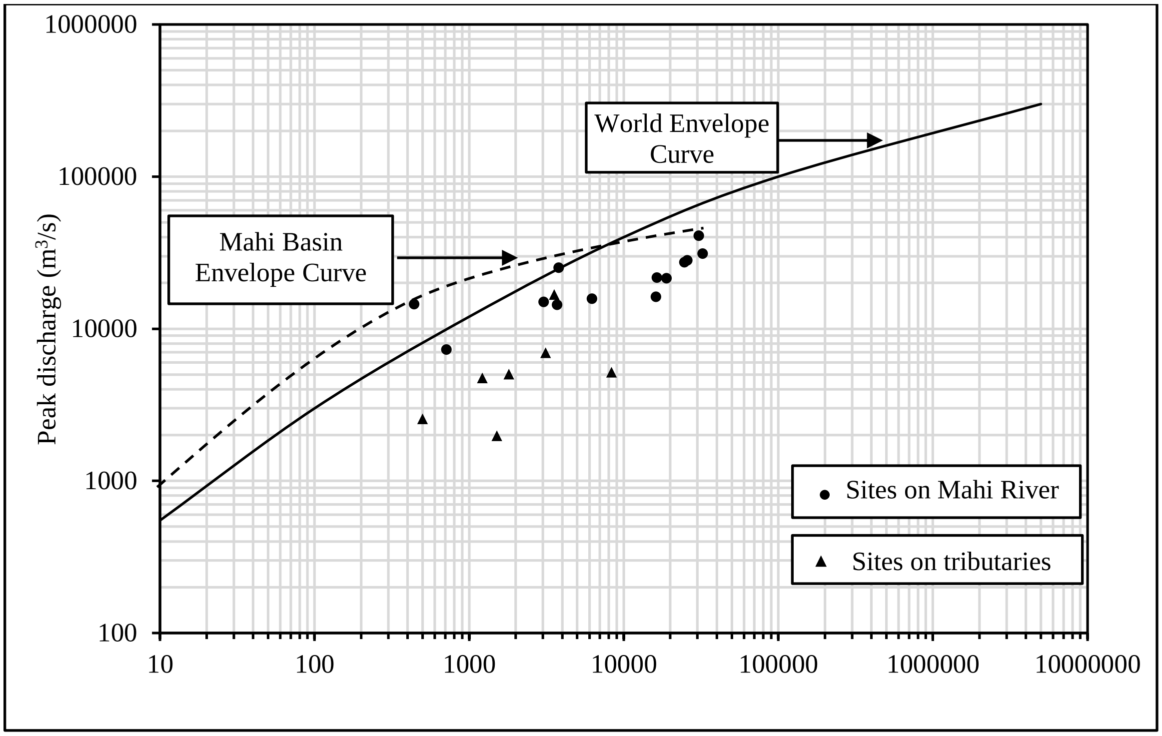


Figure 4.6: World Envelope Curve with reference to Mahi Basin;
Source: Baker, 1995; CWC; Field surveys

4.1.5 Flow duration curve or Discharge frequency curve

The flow duration curve provides the percentage of time during which any selected discharge may be equaled or exceeded (Shaw, 1988). Figures 4.7a to Figure 4.7f show flow duration curves of the Mahi River and its major tributaries based on the daily discharge data of the monsoon season. The duration of flows for different discharges estimated from the curve and summarized in Table 4.9 to Table 4.11.

Table 4.9 and Figure 4.7a to Figure 4.7f reveal that for 50 percent of time of the monsoon season, the flows of the Mahi River at Khanpur and at Paderdi Badi exceeded 363 m^3/s and 176 m^3/s respectively. The Mahi River at Khanpur and the Anas River at Chakaliya experiences higher flows more than 50% of the time as compared to the Som and Jakham Rivers. As compared to the Som and the Jakham River, the high flows in the Anas River occur for about 2% of the time (Table 4.11).

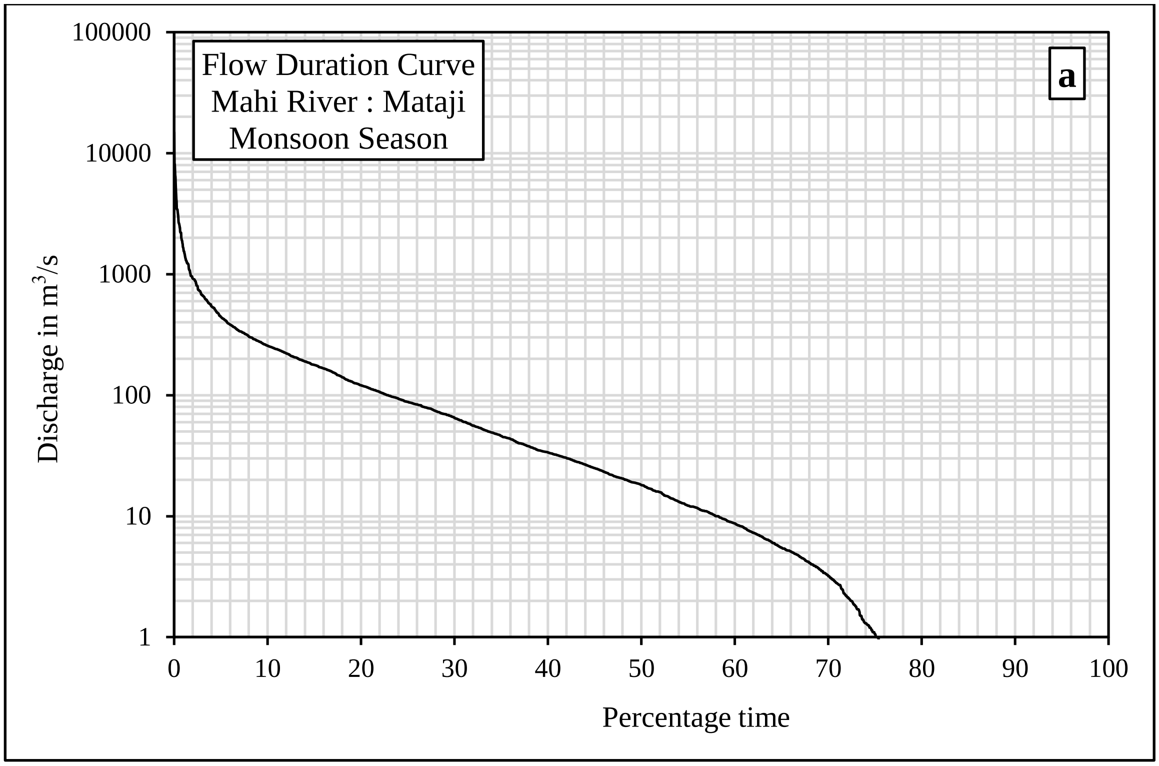


Figure 4.7a: Flow duration curve of the Mahi River: Mataji

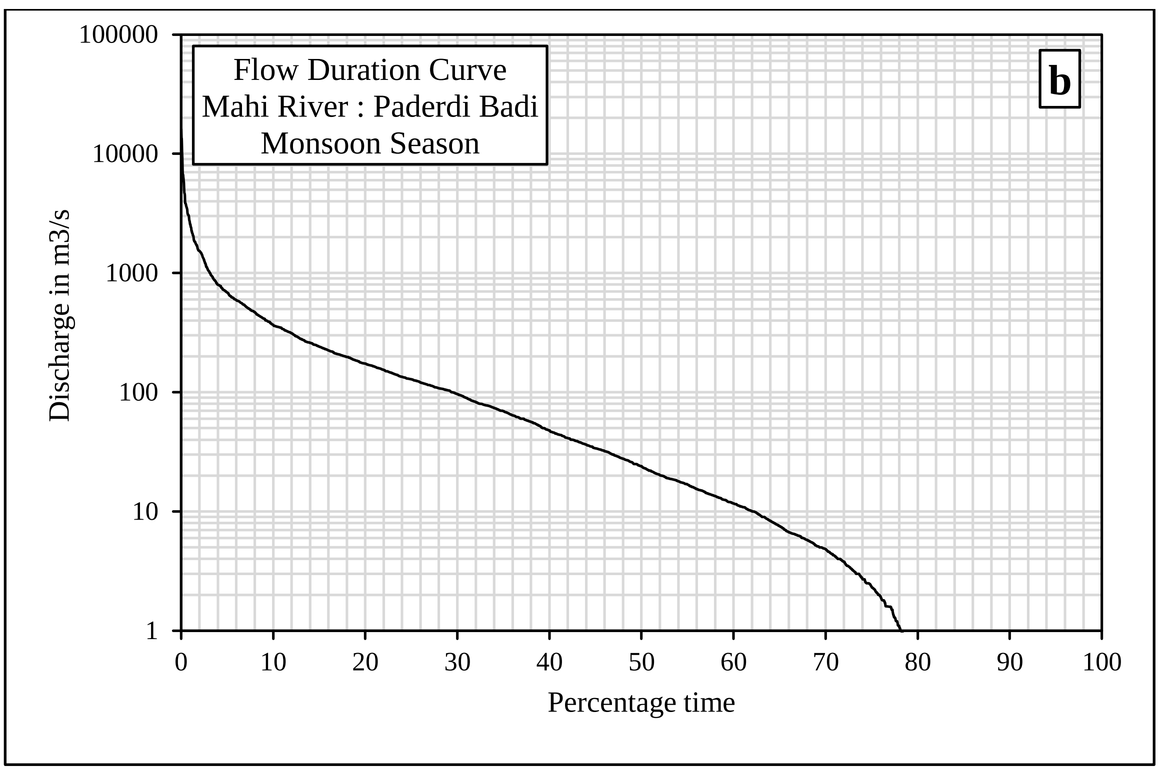


Figure 4.7b: Flow duration curve of the Mahi River: Paderdi Badi

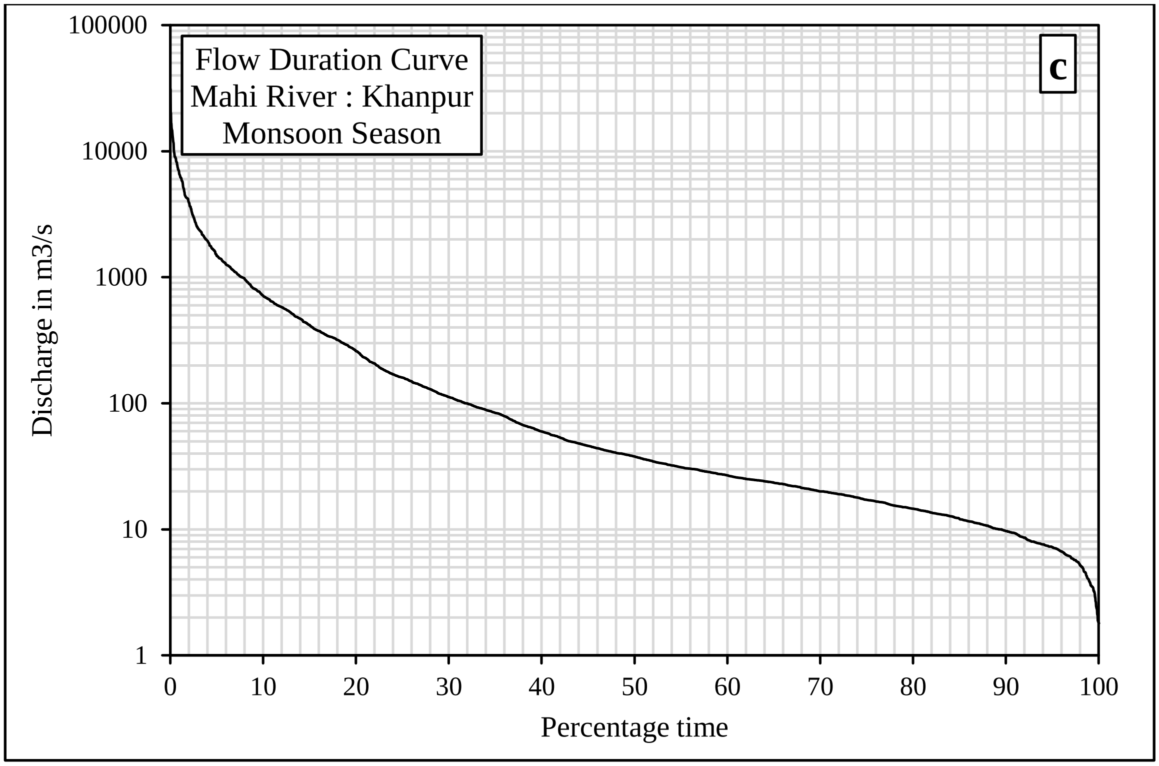


Figure 4.7c: Flow duration curve of the Mahi River: Khanpur

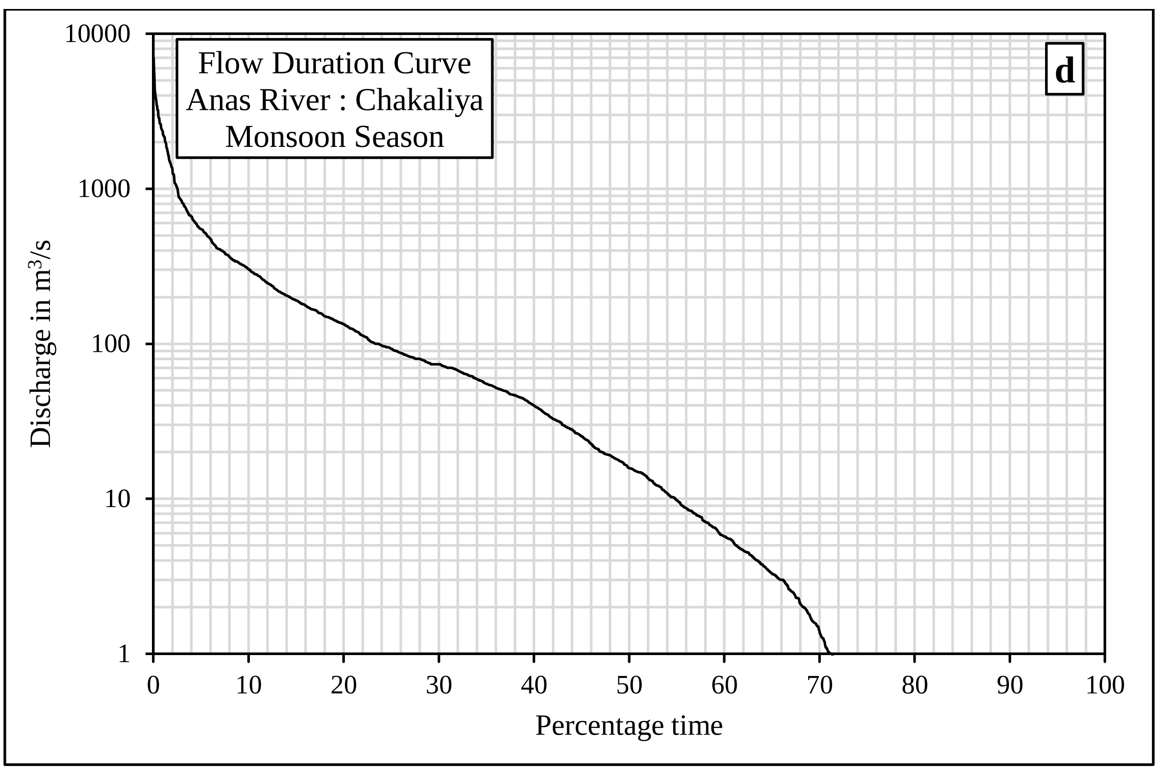


Figure 4.7d: Flow duration curve of the Anas River: Chakaliya

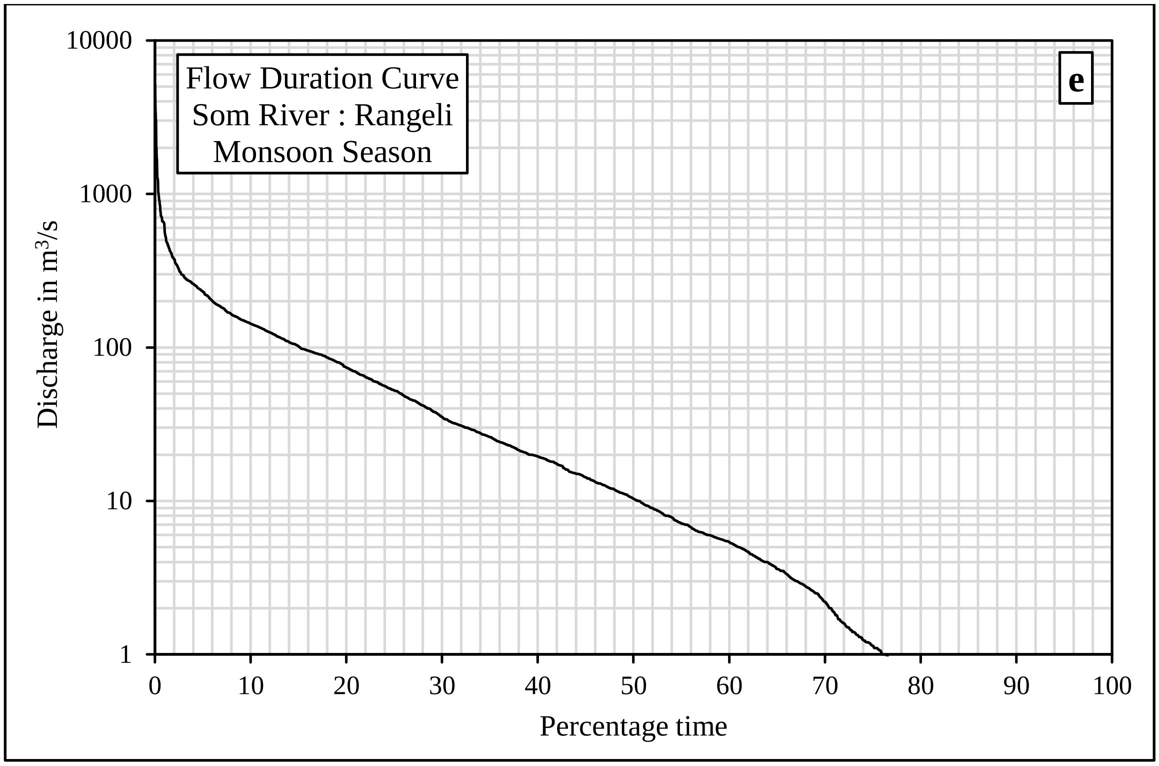


Figure 4.7e: Flow duration curve of the Som River: Rangeli

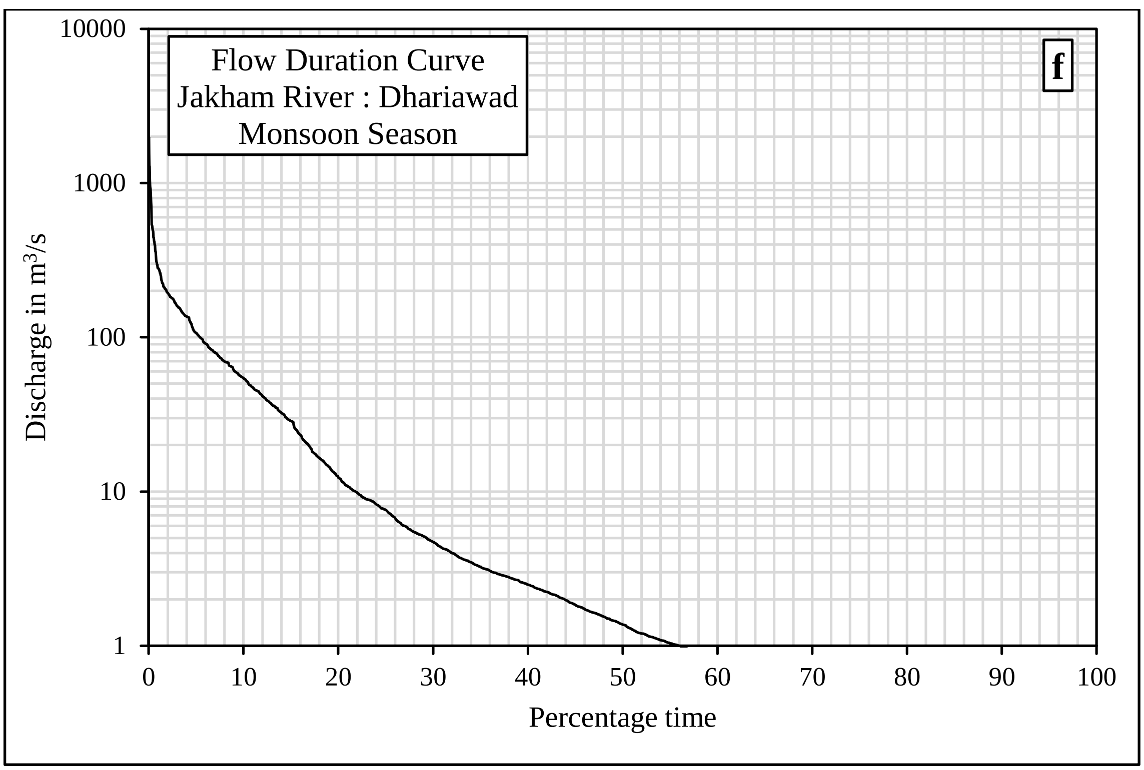


Figure 4.7f: Flow duration curve of the Jakham River: Dhariawad

Table 4.9: Duration of flows

River	Site	Mean Monsoon Flows (m^3/s)	Flows (m^3/s) exceeded for more than 50% of the time
Mahi	Mataji	120	18
Mahi	Paderdi Badi	176	24
Mahi	Khanpur	363	38
Anas	Chakaliya	134	13
Som	Rangeli	55	11
Jakham	Dhariawad	21	01

Source: CWC, See Figure 3.1 for location of sites

Table 4.10: Flow duration for different discharges on the Mahi River

Flow class in m^3/s	Time in %		
	Mataji	Paderdibadi	Khanpur
0 – 100	80	73	69
100 – 500	17	20	19
500 -1000	01	04	05
1000 – 5000	02	03	06
5000 <	0.2	0.3	02

Source: CWC, See figure 3.1 for location of sites

Table 4.11: Flow duration for different discharges on the tributaries

Flow class in m^3/s	Time in %		
	Jakham	Som	Anas
0 – 100	97	87	76
100 – 500	03	12	17
500 -1000	0.3	0.8	05
1000 **<**	0.08	0.4	02

Source: CWC, See figure 3.1 for location of sites

4.1.6 Flood hydrograph analysis

An examination of flood hydrographs (Figure 4.8a to Figure 4.8f) shows steeper rising limb and falling limb. This is mainly because of the control nature of the discharges. Except Chakaliya site on the Anas River, all gauging sites are located downstream of major dams on the Mahi River, Som River and Jakham River. Therefore, sudden release of discharge from dam caused sharp rise in the discharge at downstream and flood hydrographs show high peaks. However, the individual high flow events are long-lasting and generally occur for about 6 to 11 days.

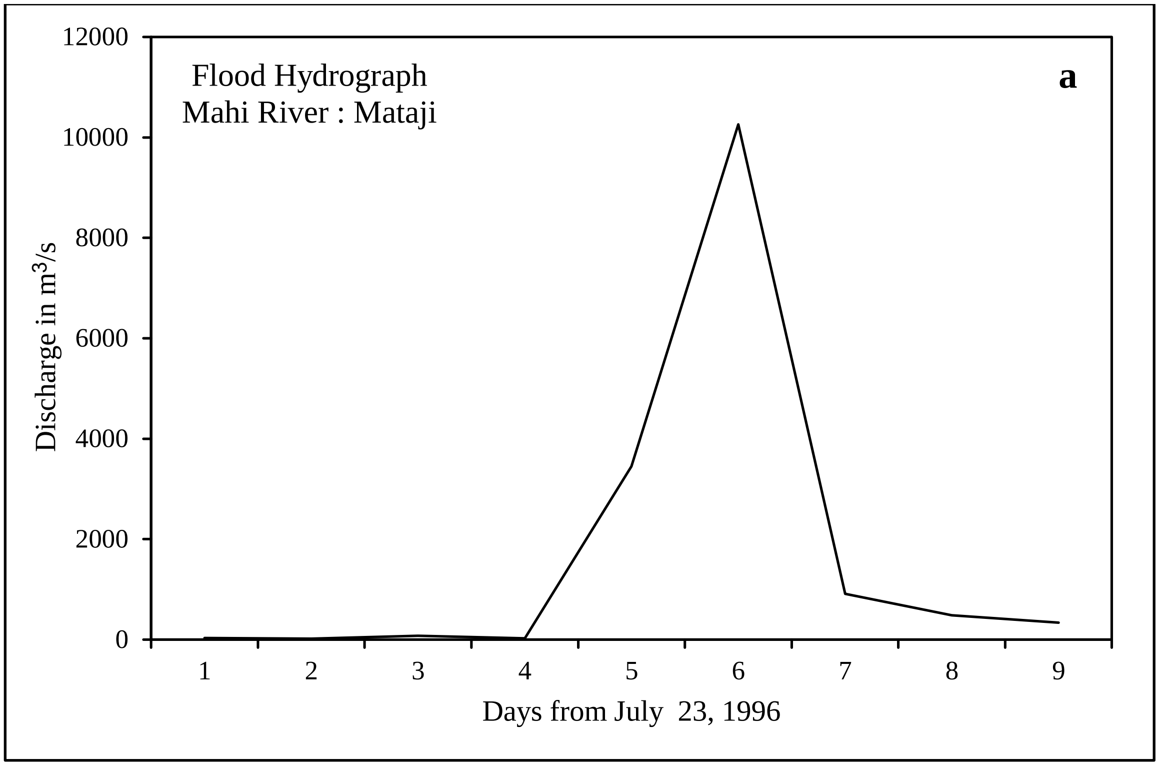


Figure 4.8a: Flood hydrograph of the Mahi River: Mataji

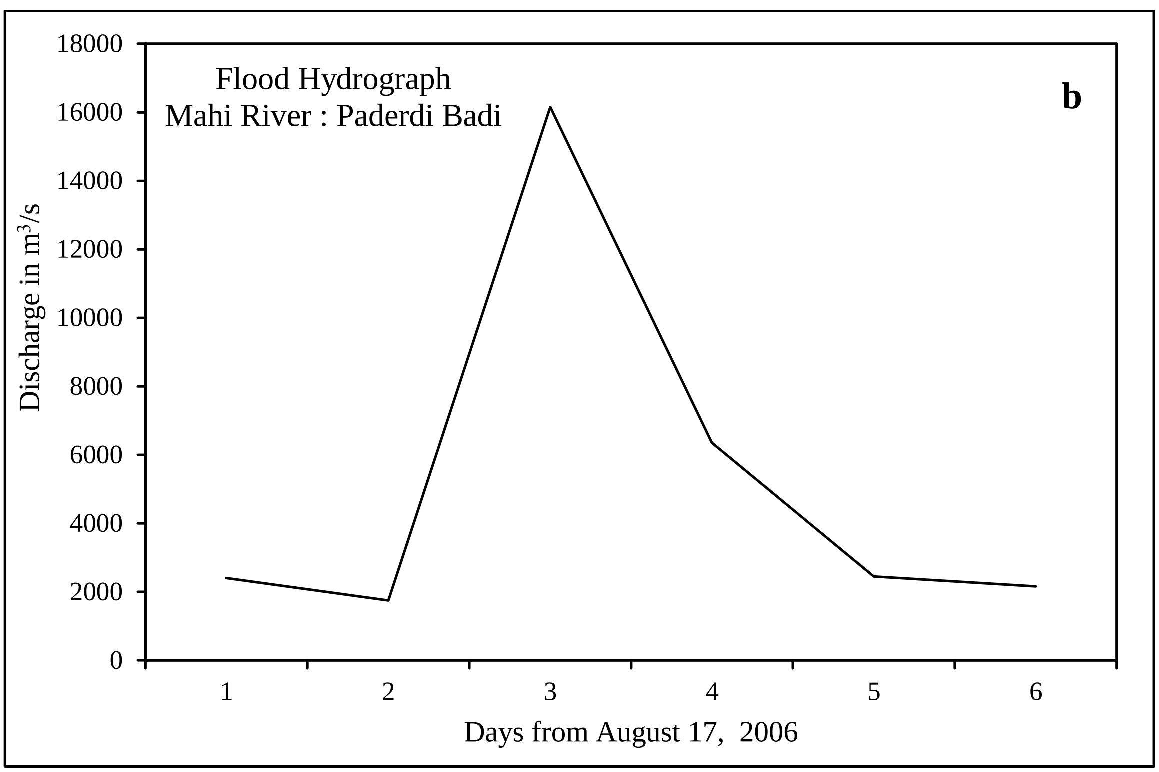


Figure 4.8b: Flood hydrograph of the Mahi River: Paderdi Badi

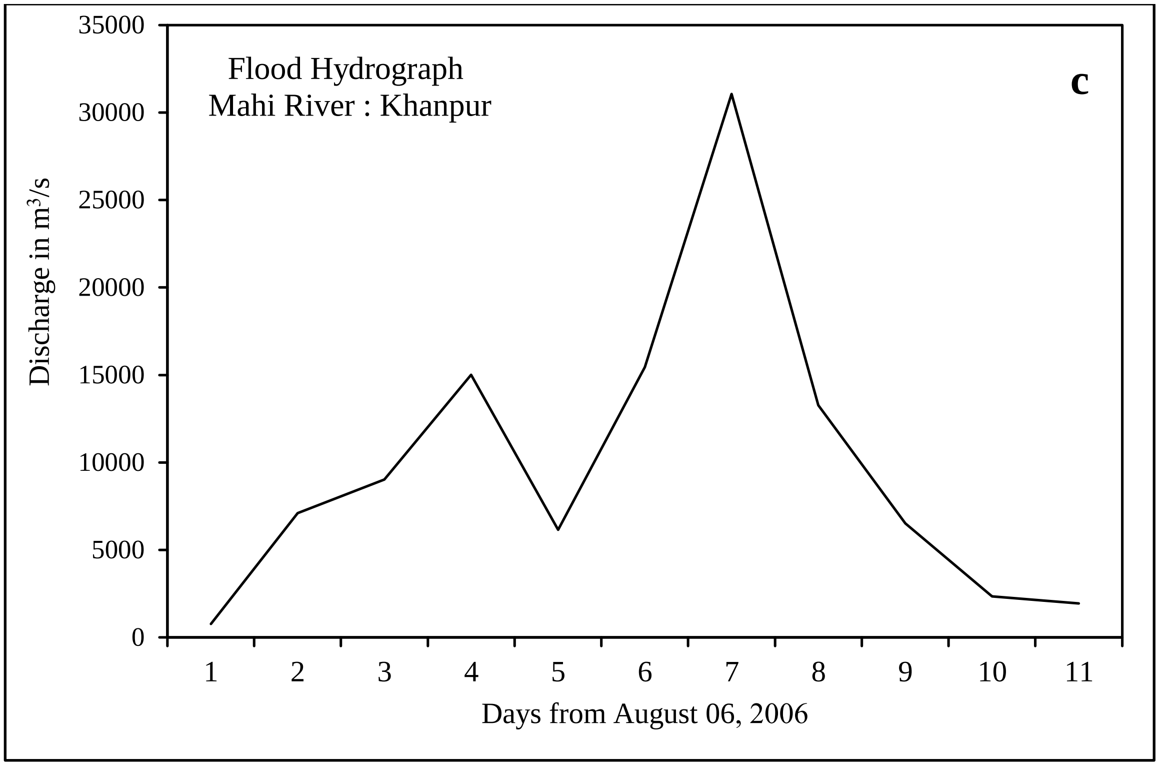


Figure 4.8c: Flood hydrograph of the Mahi River: Khanpur

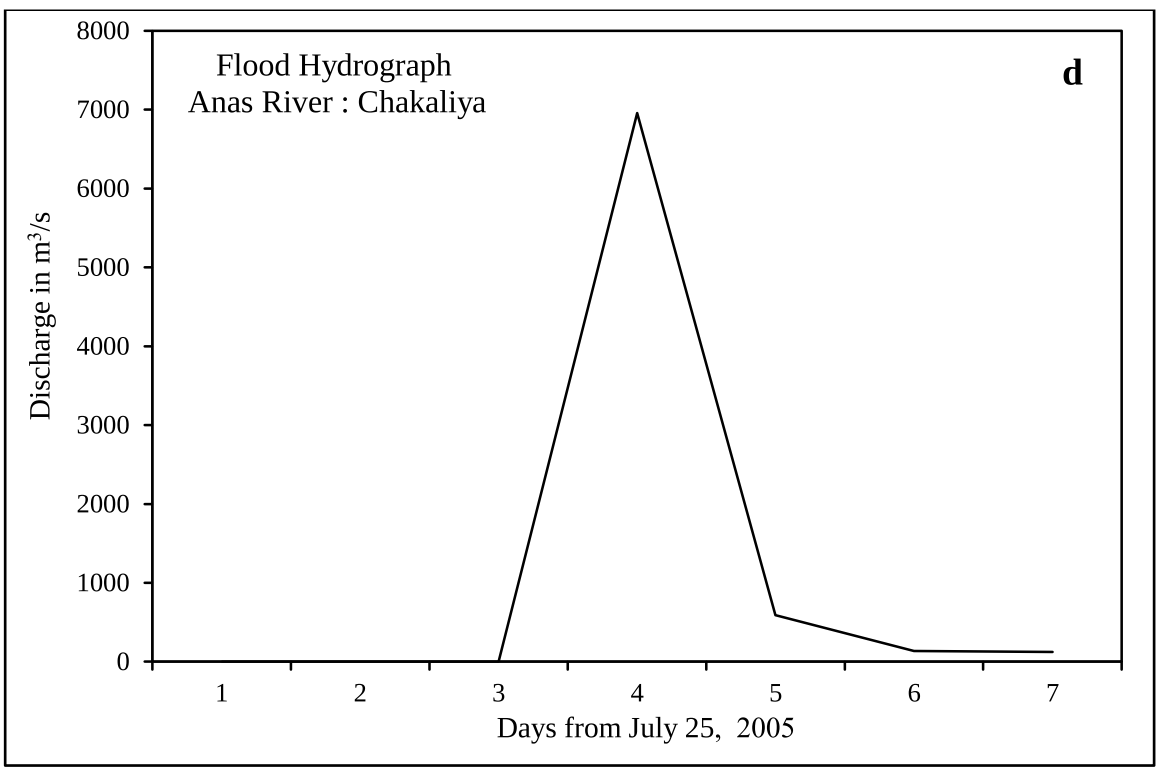


Figure 4.8d: Flood hydrograph of the Anas River: Chakaliya

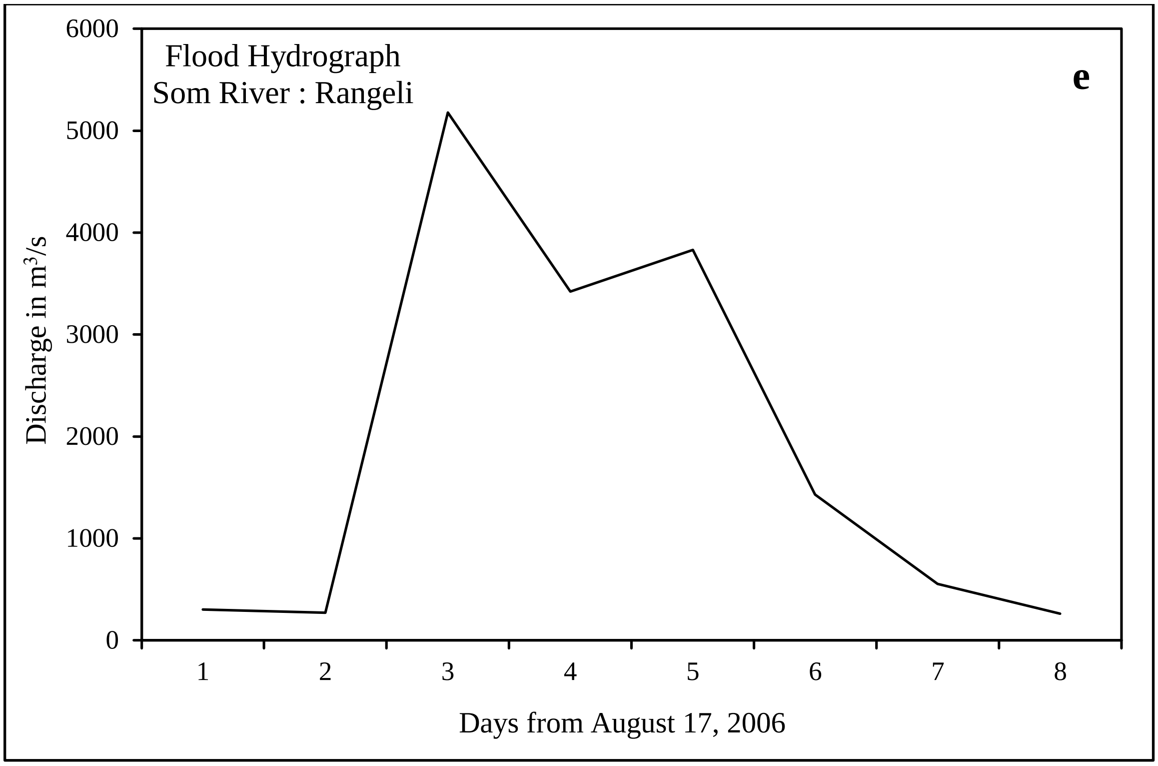


Figure 4.8e: Flood hydrograph of the Som River: Rangeli

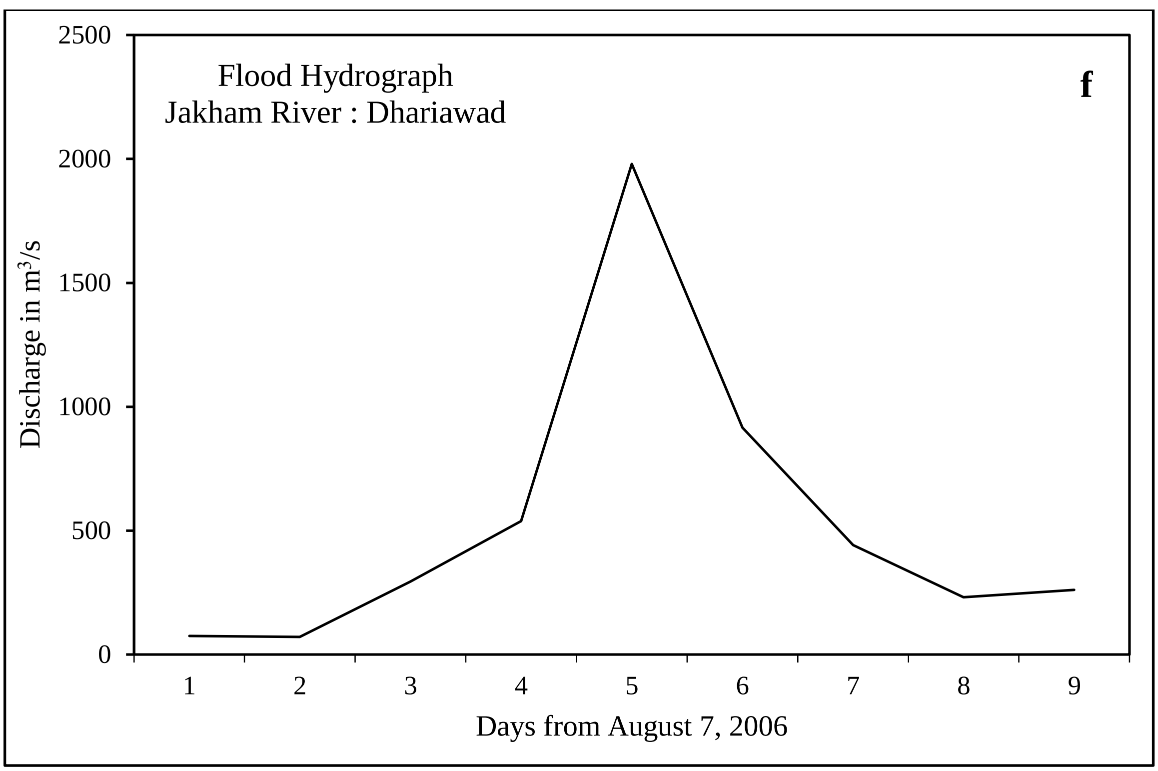


Figure 4.8f: Flood hydrograph of the Jakham River: Dhariawad

4.2 Flood Geomorphology

The Mahi Basin is prominently flood-controlled. However, the geomorphological effectiveness of the flows of extraordinary events can be determined by the channel geometry, the hydraulic characteristics of floods and the dynamics of suspended sediments. Therefore, an attempted has been made to understand the characteristics of the Mahi Basin in terms of the channel size, shape and sediment load during stage of high and low flows. In order to understand the geomorphic effectiveness of flows of different magnitude and return period, the hydraulic geometry and energy exerted by floods have also been discussed in this section.

4.2.1 Channel morphology

Channel morphology is a function of stream discharges and sediment transport rate (Lane, 1955; Blench, 1957; Schumm, 1971) and is mainly controlled by the spatio-temporal variability in discharge regime. Floods are a primary component in fluvial processes since they accelerate the rate of the geomorphic processes of erosion, transport and sedimentation (Junk et al., 1989). However, geomorphic work performed during large floods are significantly varies according to alluvial and bedrock channels (Baker and Kochel, 1988; Baker and Kale, 1998). Therefore, it is essential to describe two main types of the channel system in brief in the following paragraphs.

(I) Types of channel systems - alluvial and bedrock

The Mahi River flows through both, bedrock and alluvial reaches. Since, the Mahi River has its source on the Malwa Plateau which is composed of basalt. Channel of the Mahi River developed as bedrock channel in basalt. Whereas, the alluvial channel of the Mahi River is at lower reaches in the Gujarat plain.

(i) Bedrock channel reaches

The Mahi River flows through basalt up to the Mahi Bajaj Sagar Dam. Although, the channel of the Mahi River has developed over bedrock, it does not prominently shows typical erosional features such as potholes, inner-channel, grooves, knickpoints and waterfalls. However, a knickpoint of 7 m, potholes and grooves have been identified in the source region of the Mahi near Bola village in Sardarpur tehsil of Dhar district of the

Madhya Pradesh (Figure 4.9). Further downstream, at Kothada village, Bhairaogad, Mahudi Ka Mal and Mataji bedrock channel of the Mahi River is bounded steep cliffs of the rock on one side and gentle slope on other. However, downstream of the Mahi Bajaj Sagar Dam, Mahi River bedrock channel have developed partly in basalt rock and partly in metamorphic rocks of the Lunawada -Jhalore and ultramafics group. In this middle reaches, the channel of the Mahi River is mainly bounded by thick quaternary deposits on one bank and bedrock on other (Figure 4.10).

Besides, the Anas River, which is a major left bank tributary of the Mahi River also flows through narrow and deeply incised bedrock gorge at Bankaner where Hiran River meets the Anas River (Figure 4.11). Hiran River is also flows through narrow and deep gorge at this section Figure 4.12). The Som River and the Jakham River also have developed V-shaped valley and deep incised bedrock gorge in the bedrock reaches (Figure 4.13; Figure 4.14; Figure 4.15). The channel beds of the Mahi River and its tributaries are either covered by coarse bedload material or characterized by bare rock exposures. This significantly indicates the role of the large and infrequent flood in the formation of the channel and sediment transport.

Figure 4.9: Knickpoint and waterfall on the Mahi River at Bola village in Sardarpur tehsil (Dhar, Madhya Pradesh)

Figure 4.10: Bedrock channel of the Mahi River with thick quaternary sediment deposits on the banks near Naravali (Banswara, Rajasthan)

Figure 4.11: A view of deeply incised bedrock gorge of the Anas River near Bankaner (Banswara, Rajasthan)

Figure 4.12: A view of deeply incised bedrock gorge of the Hiran River near Bankaner (Banswara, Rajasthan)

Figure 4.13: V-shaped valley of the Som River near Saroli in Kherwara tehsil (Udaipur, Rajasthan)

Figure 4.14: Bedrock channel of the Som River near Masaron ki Obri (Udaipur, Rajasthan)

Figure 4.15: A view of deep and narrow gorge of the Jakham River downstream of Jakham Dam (Pratapgarh, Rajasthan)

(ii) **Alluvial channel reaches**

The alluvial channel reach of the Mahi River extends over the alluvial plain of Gujarat extending from Shihora upto Umeta for a distance of 80 km. After this, it comes under the coastal marine processes. The Mahi River channel cuts alluvial plain and forms meanders. The river channel is bounded by steep cliffy banks exposing sedimentary sequences. The channel has an elevation of 60 m at Balasinor where it emerges from rocky terrain and gradually falls to almost 20 m at Umeta in alluvial plain. In the alluvial plain, Mahi River shows meandering river morphology associated with depositional features like extensive point bars along its convex meander curves, sand bars and distinct unpaired terraces. Besides, badland topography is developed because of gully erosion and headward erosion by smaller gullies on the both banks of the Mahi River downstream of Balasinor (Figure 4.16). For example, the ravines extend inland upto 1.5 km to 2 km Near Shihora.

Figure 4.16: A view of the Mahi River channel (Ahmedabad-Vadodara highway); thick quaternary sediment deposits on the bank with badland

(II) Channel geometry parameters

The morphologic characteristics of a stream channel are controlled by interaction of the hydraulic of flow (velocity, discharge, roughness, and shear stress), channel configuration at the reach and immediately upstream (width, depth, shape, slope and pattern), sediment load entering the reach and composition of bed and bank material (Morisawa, 1985).

The appearance of a river can be divided as channel size and shape, channel gradient and channel pattern. The channel shape and size comprises channel width (W), average depth (D), cross section area (Ca), wetted perimeter (Wp), hydraulic radius (R) and width depth ratio (w/d). Table 4.12 shows the channel reach and cross section variables. The list of cross section sites and its location have been mentioned in Table 4.13 and Figure 3.2 respectively. Besides, channel reach and cross section parameter data for nineteen sites have been summarized in the Table 4.14 and Table 4.15.

Table 4.12: Channel cross section and reach variables used in the present study

Parameter	Symbol	Unit
Maximum width	W	m
Water surface width	w	m
Maximum depth	D	m
Mean depth	d	m
Wetted perimeter	Wp	m
Hydraulic radius	R	m
Channel capacity	Ca	m^2
Width-depth ratio/ Form ratio(F)	W/D	-
Channel slope	S	-
Flow velocity	v	m/s
Catchment area	A	Km^2
Channel length	L	Km

Table 4.13 List of channel cross section sites on the Mahi River and major tributaries

SN	River	Site	Channel morphological and hydraulic parameters
1	Mahi	Rupakheda	W, D, w, d, v
2	Mahi	Kothada	W, D, w, d, v
3	Mahi	Mahudi ka Mal	W, D, w, d, v
4	Mahi	Mataji	W, D, w, d, v
5	Mahi	Bhungda	W, D, w, d, v
6	Mahi	Jagpura	W, D, w, d, v
7	Mahi	Paderdi Badi	W, D, w, d, v
8	Mahi	Kailashpuri	W, D, w, d, v
9	Mahi	Galiyakot	W, D, w, d, v
10	Mahi	Chikhali	W, D, w, d, v
11	Mahi	Kadana	W, D, w, d, v
12	Mahi	Khanpur	W, D, w, d, v
13	Anas	Chakaliya	W, D, w, d, v
14	Anas	Thapra	W, D, w, d, v
15	Som	Saroli	W, D, w, d, v
16	Som	Masaro ki Ovari	W, D, w, d, v
17	Som	Depur	W, D, w, d, v
18	Som	Rangeli	W, D, w, d, v
19	Jakham	Dhariawad	W, D, w, d, v

Refer Table 4.12 for the notations

Table 4.14: Channel morphologic variables of cross sections of the Mahi River

SN	Site	A	L	W	D	C_a	F	Wp	R	Channel gradient
1	Rupakheda	442	28.72	167	12.38	1596	13.49	205	7.77	0.0084370
2	Kothada	716	47.52	146	8.44	909	17.27	167	5.44	0.0061240
3	Mahudi ka Mal	3046	118.58	216	16.07	2392	13.42	249	9.6	0.0016300
4	Mataji	3714	145.93	240	13.61	2486	17.63	269	9.24	0.0012000
5	Bhungda	6260	197.96	326	24.39	6430	13.35	390	16.5	0.0006000
6	Jagpura	3803	253.96	310	15.4	3803	20.13	374	10.17	0.0012170
7	Paderdi Badi	16298	285.66	333	15.32	4464	21.77	340	13.13	0.0003940
8	Kailashpuri	16471	299.77	640	16.07	7421	39.38	741	10.02	0.0003626
9	Galiyakot	18989	320.25	732	20.14	8054	36.35	778	10.35	0.0013000
10	Chikhali	24819	335.25	840	20.45	8820	41.08	848	10.4	0.0007960
11	Kadana	25884	361.72	450	29.49	9720	15.26	460	21.13	0.0001850
12	Khanpur	32837	506.38	495	18.83	5464	26.29	388	14.07	0.0008415
-	Min	-	-	146	8.44	909	13.35	167	5.44	0.0001850
-	Max	-	-	840	29.49	9720	41.08	848	21.13	0.0084370
-	Mean	-	-	408	17.55	5130	22.95	434	11.49	0.0019239
-	σ	-	-	227	5.60	2974	10.40	231	4.19	-
-	Cv (%)	-	-	56	31.93	57.97	45.33	53.2	36.46	-

Sources: CWC; Field surveys and other: A = Upstream catchment area in km^2: L = Distance from source in km: σ = Standard deviation; Cv = Coefficient of variation in %; Refer Table 4.12 for notations; See Figure 3.2 for location of the sites

Table 4.15: Channel morphologic variables of cross sections of tributaries of the Mahi River

SN	Site	A	L	W	D	C_a	F	Wp	R	channel gradient
Som River										
1	Saroli	499	26.21	120	11.46	824	10.47	303	2.72	0.002320
2	Masaro ki Ovari	1216	56.14	137	11.46	859	11.95	118	7.29	0.002000
3	Depur	1806	65.50	206	10.22	1549	20.16	207	7.49	0.000666
4	Rangeli	8498	131.00	347	7.98	1923	43.45	384	5.01	0.000776
-	Min	-	-	120	7.98	824	10.47	118	2.72	0.000666
-	Max	-	-	347	11.46	1923	43.45	384	7.49	0.002320
-	Mean	-	-	203	10.28	1289	21.51	253	5.63	0.001441
-	σ	-	-	103	1.64	539	15.24	115	2.24	-
-	Cv (%)	-	-	51	15.963	41.8	70.84	46	39.82	-
Anas River										
1	Chakaliya	3072	84.19	211	13.00	2529	16.23	327	7.74	0.000457
2	Thapra	3549	137.40	260	15.22	3072	17.08	275	11.17	0.001884
Jakham River										
1	Dhariawad	1510	58.00	225	9.50	1525	23.68	274	5.57	0.001931

Sources: CWC; Field surveys and other: A = Upstream catchment area in km^2: L = Distance from source in km: σ = Standard deviation; Cv = Coefficient of variation in %; Refer Table 4.12 for notations; See Figure 3.2 for location of the sites

(III) Channel form

The channel morphology variables are usually obtained with reference to the maximum annul peak discharge (Qmax) observed at each cross section and result of these parameters have been discussed in the following section.

(i) Channel width (W)

The distance measured across the river channel from bank to bank during bankfull stage is considered as channel width. The Figure 4.17 and Figure 4.18 show the cross sections along the Mahi River. However, Figure 4.19 indicates cross sections along the major tributaries of the Mahi River (See figure 3.2 for location of the sites). The channel of the Mahi River is narrow in the upper reaches at Rupakheda (Figure 4.17) and significantly become wider in the middle reaches at Chikhali (Figure 4.18). Table 4.14 shows that the average width of the Mahi River channel is 408 m and it varies from 149 m at Kothada to

840 m at Chikhali (Figure 4.17; Figure 4.18). Generally, at lower reaches width of the channel increases gradually, but in case of the Mahi River after Chikhali site river channel width decrease comparatively due to deeply incised channel over the thick sedimentary sequences bounded by quaternary sediment cliffs. However, the channel of the Mahi River becomes comparatively narrow at Kadana Dam where it cuts the ridges laying across the river (Table 4.14; Figure 4.18). The average channel width of the Som River is 203 m and varies between 120 m to 347 m (Table 4.15).

(ii) Channel depth (D)

Channel depth is an important parameter that determines the power per unit area and boundary shear stress at a cross section. Table 4.14 reveals that maximum channel depth (29.49 m) of the Mahi River is at Kadana where cuts the ridge extends across the channel. However, the average channel depth of the Mahi River is 18 m and varies between 8 m and 18 m (Table 4.14). The mean depth of the Som River channel is 10 m (Table 4.15). Figure 4.20 shows that there is gradual increase in depth in the downstream direction.

(iii) Channel capacity (Ca)

The channel capacity is the cross sectional area which denotes the quantity of water and sediments that can be accommodated by channel (Petts and Foster. 1985). The average channel capacity of the Mahi River is 5130 m^2 and ranges between 909 and 9720 m^2 (Table 4.14). The maximum channel capacity of the Mahi River was found at Kadana due to presence of Kadana gorge. The variation in the channel sizes of the Mahi River specifies that the discharges of sufficient magnitude had occurred in the past to create such a large channel. Mean channel capacity of the Som River is 1289 m^2 (Table 4.15).

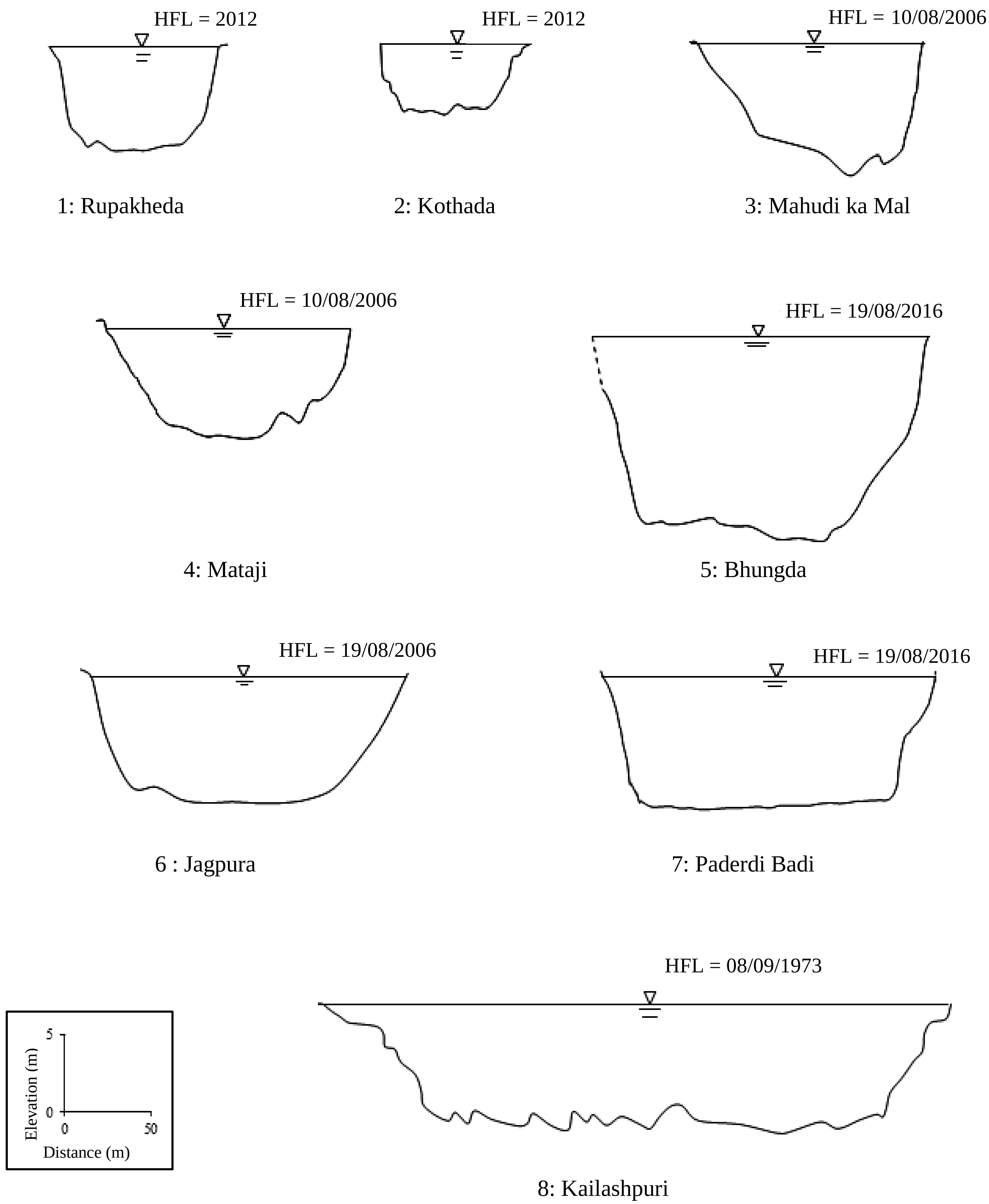


Figure 4.17: Cross sections, Mahi River; See Figure 3.3 for location of sites; HFL = High flood level

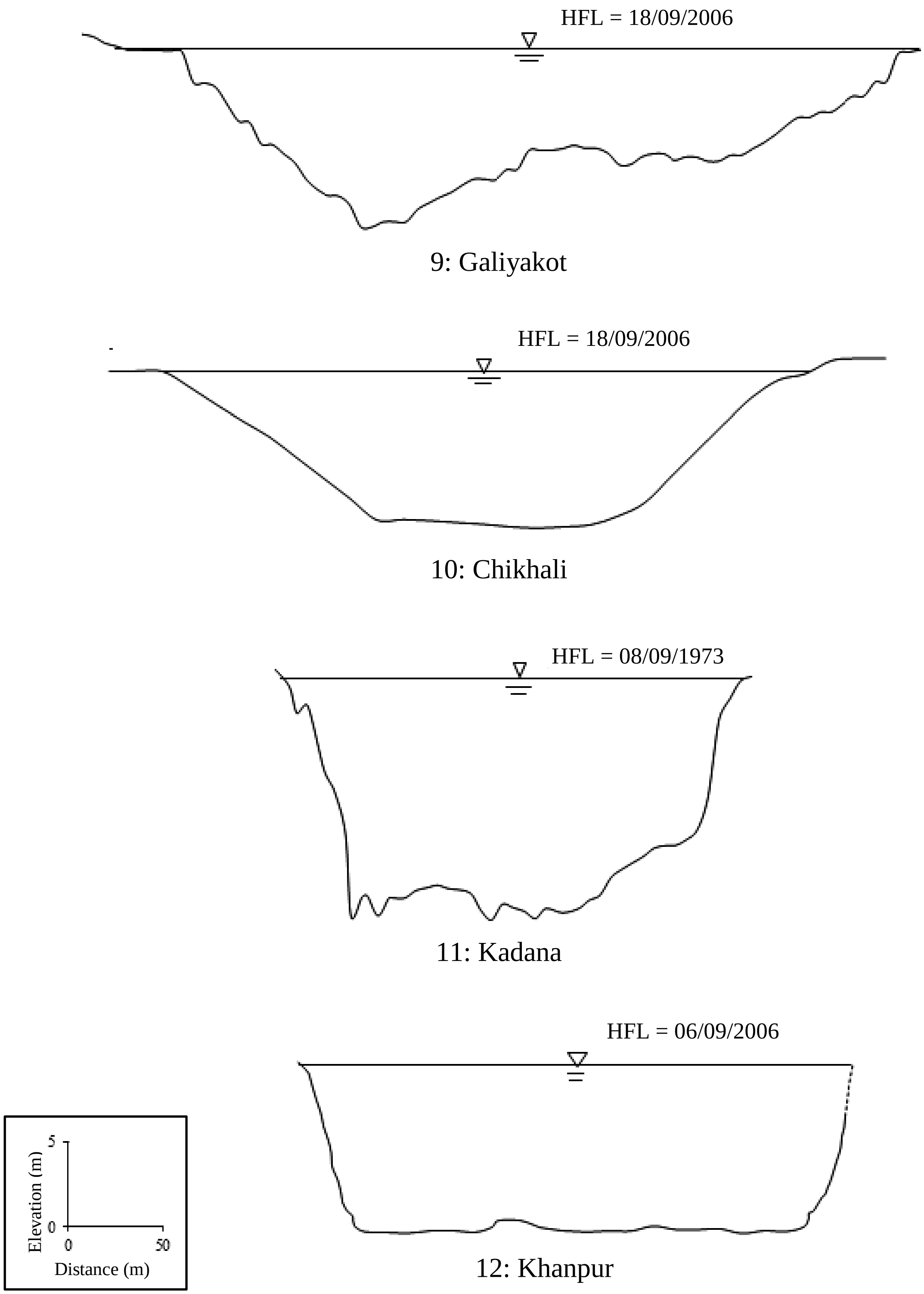


Figure 4.18: Cross sections, Mahi River; See Figure 3.3 for location of sites; HFL = High flood level

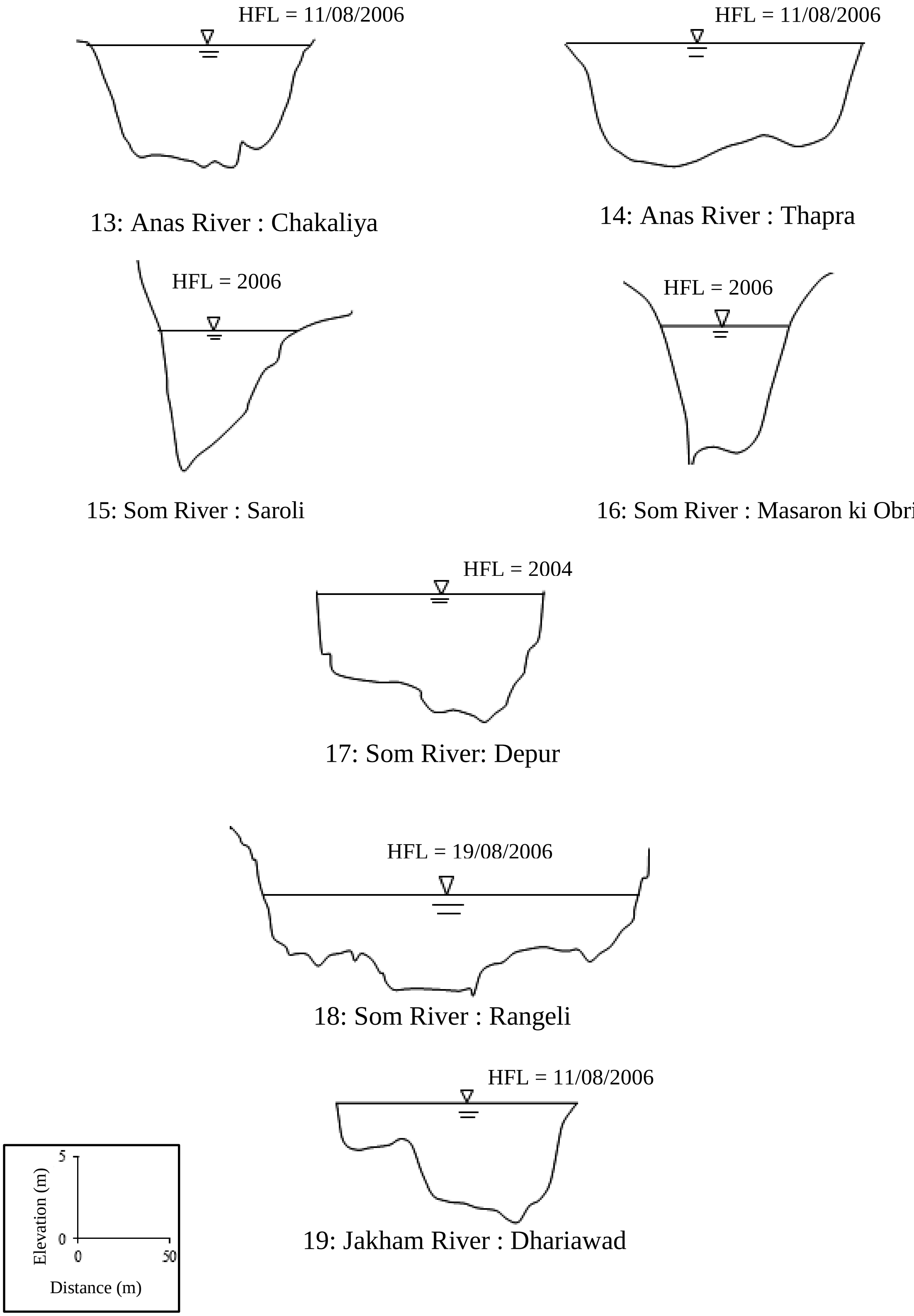


Figure 4.19: Cross sections, Anas River, Som River, Jakham River; See Figure 3.3 for location of sites; HFL = High flood level

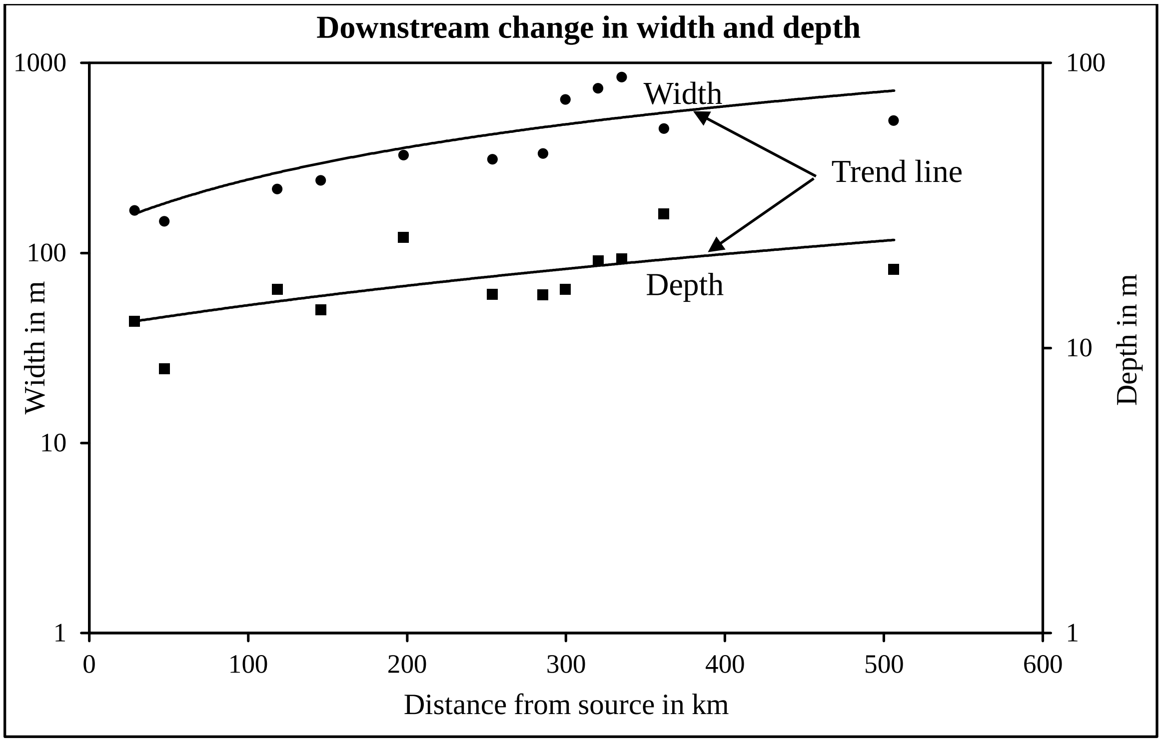


Figure 4.20: Downstream change in width and depth of the Mahi River channel

(iv) Form ratio (F)

The channel width depth ratio is known as form ratio. According to Schumm (1960) form ratio is a measure of channel shape which is related to the sediment transport and boundary resistance. The average form ratio of the Mahi River is 23 and varies between 13 and 41. The highest form ratio was found at Chikhali due to wide channel and lowest form ratio at Bhungda because channel is bounded by rock cliff of the right bank and quaternary sediment deposition on the left bank. Nevertheless, form ratio of the Som River ranges between 10 and 43 (Table 4.15).

(v) Hydraulic radius (R)

According to Petts and Foster (1985), channel efficiency is measured by hydraulic radius. The average value of the hydraulic radius of the Mahi River is 11 m and varies between 5 to 21 m (Table 4.14). Mean hydraulic radius of the Som river channel is 6 m (Table 4.15).

(vi) Channel gradient

The channel gradient is one of the significant morphological variables which determine velocity, unit stream power and geomorphic impact. The average channel gradient of the Mahi River is 0.00086 (Table 1.1) and decrease in downstream direction. In the upper reaches (upto Bhungda) the channel gradient is about 0.00113 whereas, in the middle reaches (upto Kadana Dam) the channel gradient is 0.00023. The decreasing gradient from upper to lower reaches suggests that decreasing slope may offset any increase in depth and velocity as a flood moves downstream.

4.2.2 Adjustments in channel form with discharge

(I) Change in the width-depth ratio with discharge

The channel of the Mahi River is box-shaped, with more or less flat channel floor and bounded by elevated banks of quaternary sediment deposits. Consequently, during pre and post monsoon seasons when low flows exist in the channel, water spreads and the width is high and depth is low. This reveals high width-depth ratio and channel shows all features of the shallow and wide channel. Nevertheless, during monsoon season due to heavy rainfall as stage-discharge increases, there is significant increase only in the depth of streamflows. Figure 4.21 illustrate the plot of width-depth ratios for low flows as well as high flows for different cross sections along the Mahi River.

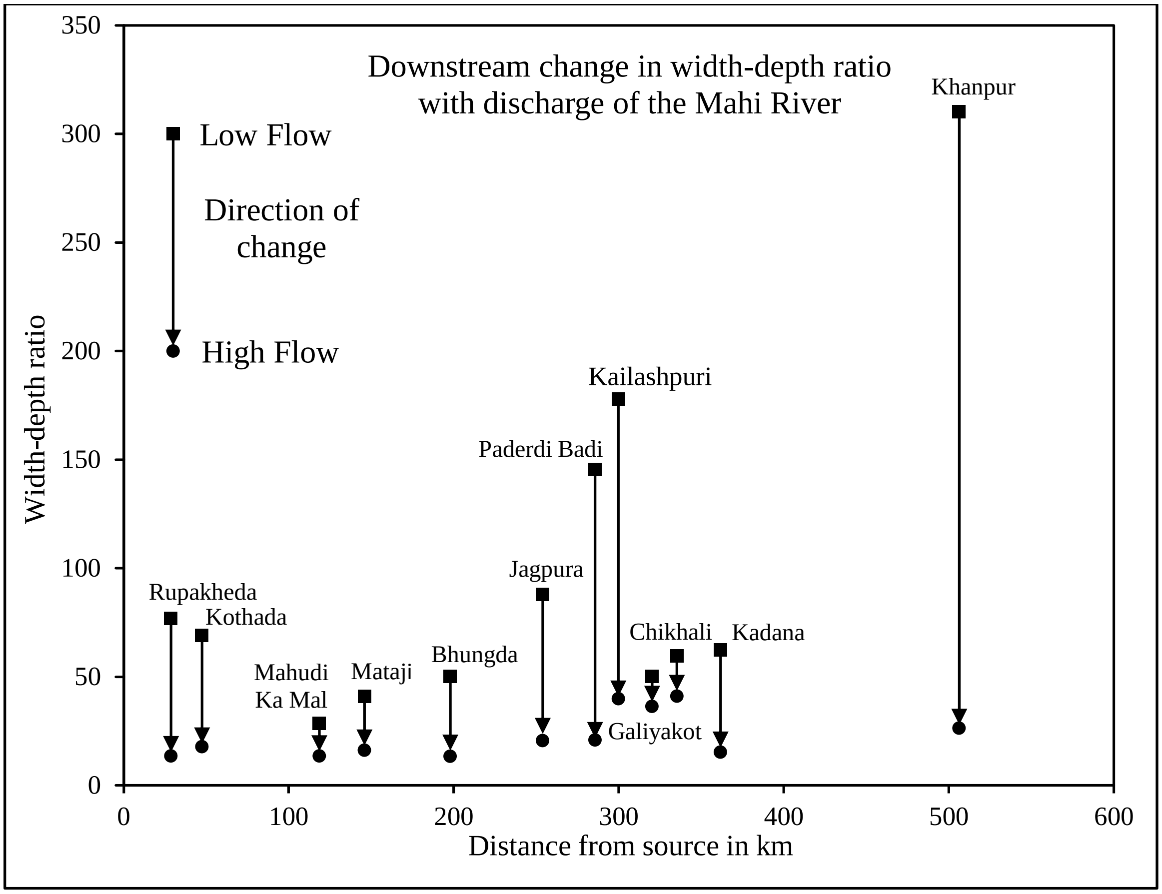


Figure 4.21: Downstream variation in width-depth ratio with discharge

Regression analysis was carried out to evaluate the relationship between width depth ratio and discharge for the Mahi River and its major tributaries (Figure. 4.22a to Figure 4.22f). The analysis shows that rate of change in width depth ratio with discharge is higher at Paderdi Badi and Khanpur where channel is almost flat and box-shaped which indicates similar characteristics as the value of r^2 is same (0.88). This indicates that the flows become deeper and efficient as the discharge increases. Gupta (1995a) and Deodhar and Kale (1999), have been found the same behaviour of other rivers of the seasonal tropics. Therefore, this suggests that large flood events are geomorphologically more effective than low or moderate flows.

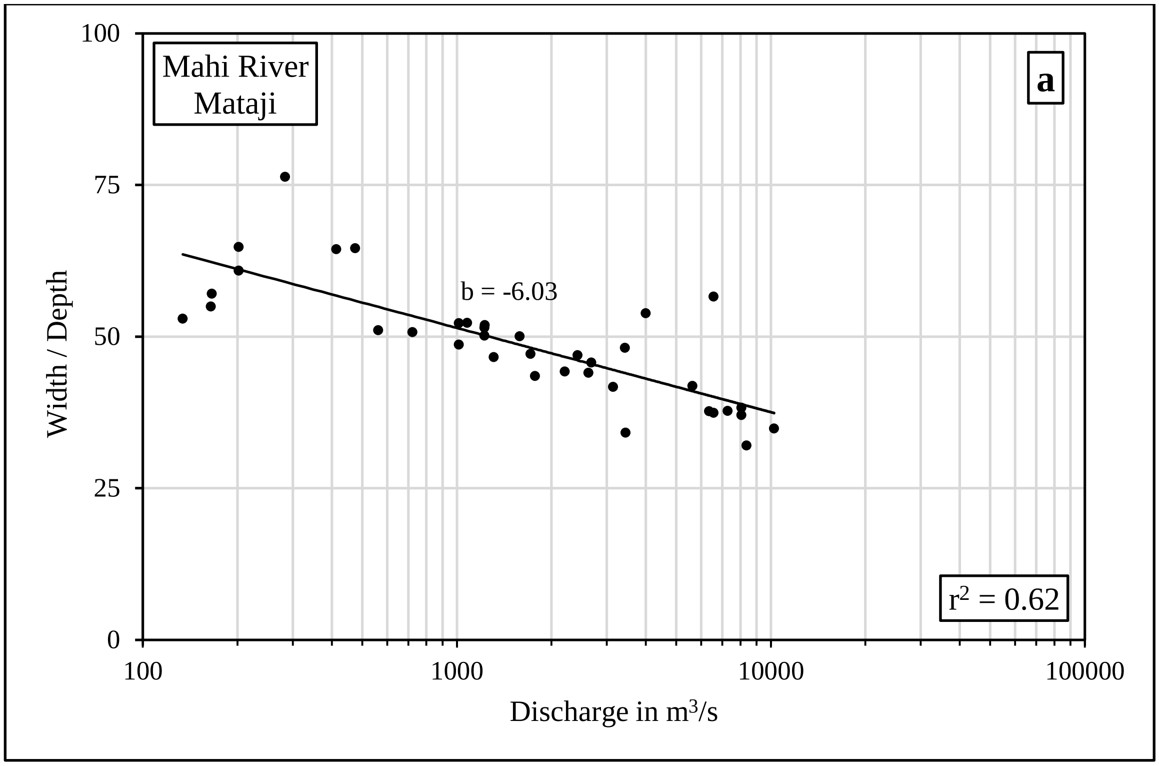


Figure 4.22a: Relation between Width/Depth and discharge; Mahi River: Mataji

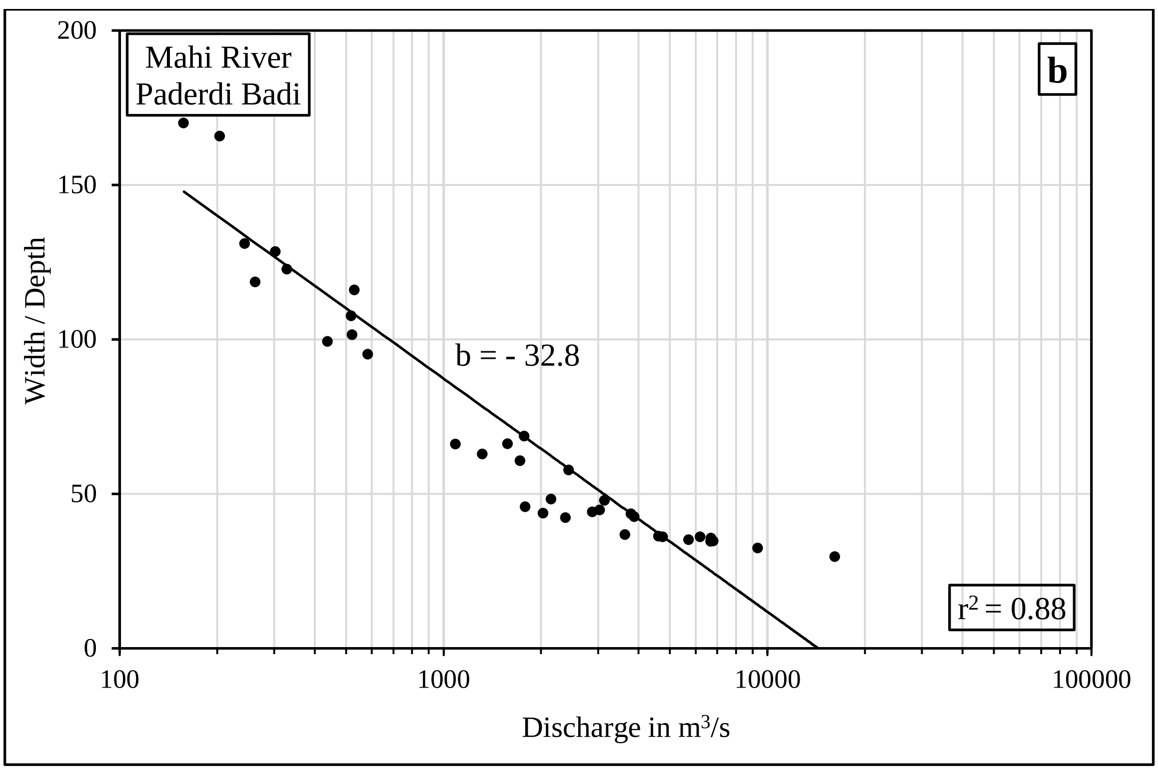


Figure 4.22b: Relation between Width/Depth and discharge; Mahi River: Paderdi Badi

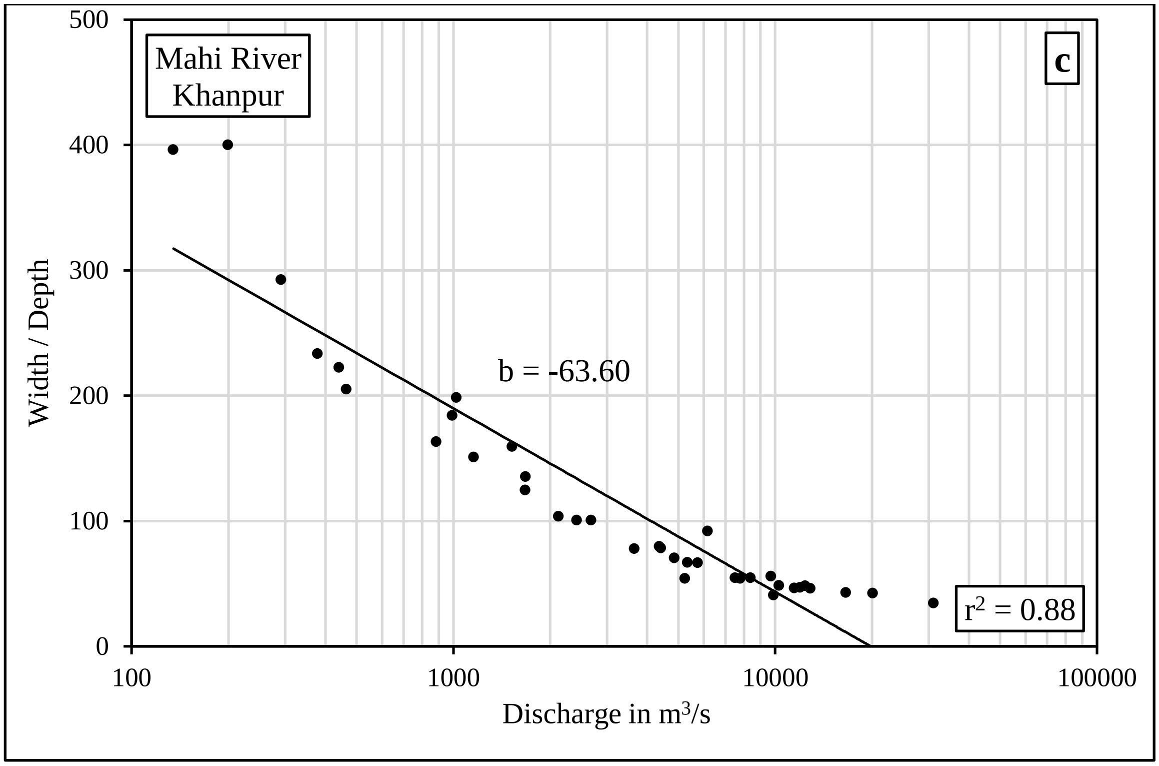


Figure 4.22c: Relation between Width/Depth and discharge; Mahi River: Khanpur

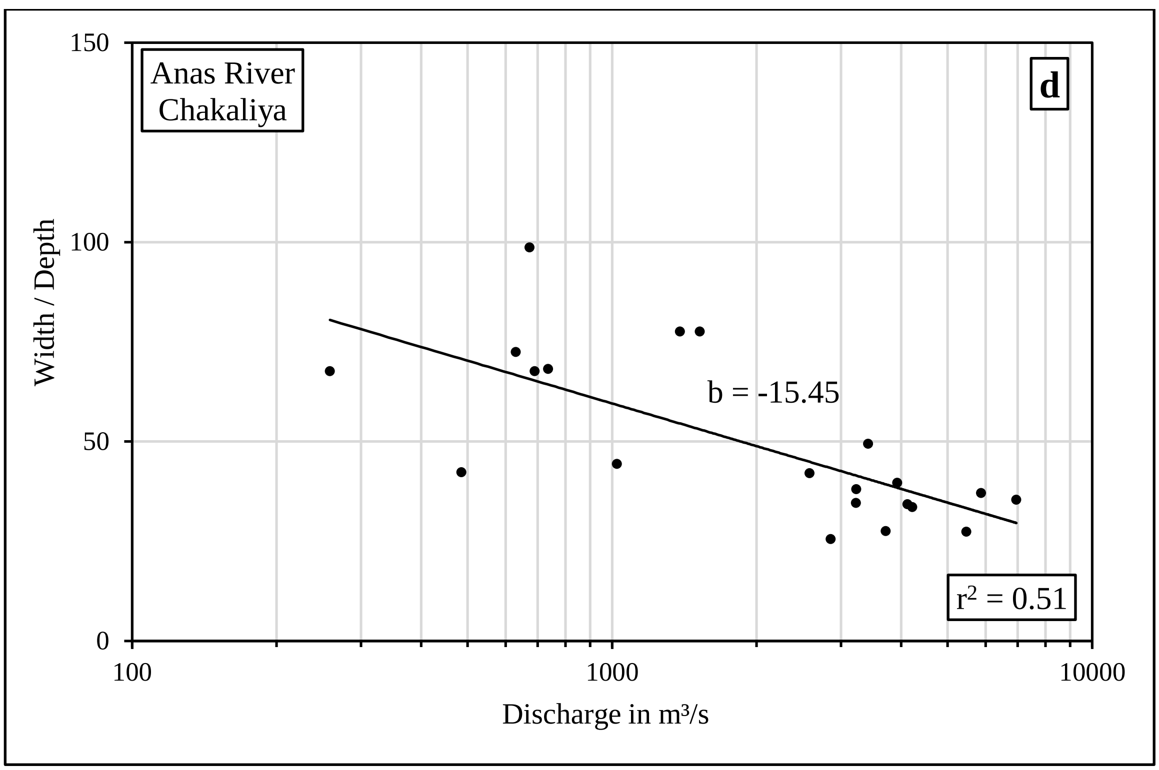


Figure 4.22d: Relation between Width/Depth and discharge; Anas River: Chakaliya

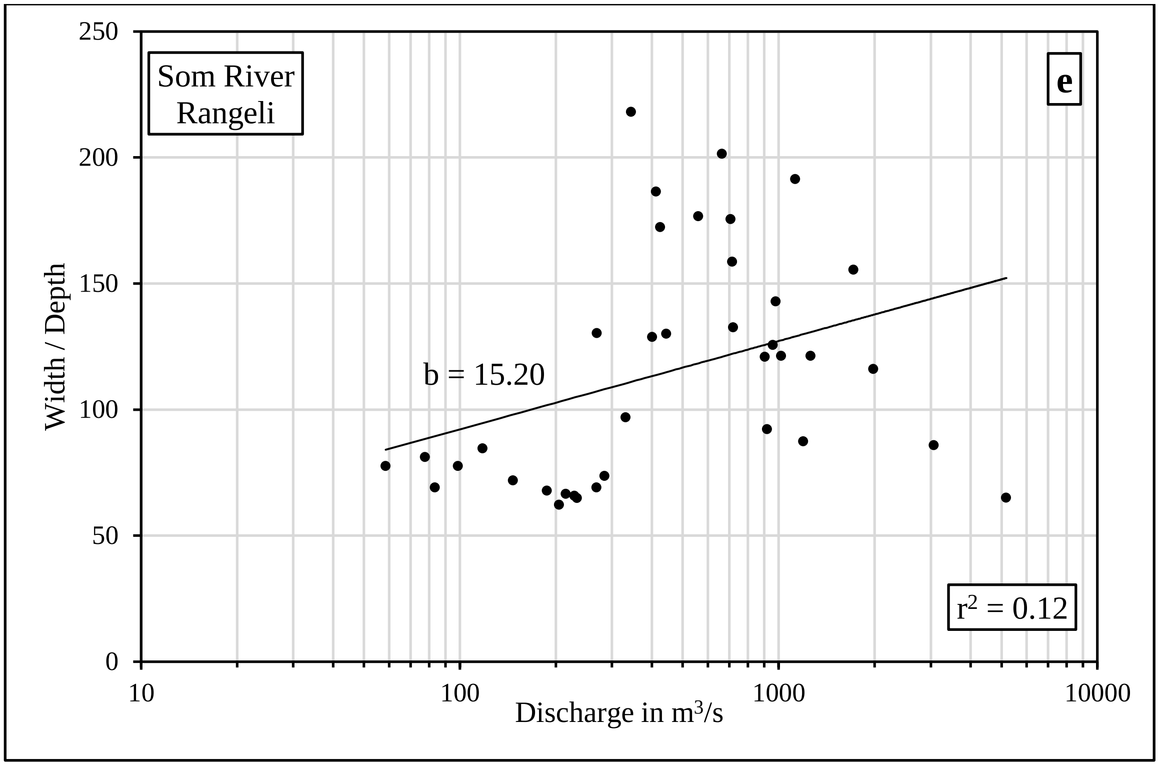


Figure 4.22e: Relation between Width/Depth and discharge; Som River: Rangeli

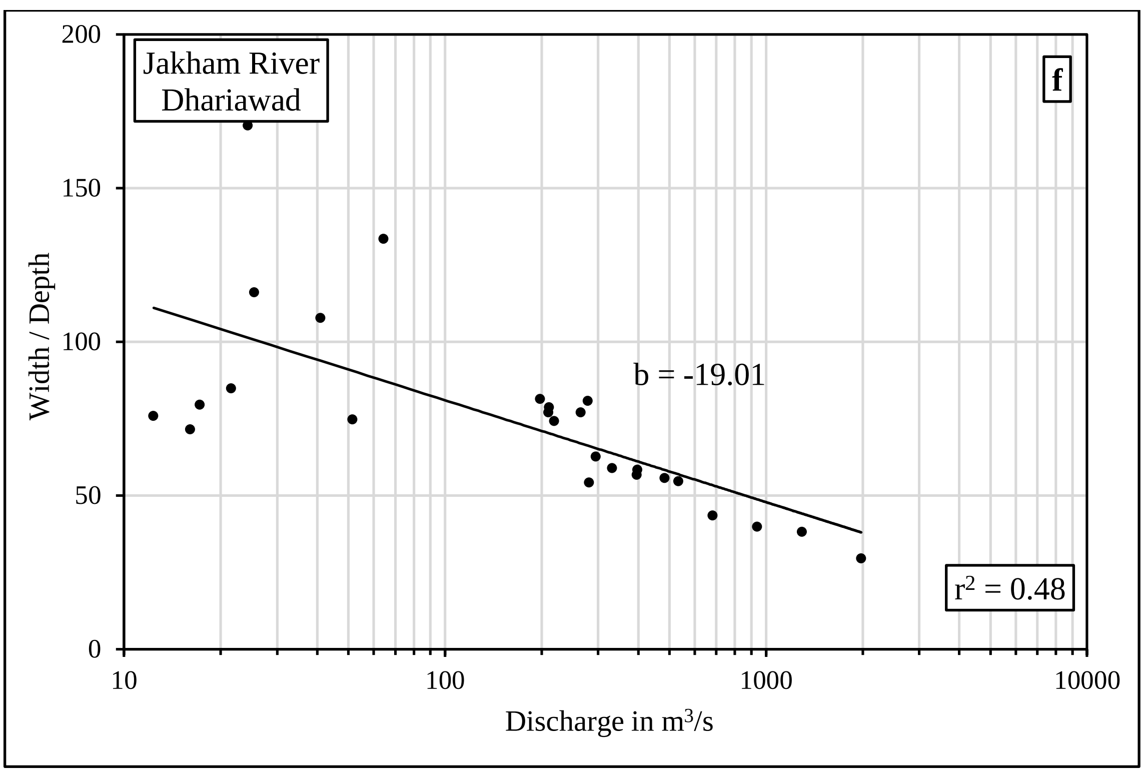


Figure 4.22f: Relation between Width/Depth and discharge; Jakham River: Dhariawad

(II) Changes in hydraulic variables with discharge

Since data of hydraulic variables for sufficiently large numbers of sites in the Mahi Basin are not available for the analysis of downstream hydraulic geometry. Therefore, at-a-station hydraulic geometry analysis has been carried out to describe the hydraulic characteristics of channel. The results of adjustments in the hydraulic variables (channel width (w), mean depth (d), and mean velocity (v)) with discharge are given in Table 4.16 and the plots are illustrated in Figure 4.23 to Figure 4.28.

Table 4.16: Exponent values of at-a-station hydraulic geometry

SN	River	Sites	Width (b)	Depth (f)	Velocity (m)	b/f ratio	m/f ratio	Total variance
1	Mahi	Mataji	0.13	0.26	0.61	0.50	2.35	0.46
2	Mahi	Paderdi Badi	0.02	0.45	0.53	0.04	1.18	0.48
3	Mahi	Khanpur	0.04	0.53	0.43	0.08	0.81	0.47
4	Anas	Chakaliya	0.15	0.45	0.40	0.33	0.89	0.39
5	Som	Rangeli	0.41	0.26	0.33	1.58	1.27	0.34
6	Jakham	Dhariawad	0.22	0.42	0.37	0.52	0.88	0.36

See figure 3.1 for location of sites

Table 4.16 and the plots (Figure 4.23 to Figure 4.28) indicate that for Paderdi Badi and Khanpur site the rate of change in b/f ratio is lowest (close to zero) due to the flat and box-shaped channel of the Mahi River. Therefore, this shows that the increase in the discharge is mostly compensated by a significant increase in depth which is important inferences for effectiveness of the channel as the flood power is directly linked to the flow depth.

In view of Rhodes (1987), the concept of minimum variance introduced by Langbein is an important concept which is linked with hydraulic geometry. Therefore, total variance values (sum of the square of the hydraulic geometry exponents) have been calculated for all the six sites in the Mahi Basin. The result indicates that the value ranges between 0.34 and 0.48 (Table 4.16). However, the total variance values of the Chakaliya, Rangeli and Dhariawad are closer to 0.333, which is the minimum theoretical value of the total variance, (Rhodes, 1987).

The highest values of total variance for Mataji, Paderdi Badi and Khanpur suggests that at the effects of changes in discharge are not well-adjusted equally by all the three variables, but by one or two hydraulic geometry variables (Rhodes, 1987). This can be due to the box-shaped form of the channel and cohesive nature of the bank material. According to Leopold et al (1964), the m/f ratio is related to the transportation of the sediment load. The higher value of the ratio suggests more rapid sediment load transportation with increase in discharge. Table 4.16 shows that the values of m/f ratio are much higher for Mataji, Paderdi Badi and Rangeli sites.

The values of b, f, and m of the six sites were plotted on the ternary diagram (Figure 4.29). It indicates that three sites fall in sector 6, two sites in sector 2 and a site in sector 3. The sector 6 shows that width-depth ratio and velocity-area ratio decreases with increasing discharge. However, the Froude number and slope-roughness ratio increases. The sector 2 reveals the decrease in width-depth ratio and increase in competence, Froude number, velocity-area ratio, and slope-roughness ratio with rising discharge. Whereas, sector 3 shows that width-depth ratio, competence, Froude number, and slope-roughness ratio increase and velocity-area ratio decrease with increasing discharge. The b-f-m diagram offers a means of grouping and comparing hydraulic geometry of the channels of the Mahi River and its tributaries and suggests empirical classification based on hydraulic geometry.

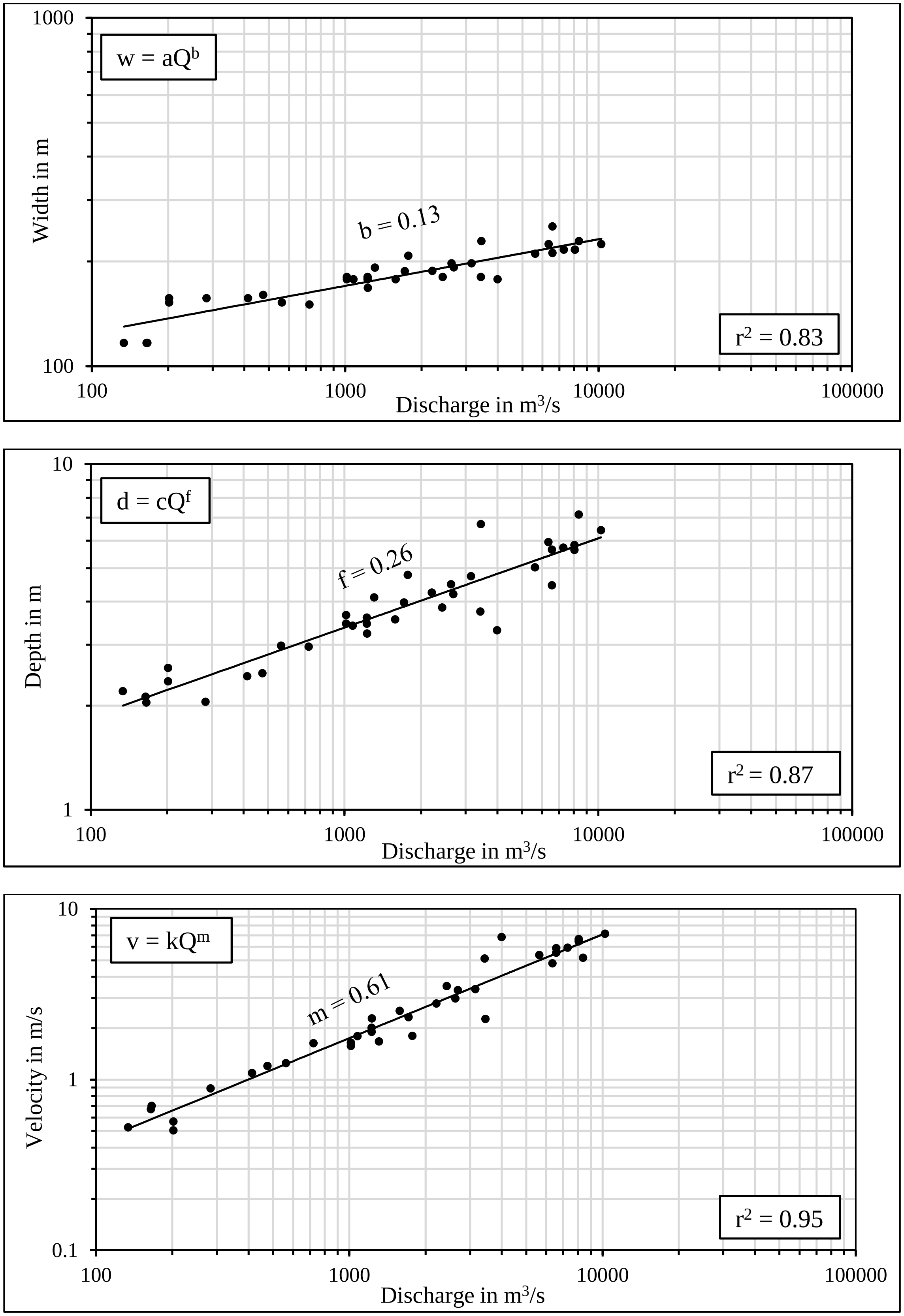


Figure 4.23: At-a-Station hydraulic geometry; Mahi River: Mataji

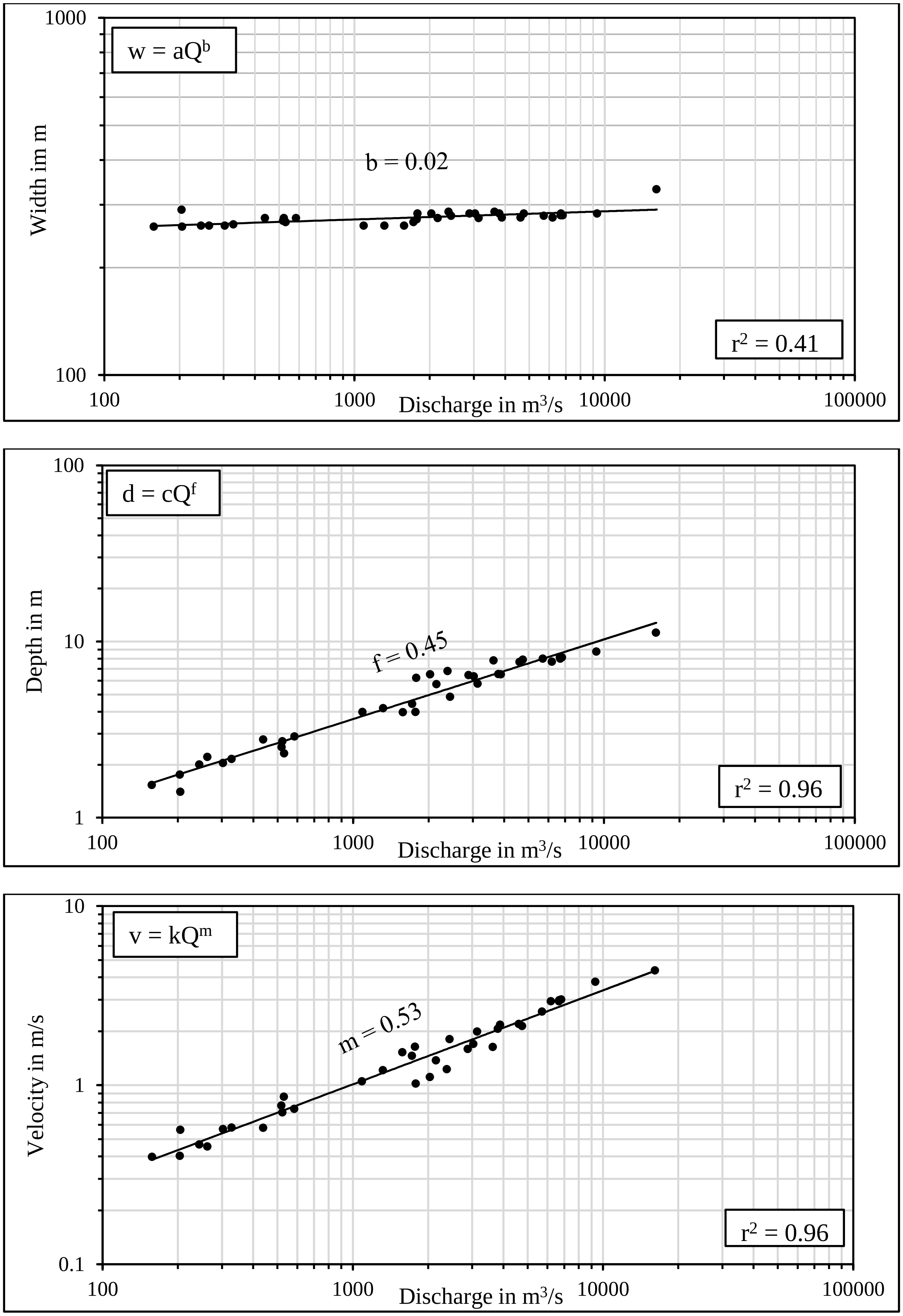


Figure 4.24: At-a-Station hydraulic geometry; Mahi River: Paderdi Badi

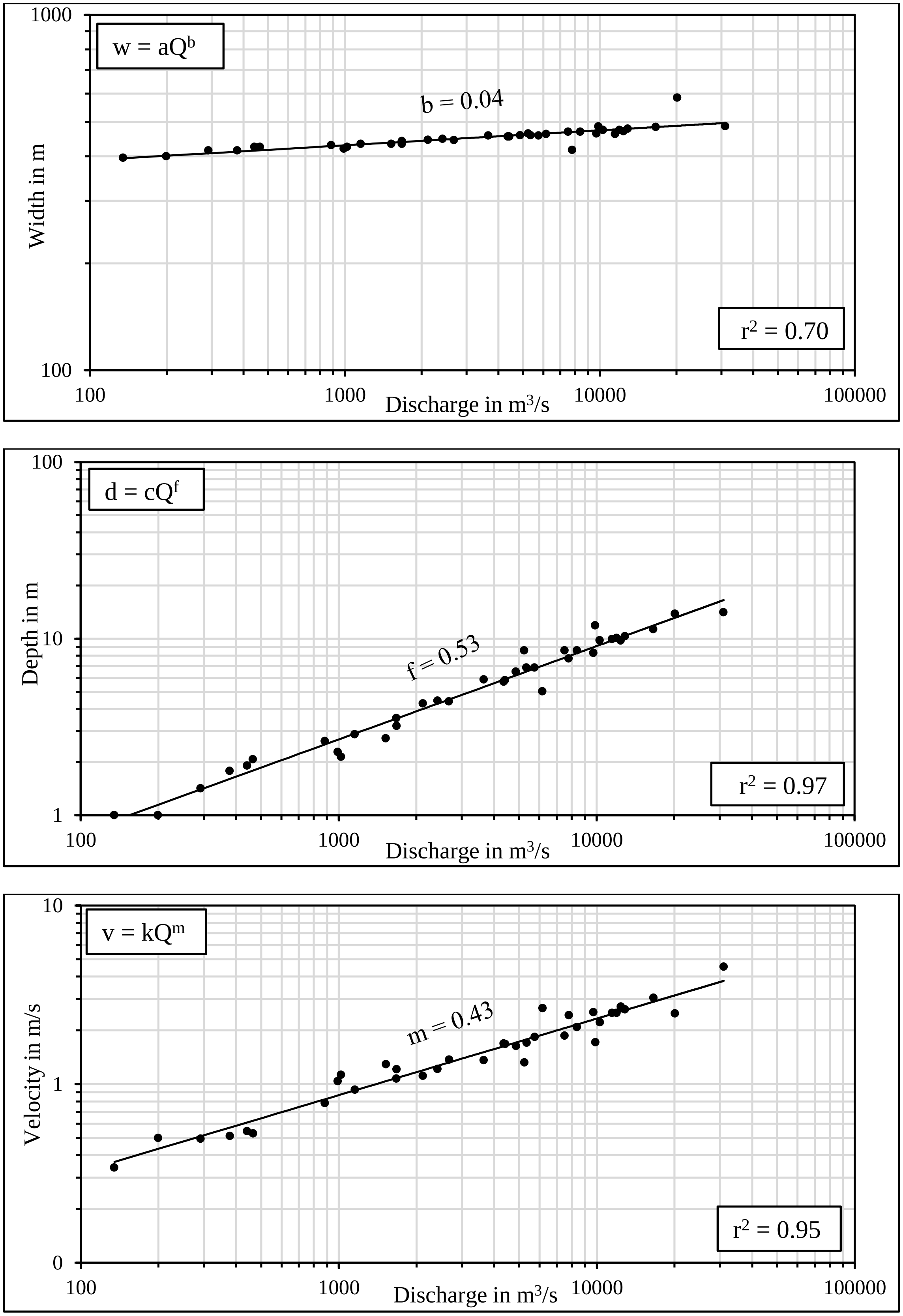
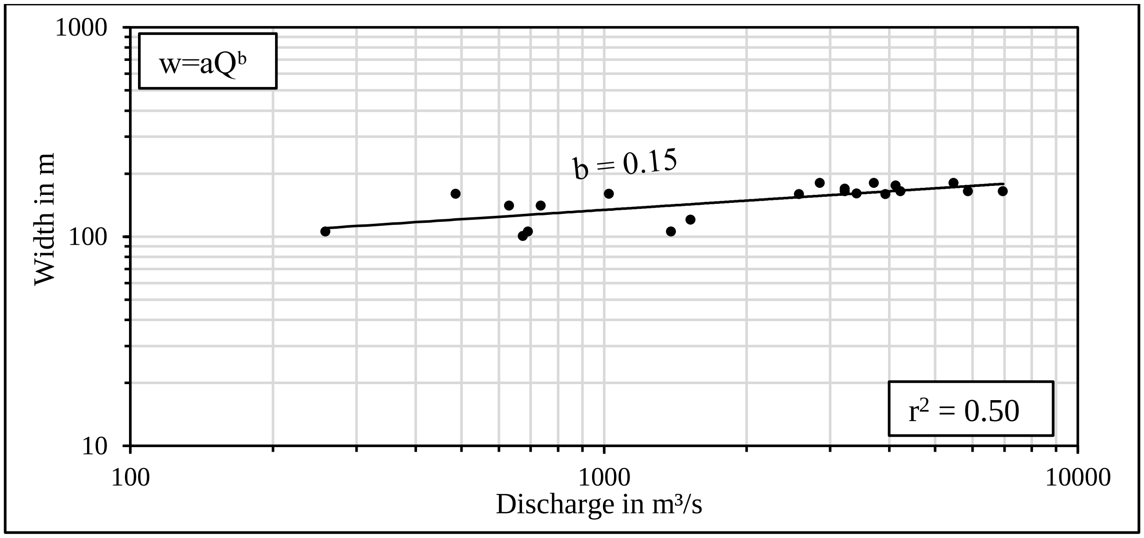
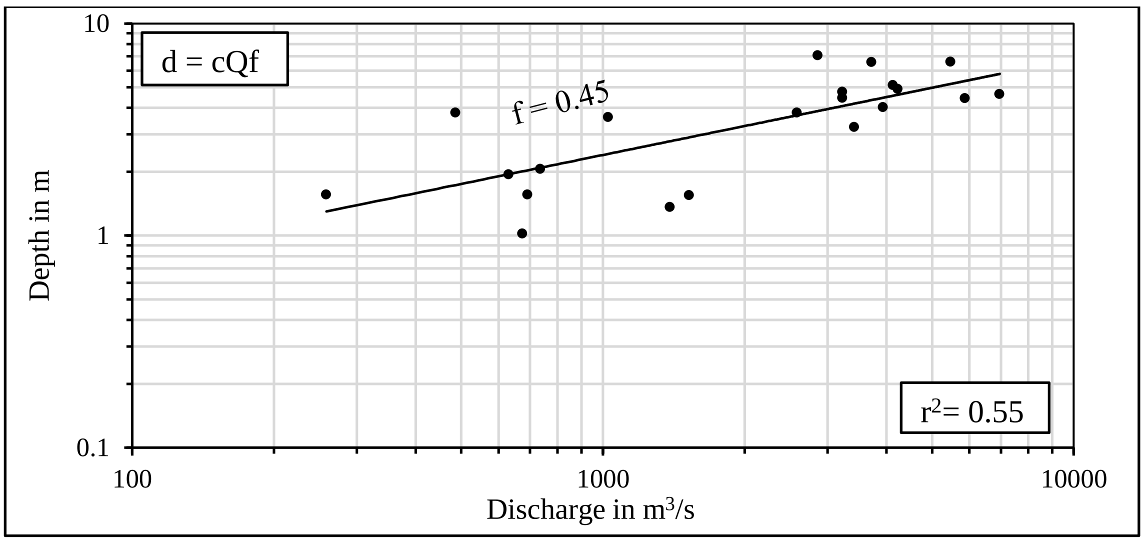


Figure 4.25: At-a-Station hydraulic geometry; Mahi River: Khanpur





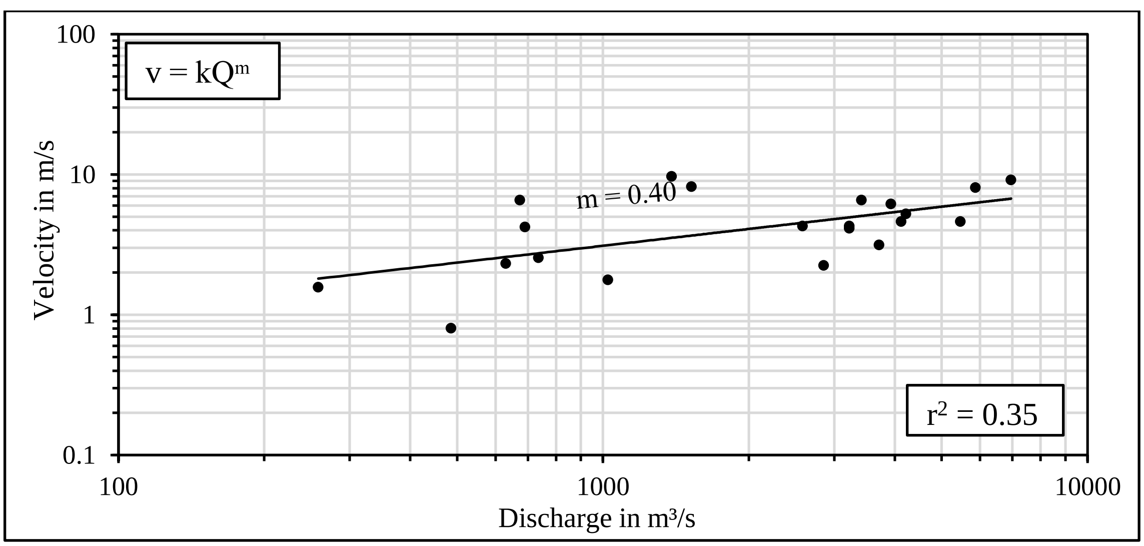


Figure 4.26: At-a-Station hydraulic geometry; Anas River: Chakaliya

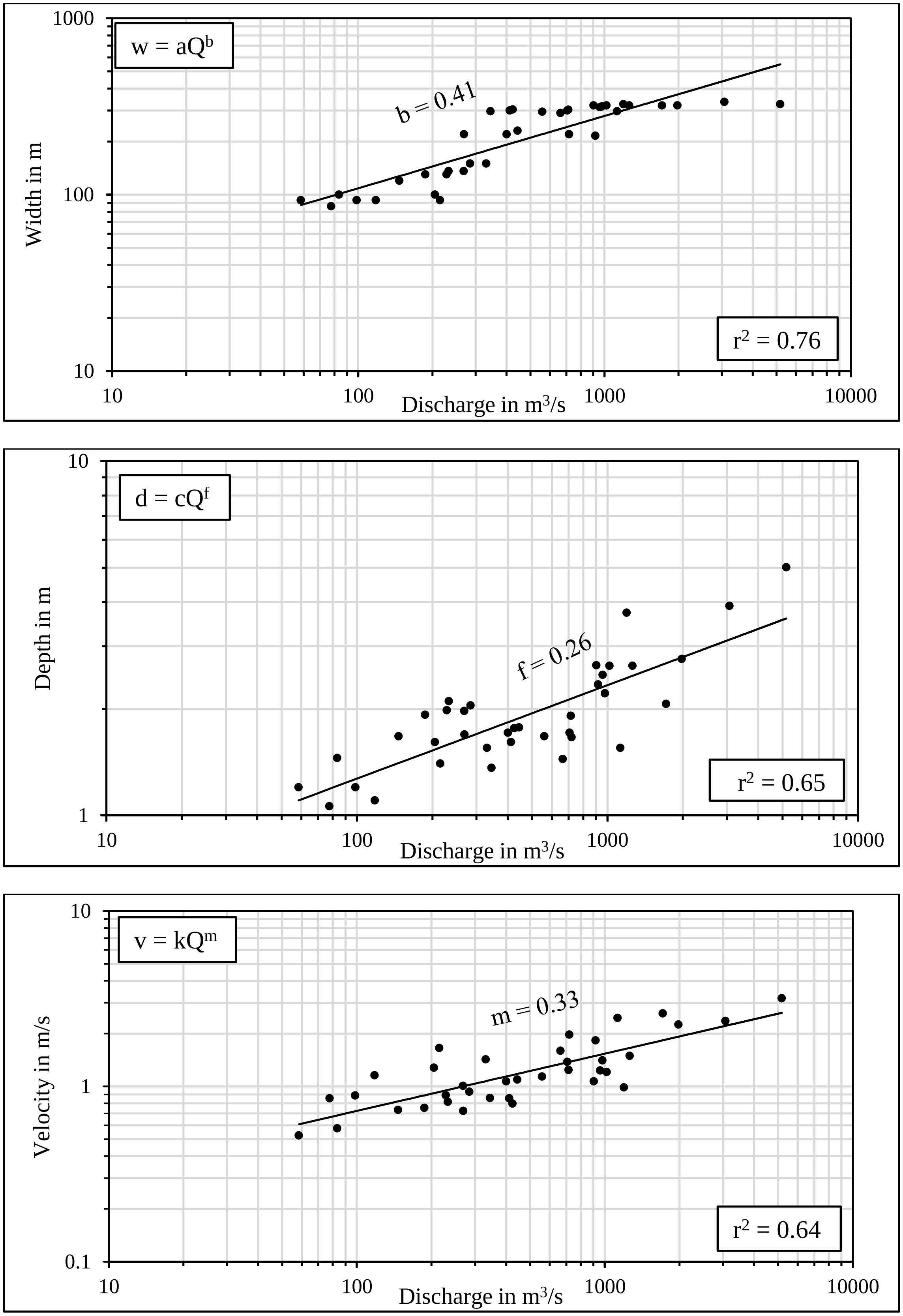


Figure 4.27: At-a-Station hydraulic geometry; Som River: Rangeli

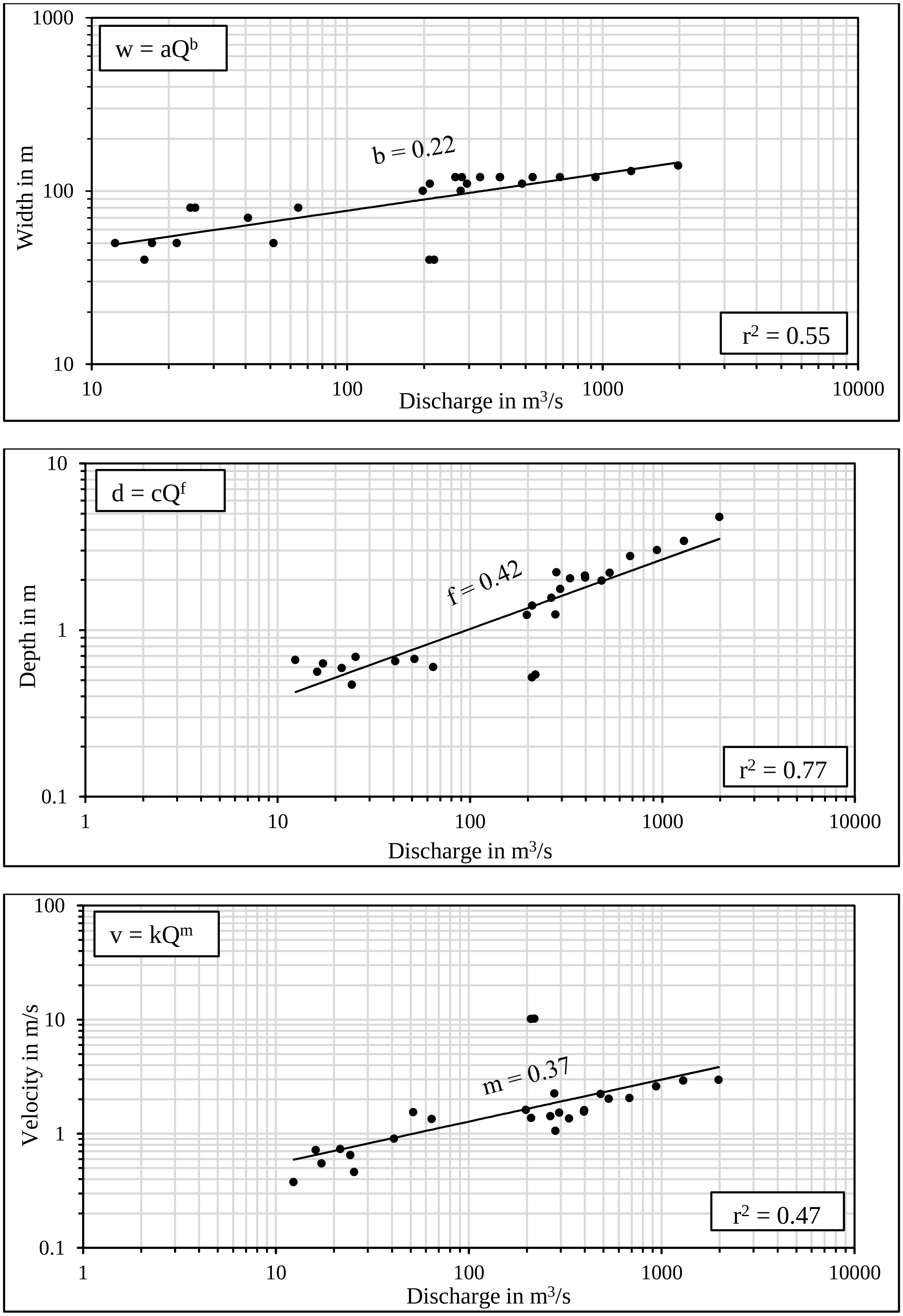


Figure 4.28: At-a-Station hydraulic geometry; Jakham River: Dhariawad

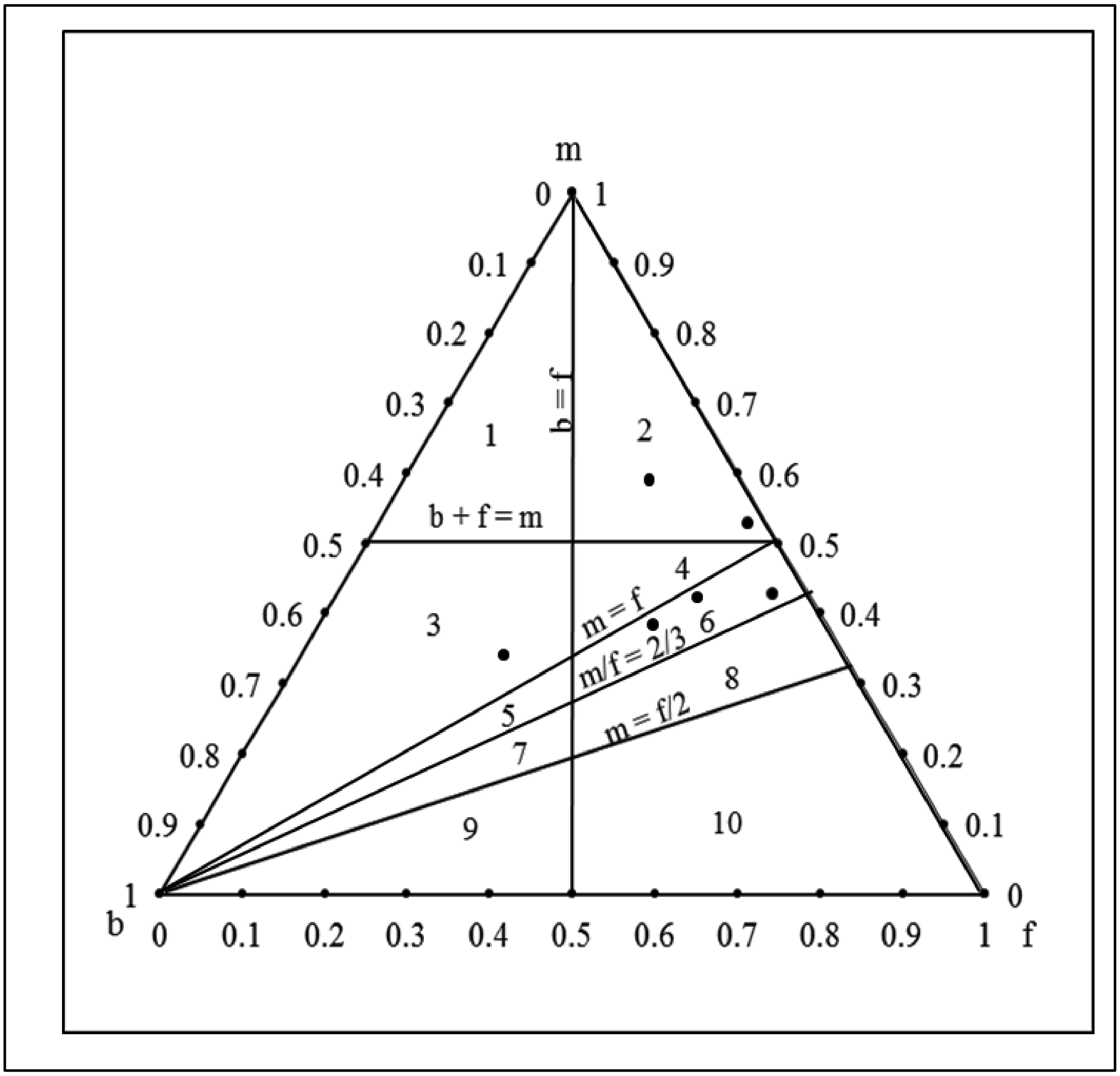


Figure 4.29: The width-depth-velocity (b-f-m) diagram

4.2.3 Hydraulic geometry parameters for different return periods

In order to understand the relationship of the hydraulic geometry parameters with minimum annual peak discharge (Qmin), mean annual flood (Qm), large floods (Qlf), and maximum annual peak discharge (Qmax), values of hydraulic parameters, such as width, mean depth, mean velocity and width-depth ratio for different return periods have been calculated by using GEVI probability distribution (Figure 4.30a to Figure 4.30f; Table 4.17). The hydraulic parameters for return period Qmin, Qm, Qlf and Qmax for all the sites are given in the Table 4.17.

Table 4.17: Hydraulic geometry parameters for different return period

River	Site	Qm^3/s	RI (GEVI)	Hydraulic parameters			
				w	$\bar{d}$	F	$\bar{v}$
Mahi	Mataji	Qmin = 134	1.22	65	1.12	40	1.24
		Qm = 3135	2.33	195	4.31	28	2.75
		Qlf = 6568	6.93	214	5.72	24	3.65
		Qmax = 14972	150.00	240	9.24	18	6.01
Mahi	Paderdi Badi	Qmin = 518	1.28	261	1.67	112	0.93
		Qm = 2968	2.33	282	5.49	40	1.70
		Qlf = 6132	6.93	287	7.05	31	2.32
		Qmax = 16153	373.00	333	13.13	22	3.62
Mahi	Khanpur	Qmin = 200	1.18	409	0.96	276	0.56
		Qm = 6448	2.33	456	6.32	56	2.04
		Qlf = 13022	6.93	472	9.87	36	2.92
		Qmax = 31062	217.00	495	14.07	26	5.69
Anas	Chakaliya	Qmin = 60	1.09	55	0.60	46	0.50
		Qm = 2329	2.33	158	4.00	26	1.52
		Qlf = 4275	6.93	178	6.66	17	2.33
		Qmax = 6956	38.06	211	7.74	16	2.75
Som	Rangeli	Qmin = 59	1.31	170	1.34	127	0.72
		Qm = 753	2.33	300	1.58	71	1.08
		Qlf = 1697	6.93	333	3.35	56	1.93
		Qmax = 5179	721.00	347	5.07	43	2.69
Jakham	Dhariawad	Qmin = 12	1.25	35	0.74	35	1.2
		Qm = 392	2.33	120	2.78	30	2.88
		Qlf = 853	6.93	130	3.42	27	3.30
		Qmax = 1980	148.00	160	4.77	25	4.11

Qmin = Minimum annual peak discharge; Qm = Mean annual peak discharge; Qlf = Large flood; Qmax = Maximum annual peak discharge; w = Width in m; $\bar{d}$= Mean depth in m; F = Form ratio; $\bar{v}$ = Mean velocity in m/s; GEVI = Gumbel Extreme Value I; RI = Recurrence interval; See Figure 3.1 for location of sites

The Table 4.17 also indicates the values of hydraulic parameters linked with the minimum annual peak discharge, whose return period is about 1-yr as per GEVI probability distribution. Table 4.17 and Figure 4.30a to Figure 4.30c specifies that the channel width increase as discharge increases. However, return periods are not as remarkable as in terms of increase in the mean depth and mean velocity. For most sites, the mean depth and mean velocity, associated with infrequent high flows, is several times higher than for low flows. Besides, low discharges (Qmin) which occur on an average once every year are associated with high form ratio. The form ratios are comparatively low during large floods and maximum peak flood on record (Qlf and Qmax) which have a return period of >6.93 yr. For instance, the form ratio for the Khanpur site during minimum annual peak discharge (Qmin) is 276, but the ratio decreases by about eleven times to 26 for the maximum peak discharge (Qmax).

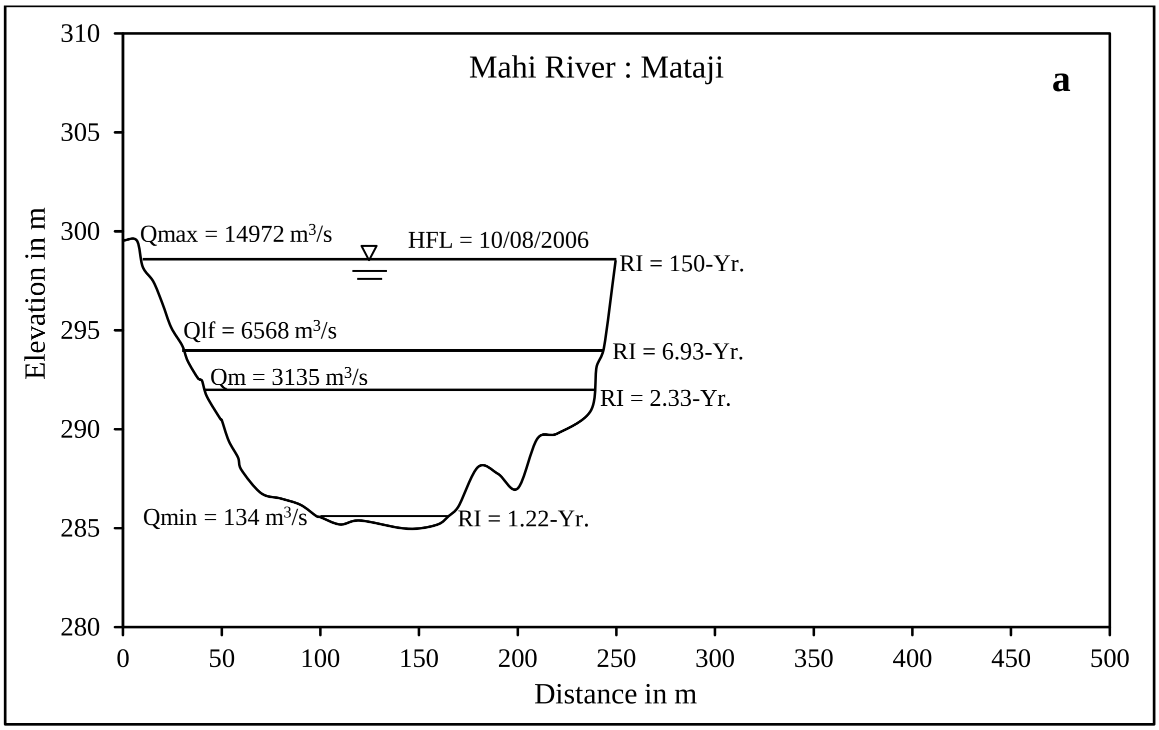


Figure 4.30a: Hydraulic geometry parameters for different discharges and return period Mahi River: Mataji; RI = Recurrence interval; HFL = High flood level; Refer Table 4.17 for other notations

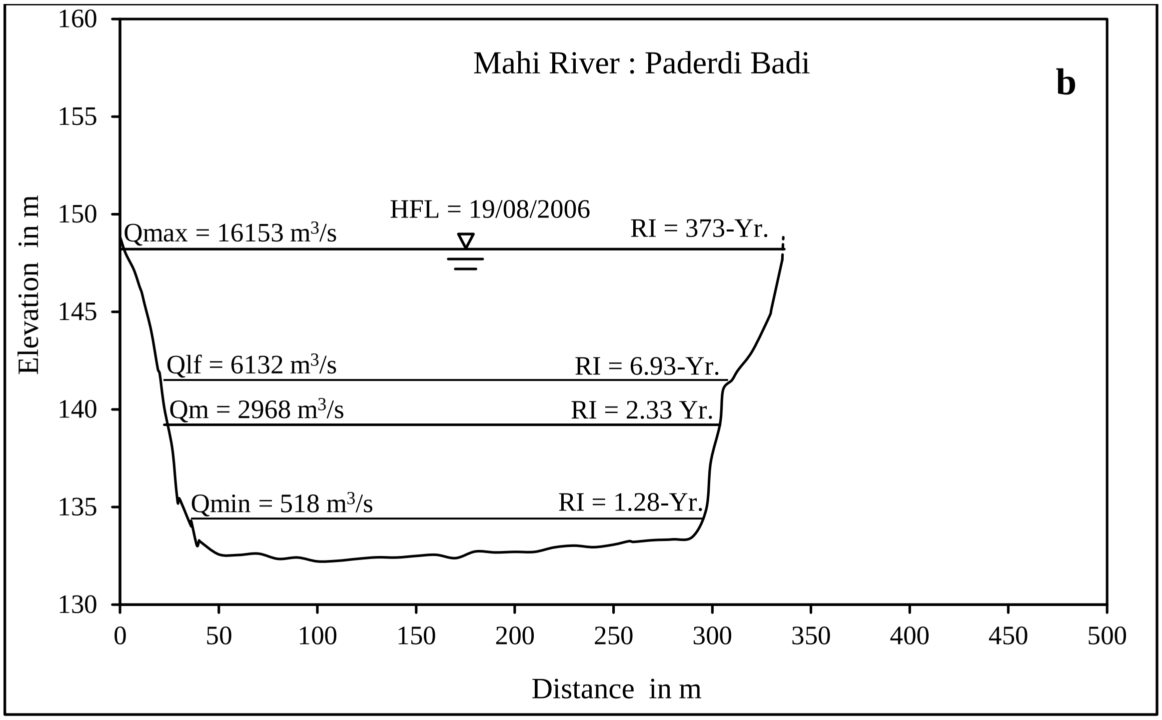


Figure 4.30b: Hydraulic geometry parameters for different discharges and return period Mahi River: Paderdi Badi; RI = Recurrence interval; HFL = High flood level; Refer Table 4.17 for other notations

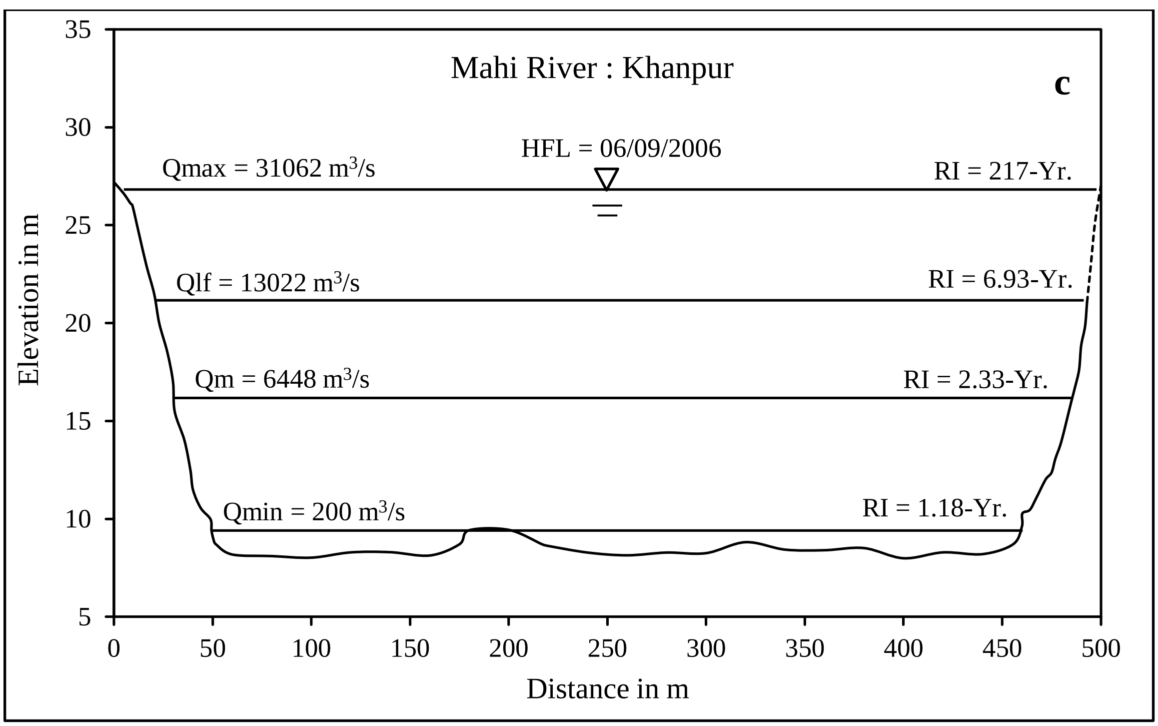


Figure 4.30c: Hydraulic geometry parameters for different discharges and return period Mahi River: Khanpur; RI = Recurrence interval; HFL = High flood level; Refer Table 4.17 for other notations

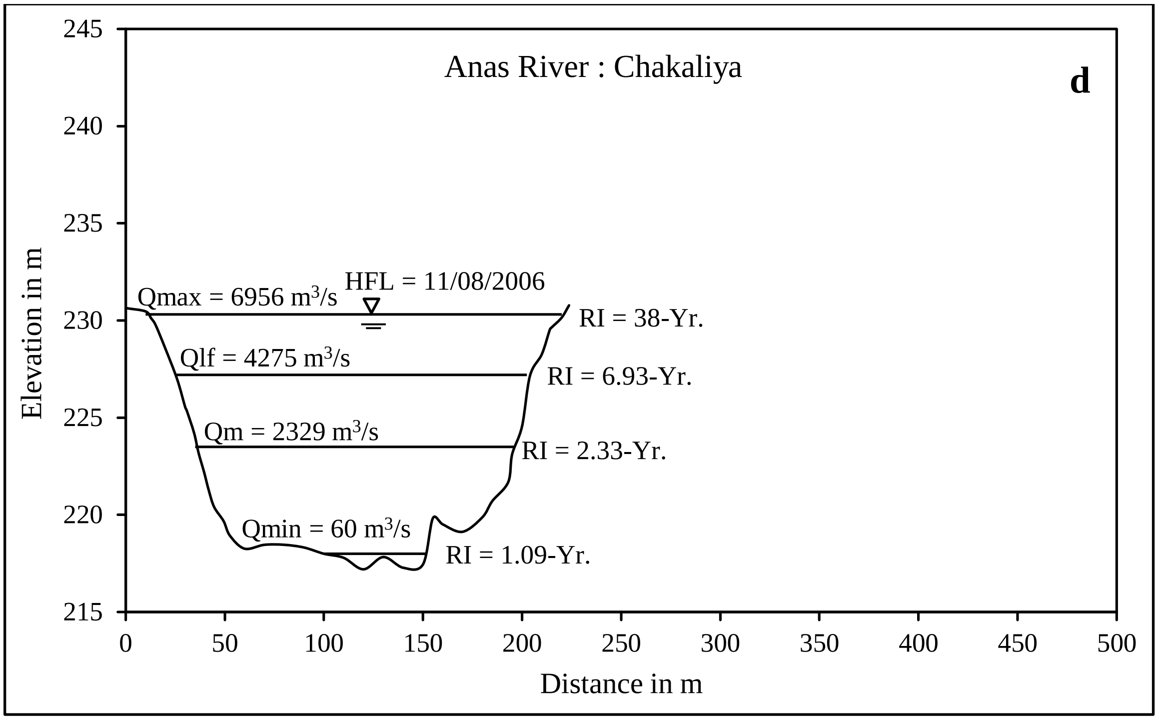


Figure 4.30d: Hydraulic geometry parameters for different discharges and return period Anas River: Chakaliya; RI = Recurrence interval; HFL = High flood level; Refer Table 4.17 for other notations

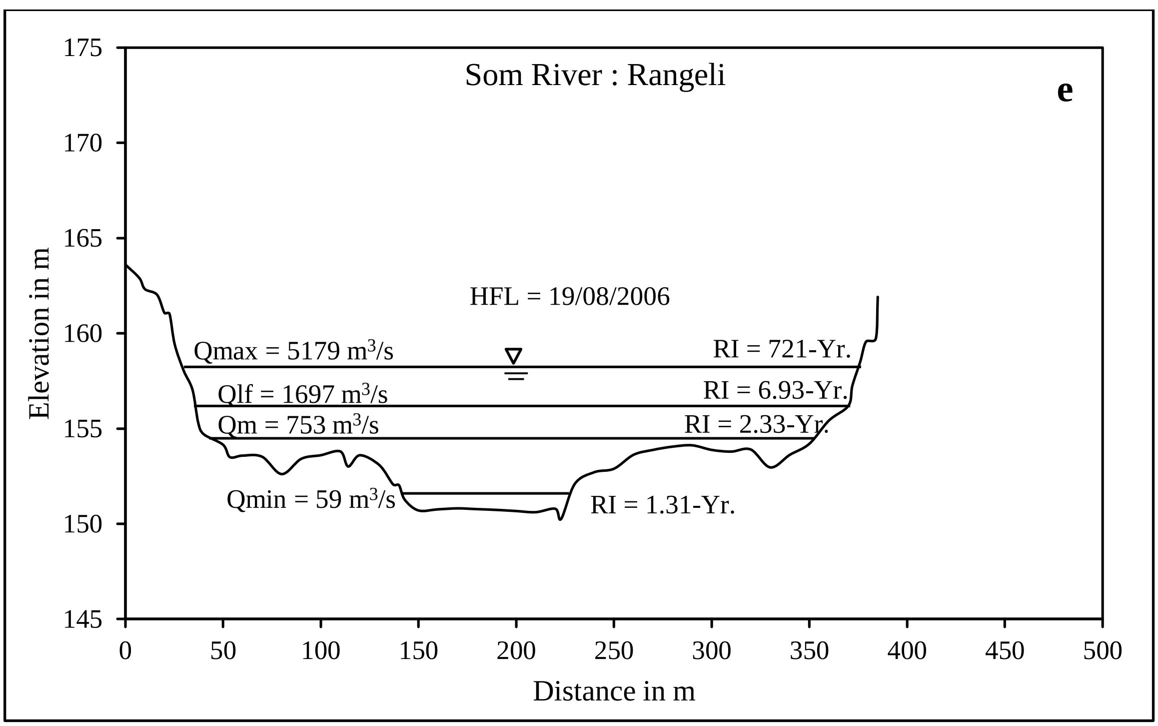


Figure 4.30e: Hydraulic geometry parameters for different discharges and return period Som River: Rangeli; RI = Recurrence interval; HFL = High flood level; Refer Table 4.17 for other notations

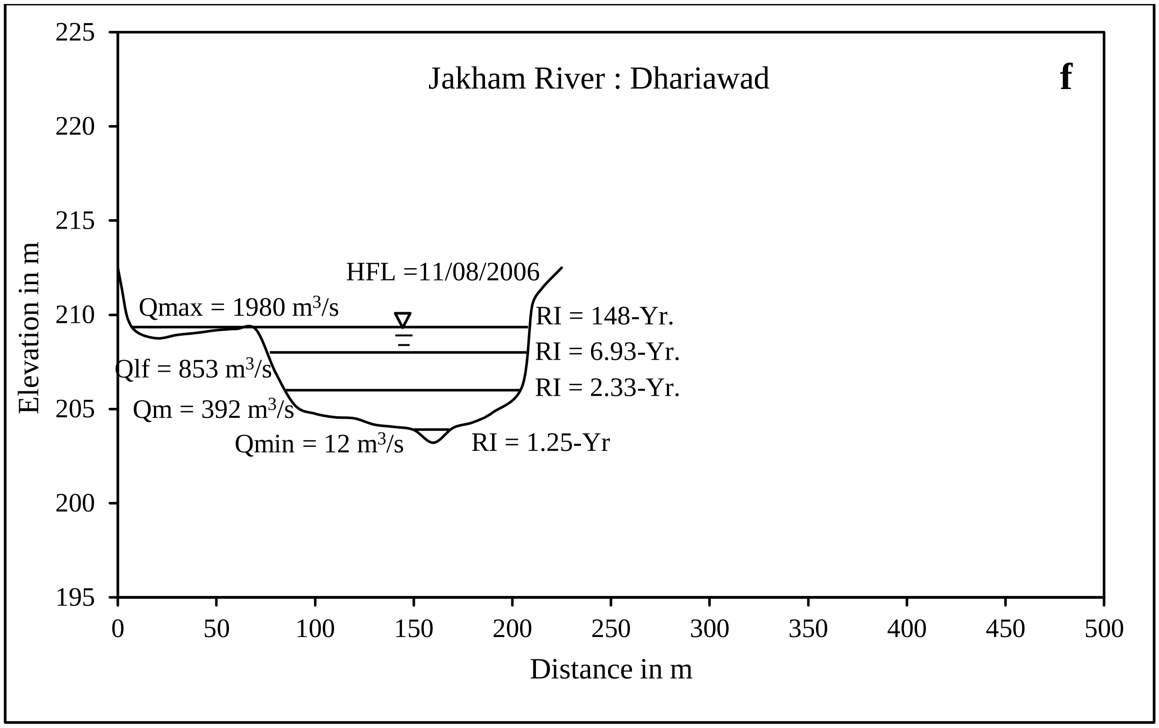


Figure 4.30f: Hydraulic geometry parameters for different discharges and return periods Jakham River: Dhariawad; RI = Recurrence interval; HFL = High flood level; Refer Table 4.17 for other notations

4.2.4 Dynamics of suspended sediment transport

The quantity suspended load and bedload is determined by availability of material, sediment size and the transporting ability of the river (Leopold et al., 1964; Petts and Foster, 1985, Nash, 1994) , the velocity, shear stress and stream power (Baker and Costa, 1987). Therefore, attempts have been made to understand geomorphic effectiveness of flows in terms of suspended sediment transport.

(I) General characteristics of suspended sediment concentration and sediment load

General characteristics of the suspended sediment concentration, suspended sediment load and sediment yield in the Mahi River have been summarized in Table 4.18. The mean suspended sediment concentration ranges between 0.02 g/l at Paderdi Badi site to 0.13 g/l at Mataji site. The maximum suspended sediment concentration ranges between 0.99 g/l at Paderdi Badi and 10.41 g/l at Mataji. At all the sites the coefficient of variability is more than 200% indicating significant fluctuations in the sediment concentration levels.

Table 4.18 Suspended sediment concentration and sediment load of the Mahi River

Parameter	Mahi river at Mataji	Mahi river at Paderdi Badi	Mahi river at Khanpur
Basin area in km^2	3880	16247	32510
Suspended Sediment Concentration (grams/liter)			
Mean	0.13	0.02	0.06
Minimum	0.00	0.00	0.00
Maximum	10.41	0.99	1.871
Coefficient of variation in %	446.15	300	216.67
Suspended Sediment Load (Metric tons /day)			
Mean	13203	689	4118
Minimum	0.00	0.00	0.00
Maximum (10^6mt)	7.30	0.16	1.00
Sediment load (10^6 mt/year)	0.20	0.01	0.63
Sediment yield (mt/Km^2/year)	51.50	0.62	11.07

Source: CWC; Based on 6 years of records (2000-2005)

The total suspended sediment load and sediment yield of some large rivers of the Deccan Peninsula is mentioned in Table 4.19. The table reveals that the value of total suspended sediment load carried by the Mahi River as well as the total sediment load contributed by per unit drainage annually in the basin are lower than that of the Godavari, Mahanadi, Narmada and Tapi Rivers, but are higher than that of the Krishna and Kaveri Rivers.

Table 4.19 Suspended sediment load of the peninsular rivers

No	River	Catchment area km^2	Sediment load (10^6t/y)	Sediment yield (t/Km^2/y)
1	Narmada	87900	70.00	769
2	Mahanadi	41000	29.89	729
3	Godavari	313000	170.00	543
4	Tapi	49000	25.00	510
5	Kaveri	66300	1.50	23
6	Krishna	251400	4.00	16
7	**Mahi**	**34845**	**9.70**	**380**

(II) Temporal variations in discharge and sediment concentration

The temporal variations in flows and suspended sediment concentration have been represented by time series for one year (Figure 4.31a to Figure 4.31c). For each site, a year with some remarkable high flows was selected. Figure 4.31a to Figure 4.31c indicates low concentration of sediment in the month of June and July. However, concentration of the suspended sediment increases from the last week of the June. The basic reason is that Mahi Basin receives rainfall typically between July and September and the flow is influenced by the construction of dams and weirs along the main channel and tributaries such as Mahi Bajaj Sagar Dam, Kadana Dam and Wanakbori weir. As a result, reservoirs can trap and permanently store virtually the entire sediment load delivered from the upstream basin (Brune, 1953; Petts, 1979; Williams and Wolman, 1984). Thus, immediately downstream of a dam, a river's sediment load is greatly reduced. All these three gauging sites are having location downstream of dams and weirs (see Figure 3.1 for location of sites). In addition, typically downstream changes in the flow regime includes a reduction in the magnitude of peak flow and a possible increase in the magnitude of low flows (William and Wolman, 1984).

Generally, the peak of highest suspended sediment concentration occurs before the rising limb of the flood hydrograph. However, the peak of the suspended sediment concentration and peak of the flood hydrograph coincide for the Mataji (Figure 4.31a) and Paderdi Badi sites (Figure 4.31b). The highest peak of suspended sediment concentration and flood hydrograph for these sites were observed in the month of August could be because of release of discharge from upstream dams and weirs as well as heavy rainfall. Hence, there is sudden increase in flow level downstream. In case of Khanpur site peak of suspended sediment concentration starts just before the peak of the flood hydrograph (Figure 4.31c). This shows fairly normal situation of peak of sediment concentration and peak of flood.

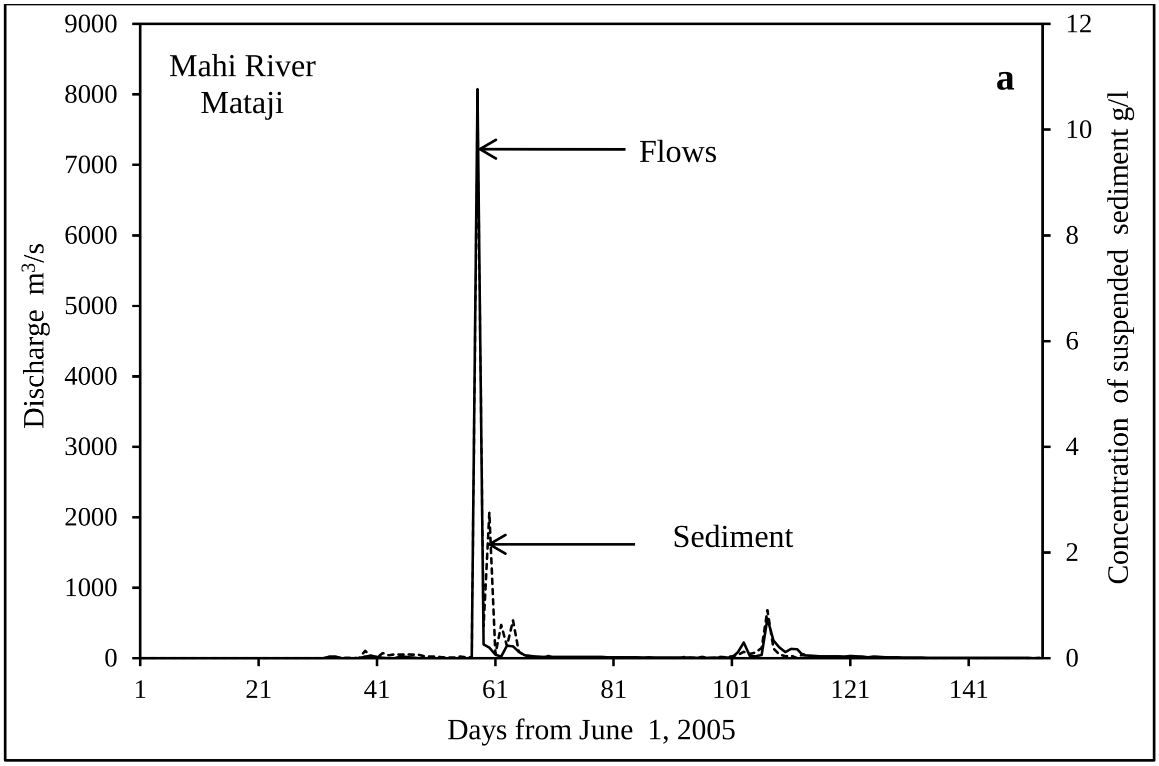


Figure 4.31a: Time series plot of discharge and sediment concentration; Mahi River: Mataji

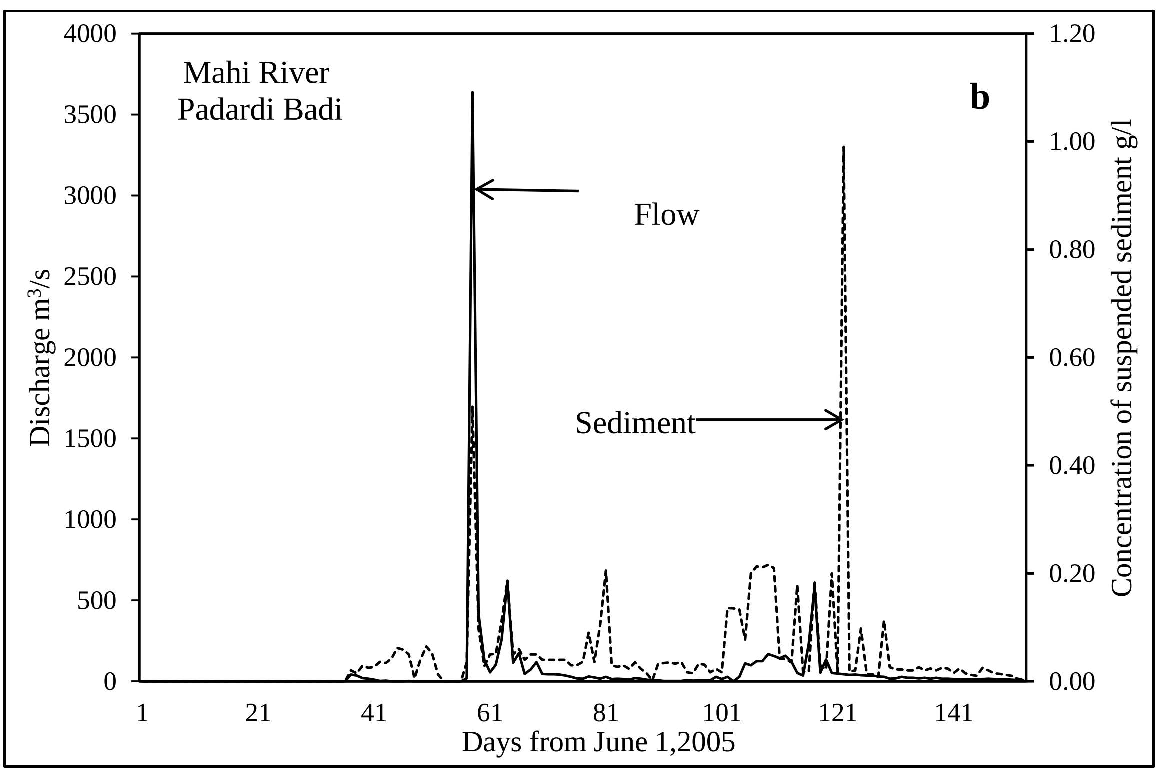


Figure 4.31b: Time series plot of discharge and sediment concentration; Mahi River: Paderdi Badi

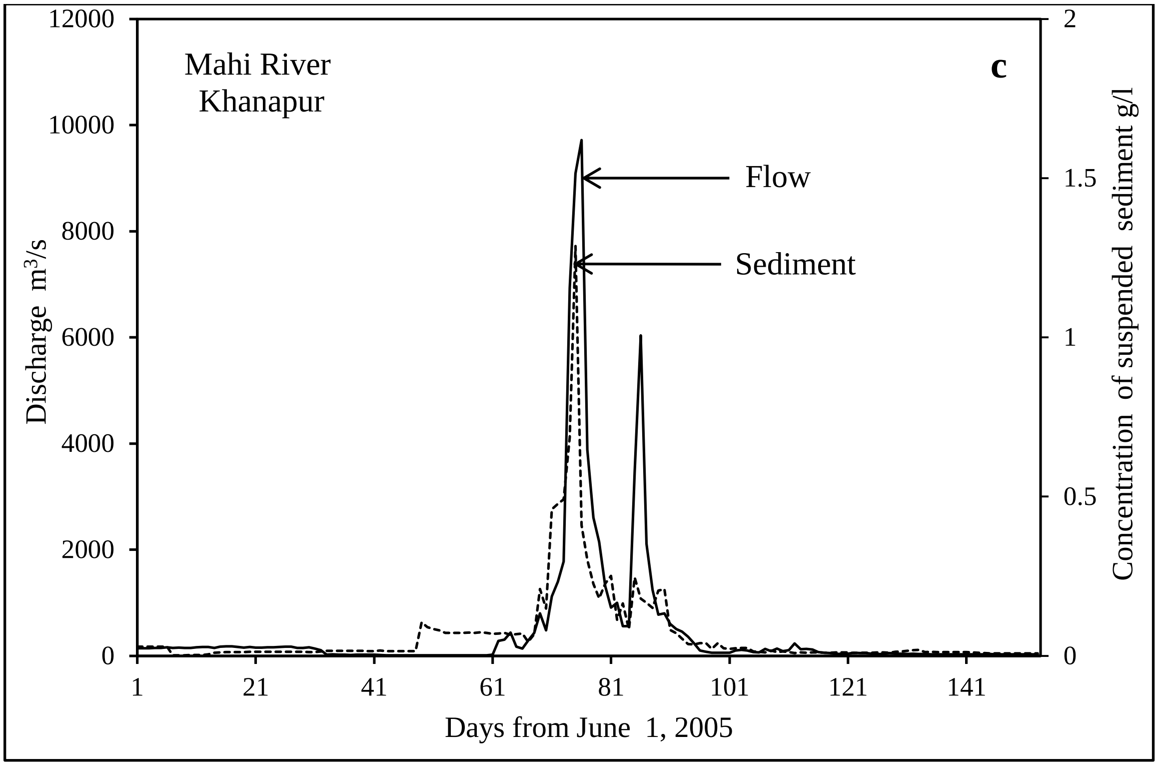


Figure 4.31c: Time series plot of discharge and sediment concentration; Mahi River: Khanpur

(III) Discharge-suspended sediment concentration relationship

The linear regression has been used for all the sites on the Mahi River the relationship between flows and suspended sediment concentration (Figure 4.32a to Figure 4.32c). The co-efficient of correlation (r) for Mataji is 0.76, which indicates high positive correlation between discharge and suspended sediment concentration. For Paderdi Badi and Khanpur sites co-efficient of correlation (r) is 0.58 and 0.50 respectively. It shows positive correlation between discharge and suspended sediment concentration.

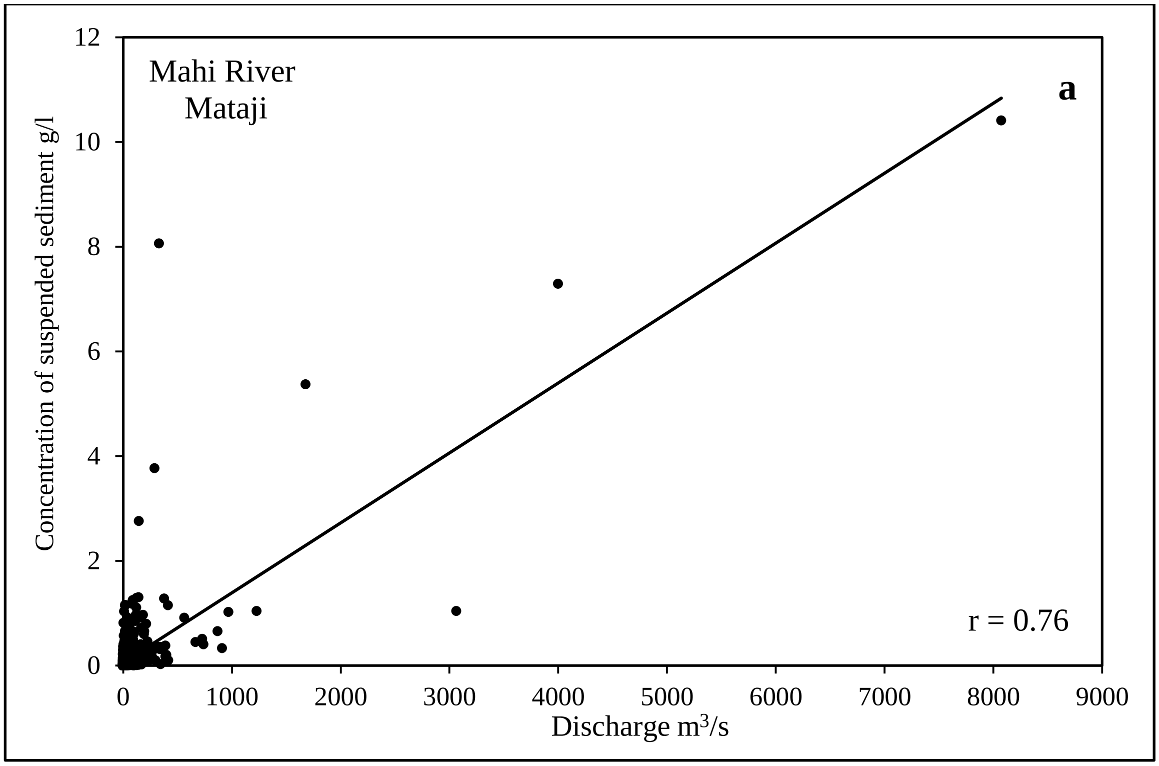


Figure 4.32a: Relation between concentration of suspended sediment and discharge; Mahi River: Mataji

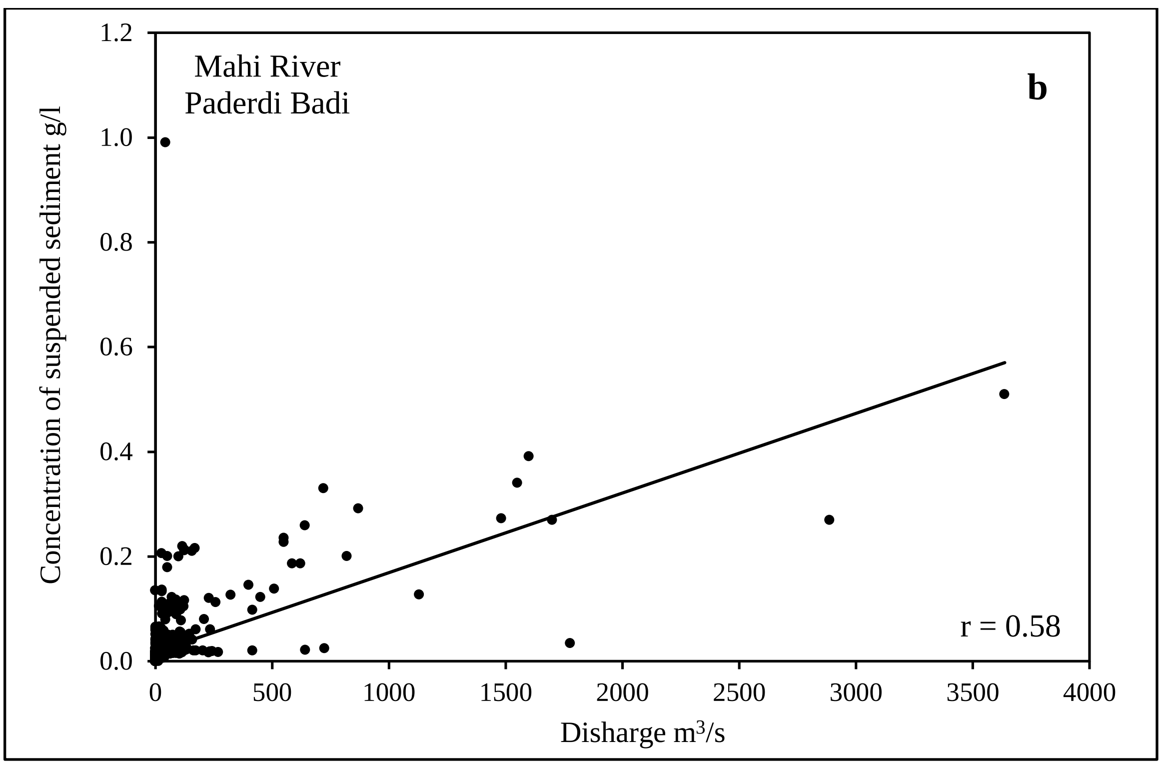


Figure 4.32b: Relation between concentration of suspended sediment and discharge; Mahi River: Paderdi Badi

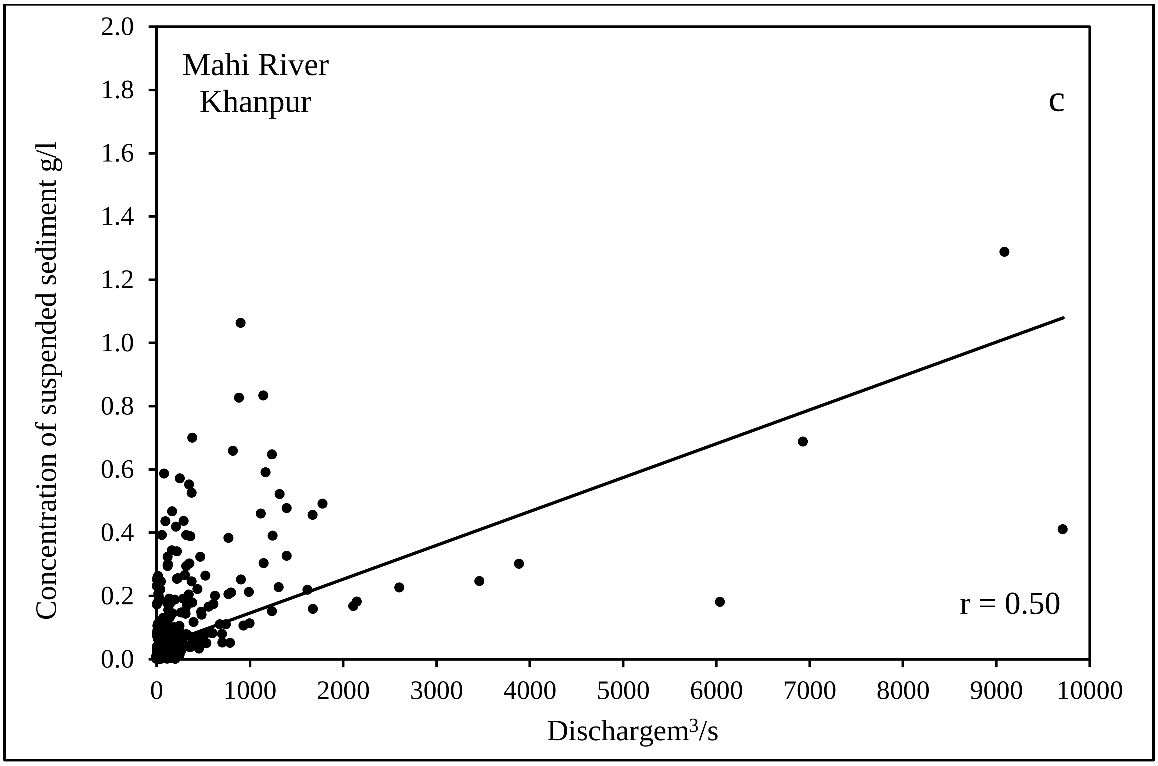


Figure 4.32c: Relation between concentration of suspended sediment and discharge; Mahi River: Khanpur

(IV) Discharge and suspended sediment concentration variation during passage of flood

Figure 4.33a, Figure 4.34a and Figure 4.35a illustrate the nature of discharge and sediment concentration during the flood events. The hydrographs reveal that the maximum suspended sediment concentration coincided with the maximum discharge for the 2005 flood on the Mahi River at Mataji (Figure 4.33a) and at Paderdi Badi (Figure 4.34a). However, at Khanpur, the suspended sediment concentration peaks preceded the peak discharge (Figure 4.35a). Therefore, it shows very good hysteresis curve.

Besides, in order to recognize the hysteresis in the relationship between discharge and sediment concentration during a flood event, concentration discharge plots for diurnal streamflow variations were made. The Figure 4.33b, Figure 4.34b, and Figure 4.35b show clockwise and anticlockwise hysteresis loops in discharge concentration.

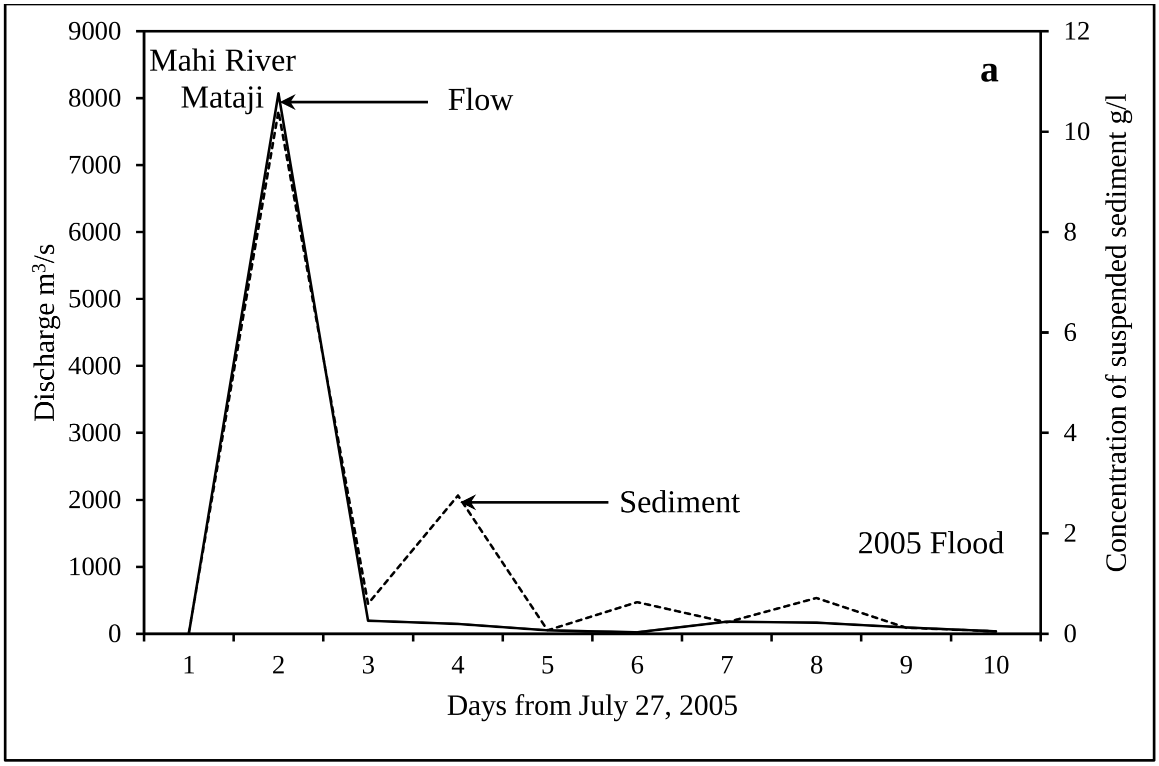


Figure 4.33a: Relation between discharge and concentration of suspended sediment - 2005 flood; Mahi River: Mataji

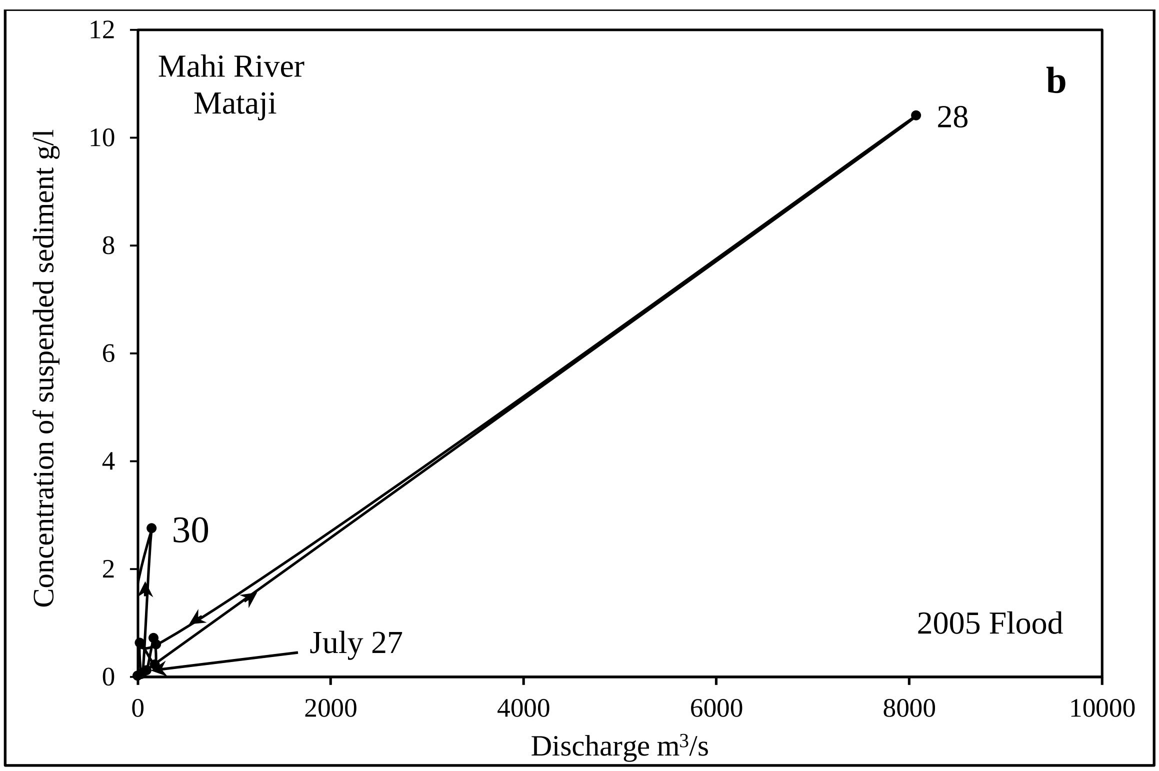


Figure 4.33b: Hysteresis loop; Mahi River: Mataji

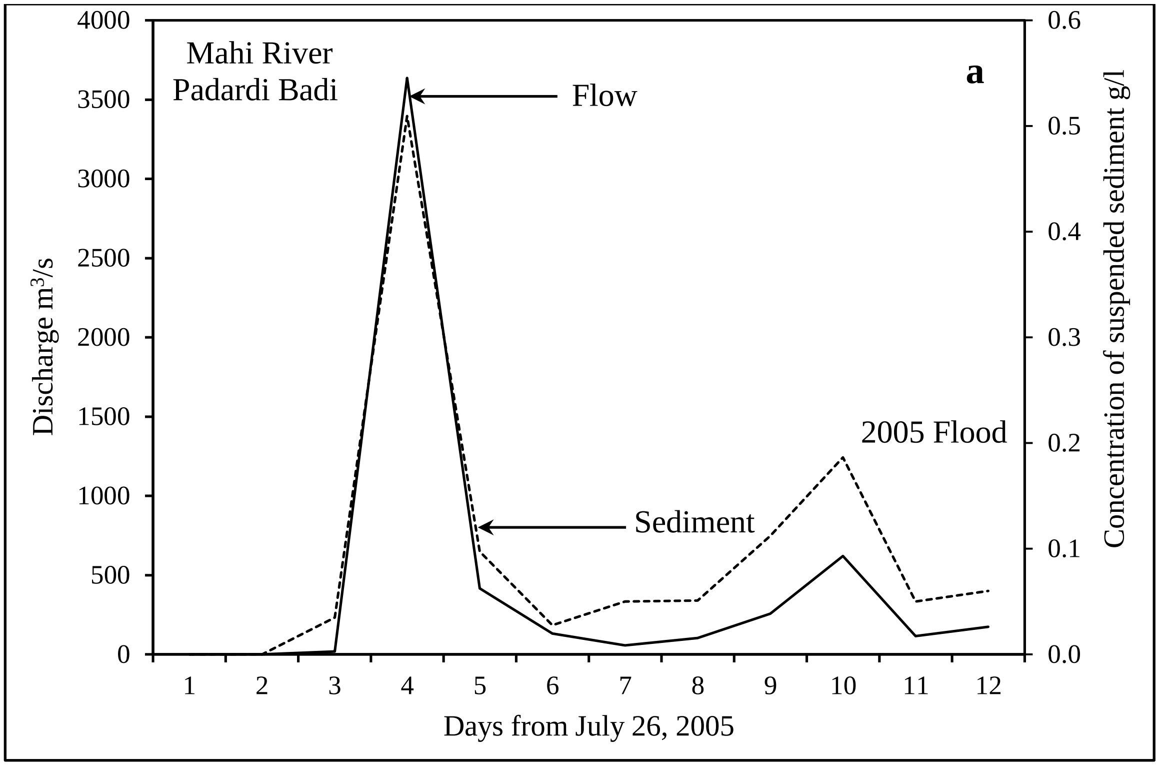


Figure 4.34a: Relation between discharge and concentration of suspended sediment - 2005 flood; Mahi River: Paderdi Badi

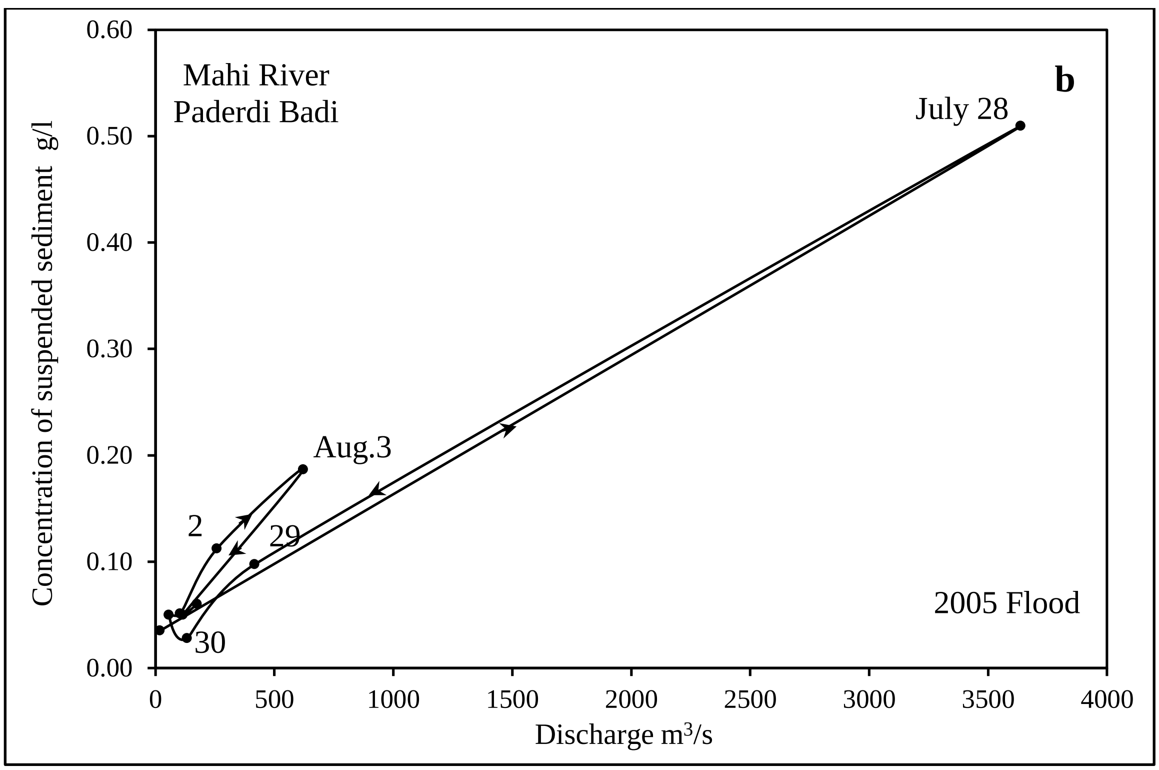


Figure 4.34b: Hysteresis loop; Mahi River: Paderdi Badi

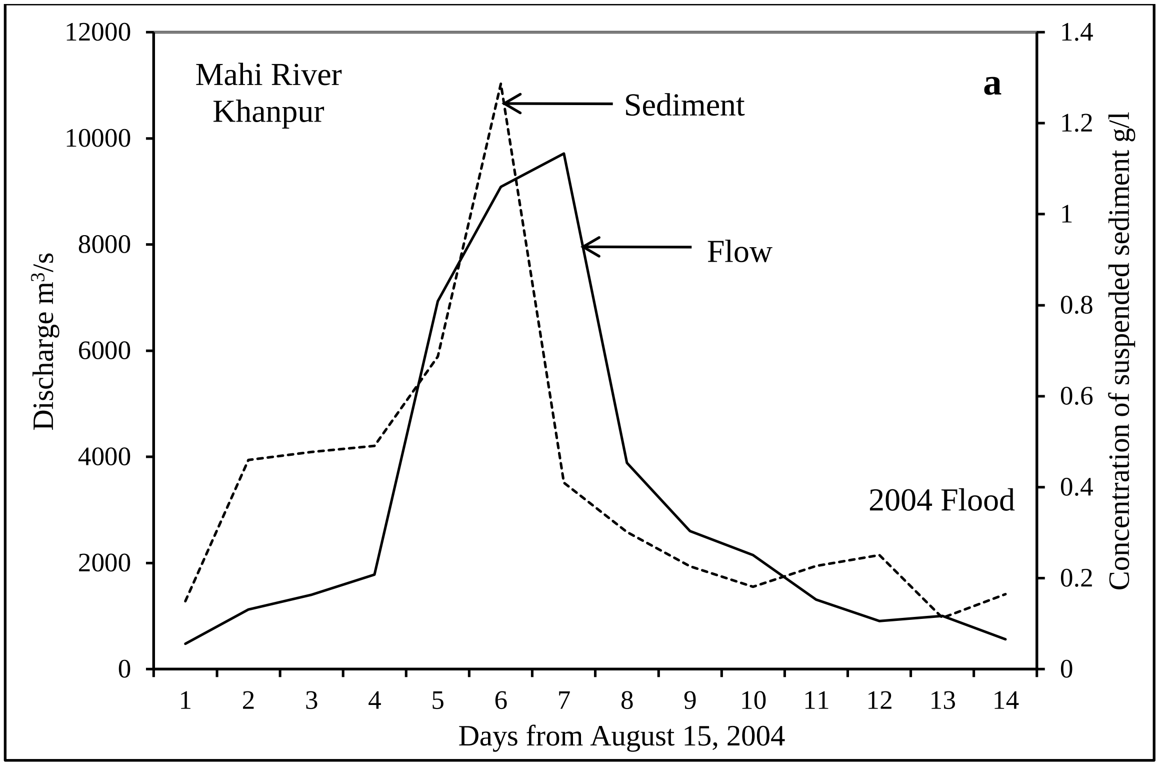


Figure 4.35a: Relation between discharge and concentration of suspended sediment - 2004 flood; Mahi River: Khanpur

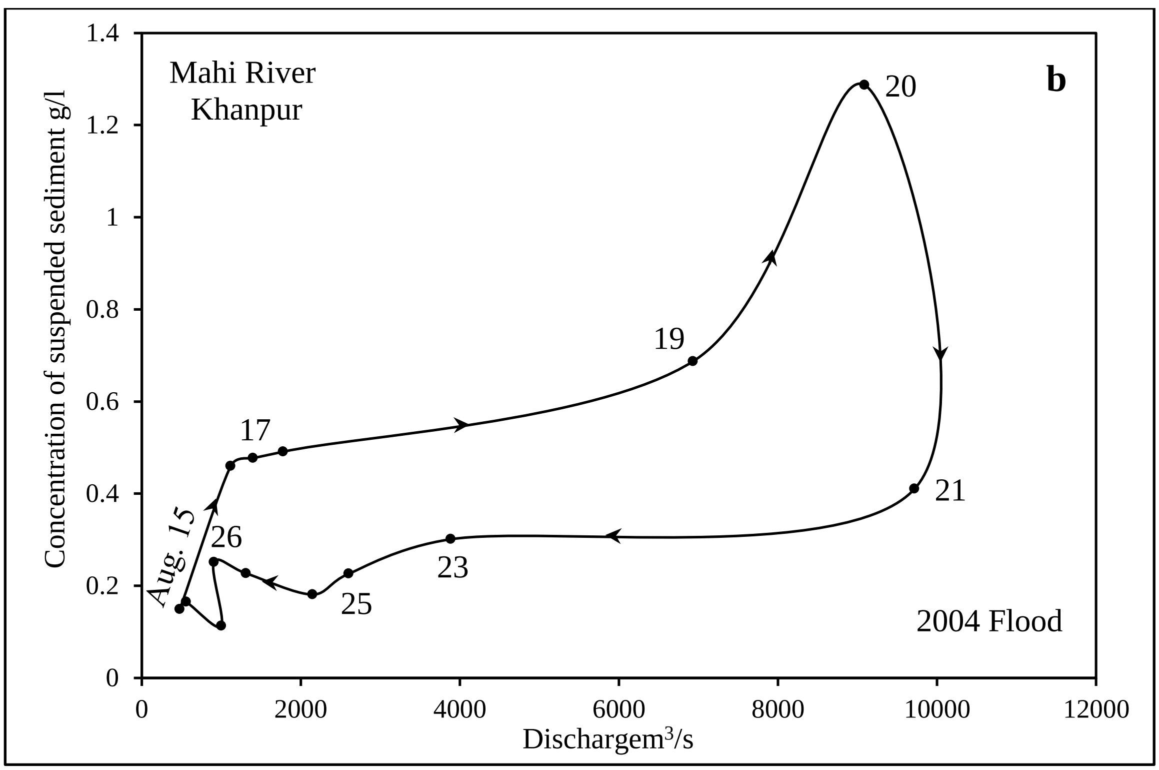


Figure 4.35b: Hysteresis loop; Mahi River: Khanpur

(V) Suspended sediment transport by large flows

The quantities for suspended sediment transport by large streamflows were obtained by calculating the percentages of suspended load carried by floods (Qf) during a particular year. The results of the analysis are given in Figure 4.36. The results reveal that floods (Qf) usually transport between 2% and 55% of the total annual sediment load and about 6% to 69% total annual flow. The maximum flood discharge of about 69% occurred on July 28, 2005 on the Mahi River at Mataji site. This event transported about 55% of suspended sediment. The minimum flood discharge of about 6% occurred on September 27, 2003 which transported only 1% of the total suspended sediment.

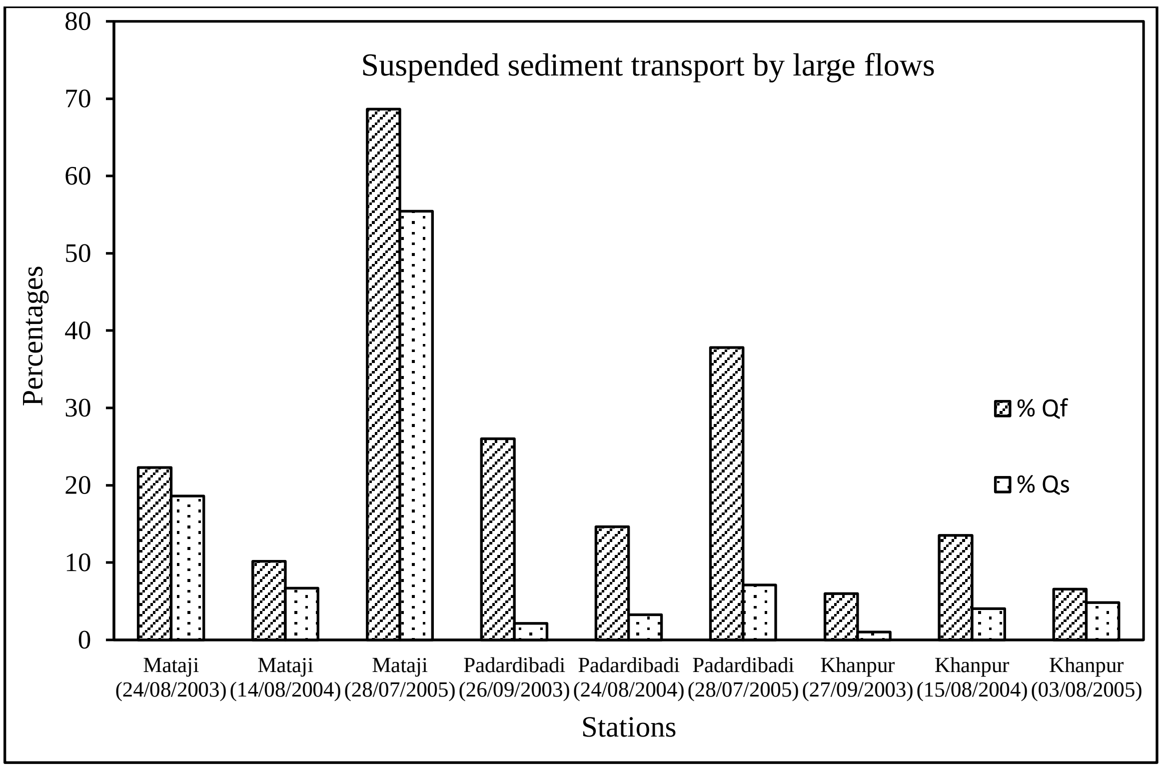


Figure 4.36: Suspended sediment transport by large flows

4.2.5 Geomorphic effectiveness of floods

Wolman and Miller (1960) have been defined the term geomorphic effectiveness in terms of the amount of suspended sediment transport by a flood. According to Wolman and Gerson (1978) stated that geomorphic effectiveness is an ability of flood to modify landforms. Over the period of time, several studies have discussed this problem and various measures of flow and their effect have been used by various workers (Table 4.20).

Table 4.20: Measures of geomorphic effectiveness and work

Researchers	Measures of effectiveness	Flood magnitude-frequency
Wolman and Miller (1960)	Suspended sediment transport	Moderate-magnitude High frequency
Pickup and Warner (1976)	Bedload transport, Channel changes	Series of discharges, Both moderate-magnitude high frequency and infrequent large-magnitude
Baker (1977)	Flood potential, Transportation of boulders, Resistance force of channel boundaries	Large-magnitude infrequent
Wolman and Gerson (1978	Persistence of flood effects and channel recovery	Large-magnitude infrequent in arid regions
Baker and Costa (1987)	Bed shear stress and unit stream power	Large-magnitude infrequent
Beven and Carling (1989)	Sequence of flood events	Ordering of effective flows
Costa and O'Connor (1995)	Duration of effective flows and stream power	Large-magnitude infrequent, long duration and exceeding certain threshold

Source: Hire, 2000

(I) Bedload sediment transport

Generally, suspended load is moved during all flow events. However, low flows may not be capable of transporting coarse sediments. The rivers bedload may be transported merely during large flow episodes. Therefore, transport of bedload is measured as geomorphic effectiveness of flood (Pickup and Warner, 1976). In the lack of bedload data some idea about the bedload transport can be derived by estimating the stream power and shear stress (Baker and Costa, 1987). Accordingly, these measures of flood power were estimated for some sites in the alluvial and bedrock reaches, and are summarized in Table 4.21 for different recurrence interval. The bedload sediment deposited in upper and middle reaches of the Mahi River is mainly composed of cobble, pebbles and boulders (Figure 4.37 to Figure 4.39). Therefore, to evaluate the mobility of these coarse sediment theoretically, the sediment-transport equations developed by Williams (1983) were used and result have been summarised in Table 4.22.

Table 4. 21: Flow dynamics of the Mahi River and its tributaries

River	Site (Channel Type)	Qm^3/s	Return Period GEVI	ω W/m^2	τ N/m^2	$\bar{v}$ m/s	Fr	Re $x10^7$
Mahi	Mataji (Bedrock)	Qm = 3135	2.33	189	51	2.75	0.42	11.87
		Qlf = 6568	6.93	361	67	3.65	0.49	20.88
		Qmax = 14972	150	734	109	6.01	0.63	55.55
Mahi	Paderdi Badi	Qm = 2968	2.33	40	21	1.7	0.23	9.31
		Qlf = 6132	6.93	83	27	2.32	0.28	16.38
		Qmax = 16153	373	187	51	3.62	0.32	47.52
Mahi	Khanpur (Alluvial)	Qm = 6448	2.33	116	52	2.04	0.26	12.87
		Qlf = 13022	6.93	228	81	2.92	0.30	28.86
		Qmax = 31062	217	518	116	5.69	0.48	79.99
Anas	Chakaliya (Bedrock)	Qm = 2329	2.33	66	18	1.52	0.24	6.10
		Qlf = 4275	6.93	108	30	2.34	0.29	15.55
		Qmax = 6956	38	148	35	2.75	0.32	21.29
Som	Rangeli (Alluvial)	Qm = 753	2.33	19	12	1.07	0.27	1.70
		Qlf = 1697	6.93	39	25	1.93	0.34	6.48
		Qmax = 5179	721	113	38	2.69	0.38	13.48
Jakham	Dhariawad	Qm = 392	2.33	62	34	1.61	0.38	2.86
		Qlf = 853	6.93	115	65	2.6	0.45	8.90
		Qmax = 1980	148	268	90	3.24	0.47	15.47

Qm = Mean annual peak discharge; Qlf = Large flood; Qmax =Maximum annual peak discharge; ω = Unit stream power in W/m^2; τ = Boundary shear stress in N/m^2; $\bar{v}$ = Mean velocity in m/s; Fr = Froude number; Re = Reynolds number; GEVI = Gumbel Extreme Value I; See Figure 3.1 for location of sites

Table 4.22: Boulder dimensions in the channel of the Mahi River and its tributaries and associated theoretical entrainment values

River	Site	I axis cm	$\bar{v}$ m/s	τ N/m^2	ω W/m^2	W's T Shear stress τ	W's T Stream power ω	W's T Velocity $\bar{v}$
Mahi	Rupakheda	150	9.07	642	7169	2.52	255	854
Mahi	Kothada	120	7.97	326	2985	2.25	204	643
Mahi	Mahudi ka Mal	120	5.99	153	1061	2.25	204	643
Mahi	Bhungda	226	3.90	97	452	3.09	384	1437
Mahi	Kailashpuri	508	2.90	36	120	4.63	864	4019
Anas	Thapra	170	5.47	206	1192	2.68	289	1001
Som	Masaron ki Obri	75	5.53	143	680	1.78	128	354

I-axis = Intermediate axis; $\bar{v}$ = Mean velocity in m/s; τ = Boundary shear stress in N/m^2; ω = Unit stream power in W/m^2; W's T = William's Threshold value of entrainment; See figure 3.2 for location of sites

The theoretical threshold entrainment values were compared to the hydraulic variables for varying discharges of different return periods. Table 4.21 indicates that, sand and pebbles are moved during all flows, all floods on the Mahi River are capable of transporting cobble sized sediments, and most of the large floods, with a recurrence interval of almost 40-720 years, are competent to move large boulders more than 0.5 m in diameter. Further, available data regarding velocities indicate that the maximum surface velocities during very large floods range between 3 and 6 m/s. Therefore, it clearly shows that transport of coarse bedload, high flows and floods are more important than frequent events of lower magnitude (Kale et al., 1994).

Figure 4.37: Largest boulder with 5080 mm i-axis upstream of the Mahi Bridge at Kailashpuri; See Figure 3.2 for location of the site

Figure 4.38: Boulder berm in the channel of the Mahi River at Mahudi ka Mal in Ratlam district of Madhya Pradesh; See Figure 3.2 for location of the site

Figure 4.39: Coarse sediment deposits in the channel of the Mahi River in Banswara district of Rajasthan

(II) Flood hydraulics and hydrodynamics

In view of the Baker and Costa (1987) flood power in terms of channel boundary shear stress is related with geomorphic effectiveness and power per unit area of bed. Baker (1988) and Wohl (1993) noted that erosion and transport of coarse sediment is the combine effect of the regime conditions of the flows and the degree of turbulence. Table 4.21 shows that the unit stream power ranges between 19 and 734 W/m^2 and whereas, bed shear stress between 12 and 116 N/m^2 respectively. These values indicate ability of the stream to erode and transport coarse sediment (Table 4.22).

The values Froude numbers varies between 0.23 between at Paderdi Badi to 0.63 at Mataji. However, the values of Reynolds number ranges from 1.70 at Rangeli to 79.99 at Khanpur. However, large floods, having a recurrence interval of 38 to 721 years are more effective in terms of erosion and sediment transport on the Mahi River and its tributaries (Table 4.21). These values are higher by one or two orders of magnitude than those produced by moderate flows, such as mean annual peak discharge which occur at an interval of about 2.33 yr (Table 4.21).

(III) Geomorphological impacts of floods

(i) Changes in channel cross sections

According to Pickup and Warner (1976), the measure of the geomorphic effectiveness of floods can be measured as modifications in river channel cross sectional profile and erosion of river bank. Therefore, to evaluate the flood associated modifications in the river banks and channel bed, multi-date cross profiles have been prepared for three sites on the Mahi River and three sites on its tributaries (Figure 4.40a to Figure 4.40f). The profiles show that over a period of time, there are no significant modifications in cross sections in terms of channel widening, deepening or deposition in the bed or bank.

Besides field observations at several locations indicate that the high channel banks are steep and there is almost complete absence of vegetation cover. This suggests that the banks are being acted upon during high monsoon flows. Besides, in the lower reaches the high banks are heavily gullied. Some gullies are short and confined to banks, and other gullies extend beyond the banks.

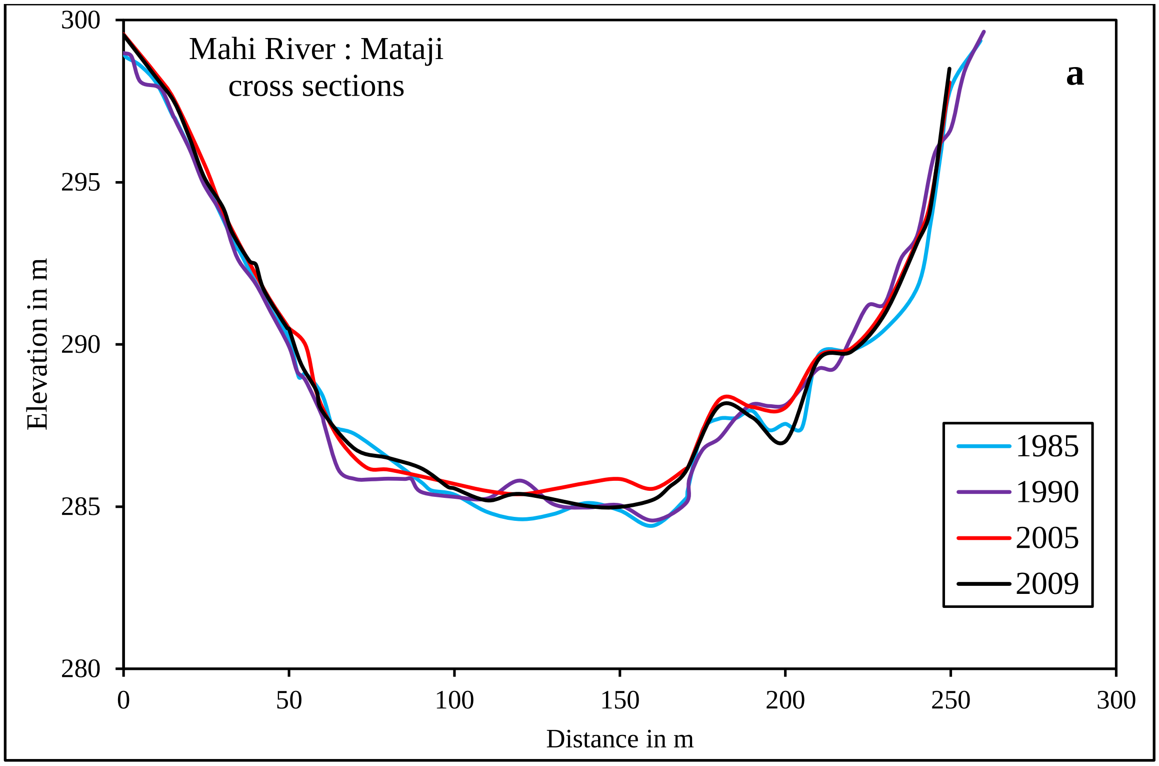


Figure 4.40a: Multi-date cross sections; Mahi River: Mataji

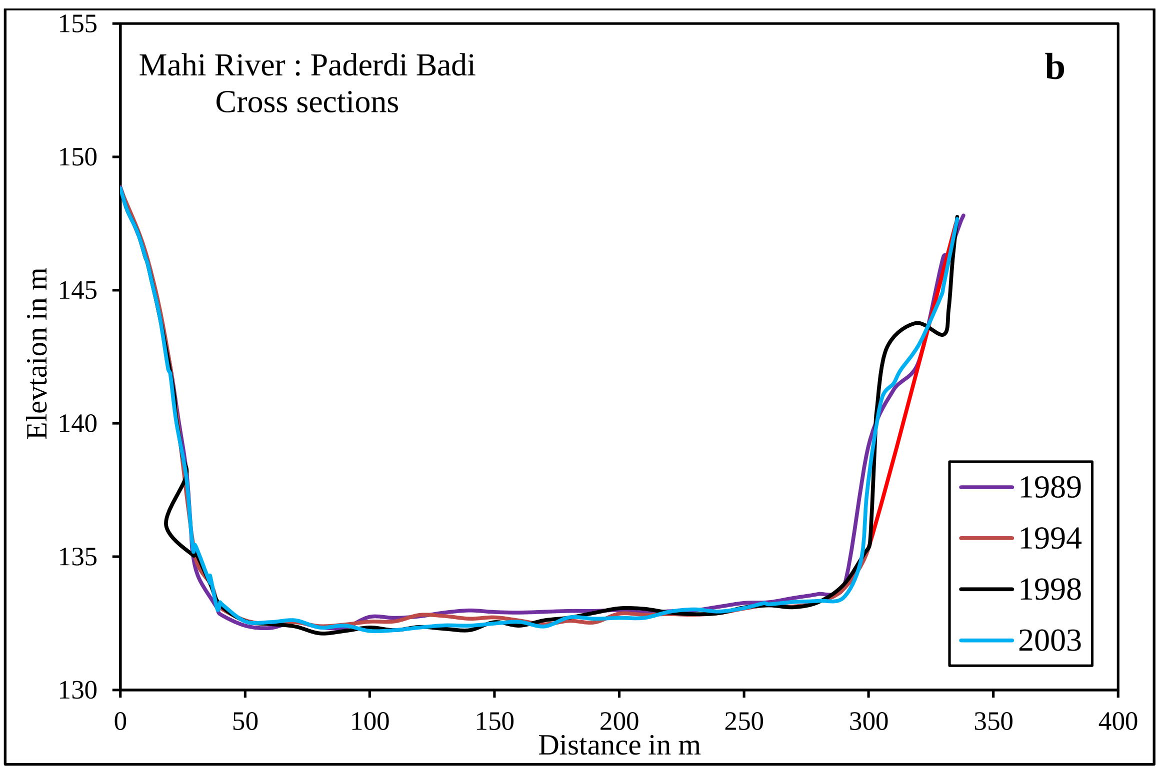


Figure 4.40b: Multi-date cross sections; Mahi River: Paderdi Badi

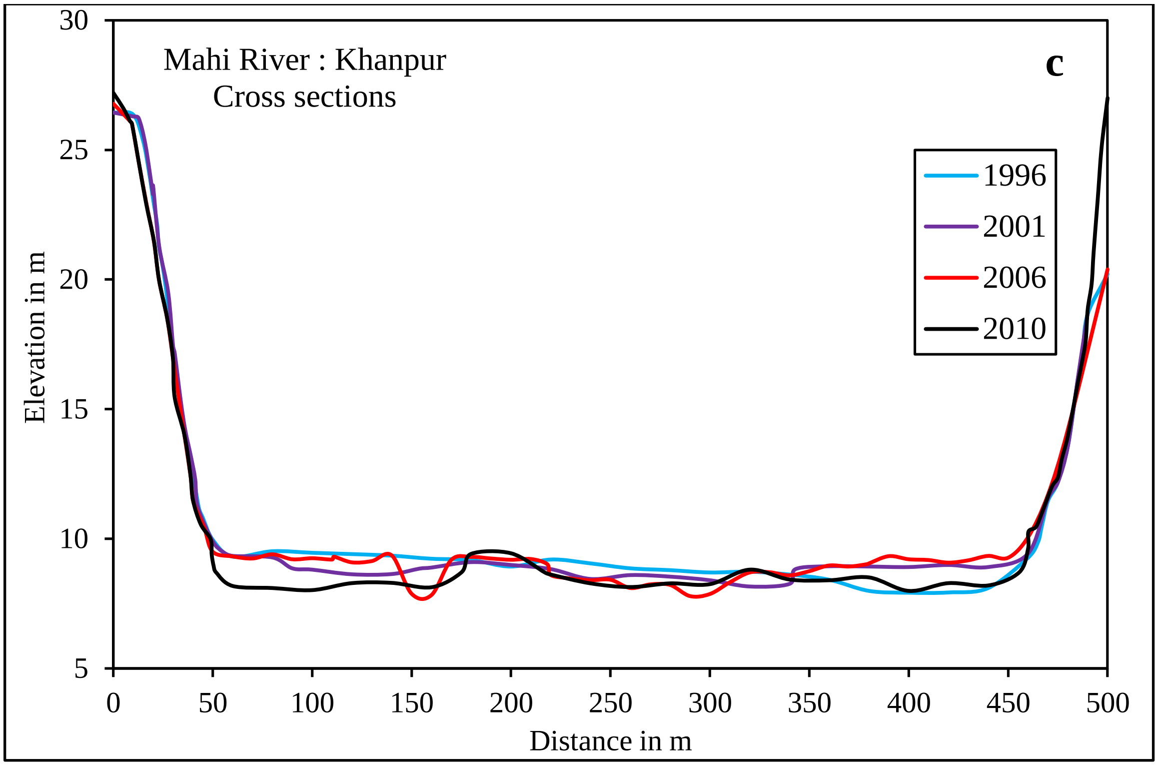


Figure 4.40c: Multi-date cross sections; Mahi River: Khanpur

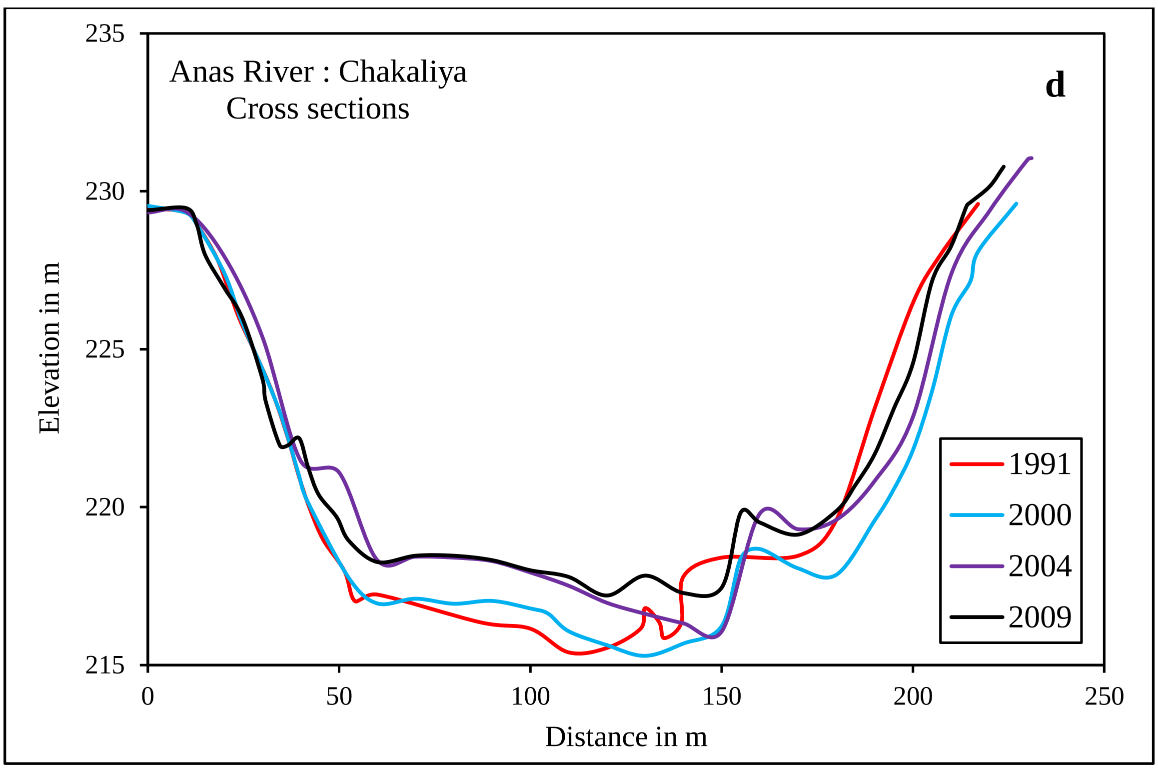


Figure 4.40d: Multi-date cross sections; Anas River: Chakaliya

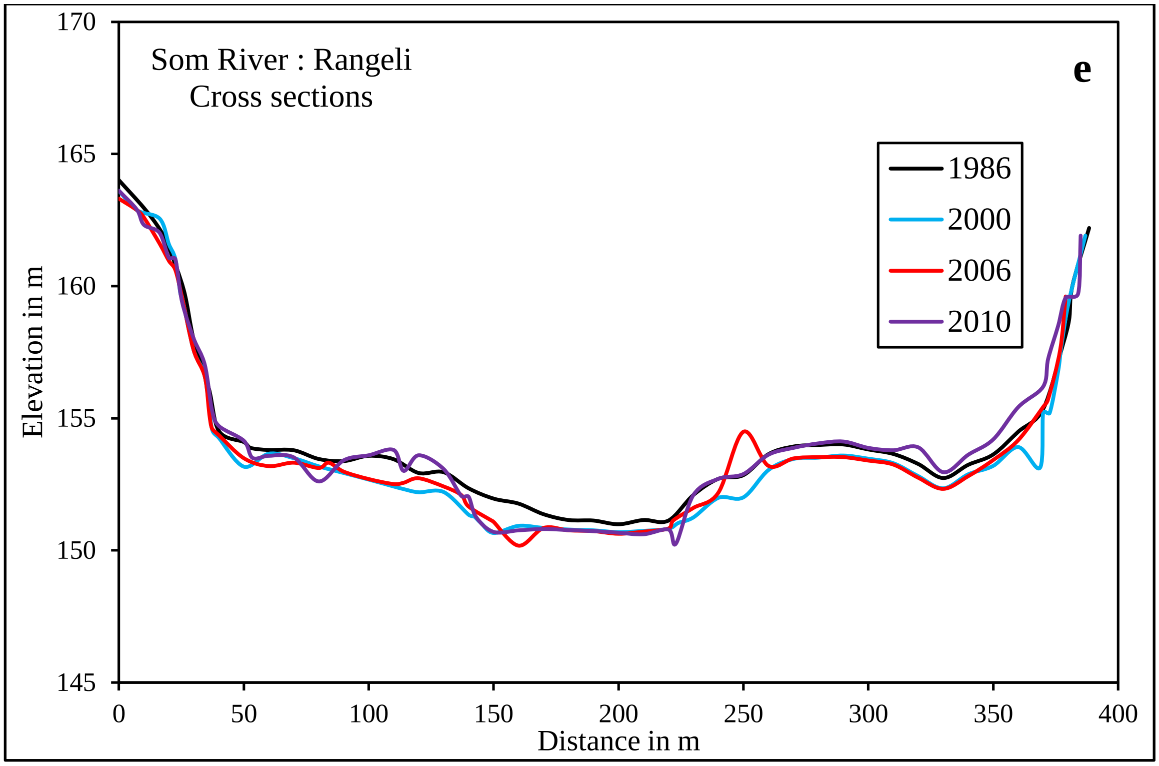


Figure 4.40e: Multi-date cross sections; Som River: Rangeli

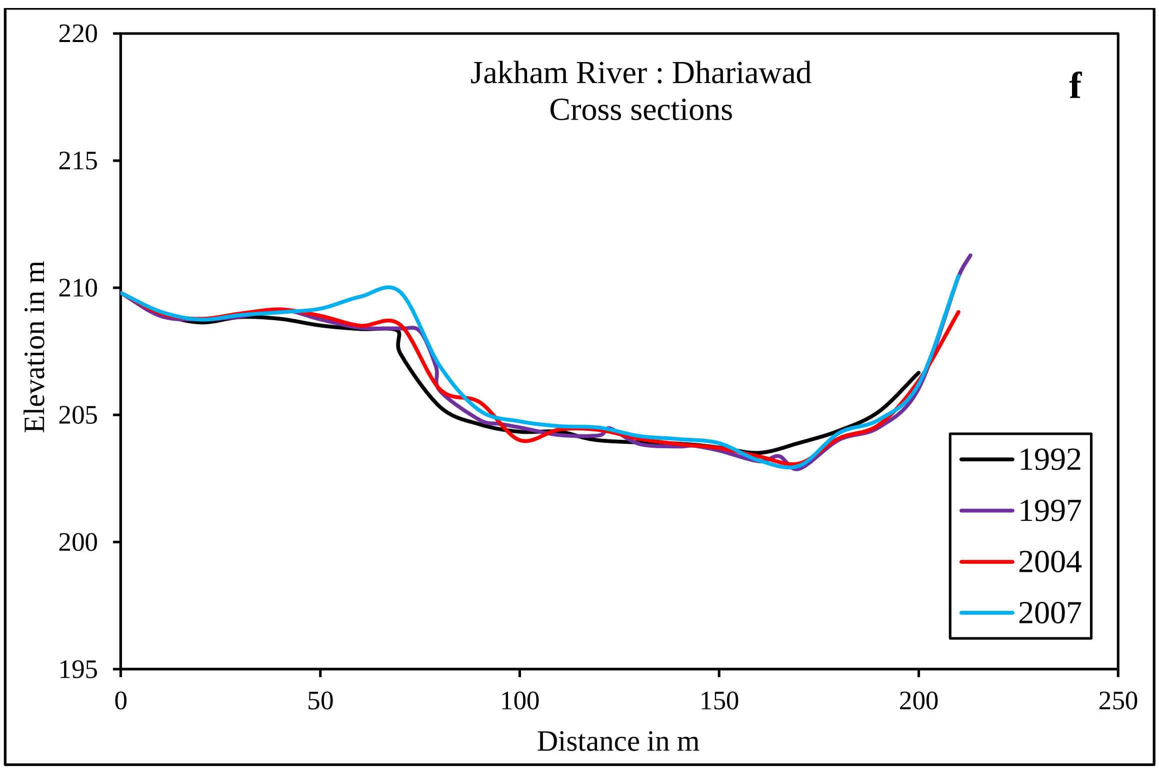


Figure 4.40f: Multi-date cross sections; Jakham River: Dhariawad

(ii) Geomorphic effects of recent floods

(a) September 1973 Flood

The flood of 1973 was observed in the whole Mahi Basin due to heavy to very heavy rainfall associated with the low pressure system. The rainstorm was centered at Modasa located in vicinity of the Mahi Basin, where 343 mm rainfall was recorded in 24-hr on 30th August 1973. However, this rainstorm recorded 576 mm rainfall in a period of 3 days from August 29-31, 1973. This rainstorm caused large flood in the Mahi Basin. The records of geomorphic effectiveness of 1973 flood have been collected during field work. The flood levels of the 1973 on the Mahi River has been obtained from the marking on the railway bridge at Bhairograh (upper reaches) in the Dhar district of Madhya Pradesh, at Mahi Bridge near Kailashpuri (middle reaches) and on the railway bridge at Timba Road railway station (Figure 4.41) and at Vasad (Figure 4.42) in Gujarat (lower reaches). The flood level of 1973 was also marked at Khanpur discharge gauging site (Figure 4.43). In addition to this, 1973 flood level was also identified on the Som River at Depur on the railway bridge (Figure 4.44). The 1973 flood level of the Jakham River was at noticed at Dhariawad gauging site (Figure 4.45).

One of the significant effects of the 1973 flood was noticed at Kailashpuri where a newly constructed bridge on the Banswara-Sagwara highway was washed out due to 21553 m^3/s volume of discharge (Figure 4.46). The bridge was completed in the year 1972. Besides, the huge discharge faulty design of the bridge i.e. low height of the bridge and less spacing between two pillars. This suggests importance of accurate estimation of design flood for hydraulic structures. The estimated discharge based on the cross sectional survey on the Mahi River at Mahi bridge near Kailashpuri is 21553 m^3/s with reference to HFL of 1973. The slabs and pillars of the bridge were observed at 50-60m distance from the present pillars of the bridge.

Similarly, 1973 flood was more significant for the construction of the Kadana Dam. The initial design flood of the Kadana Dam was 31087 m^3/s. This design flood was revised after 1968 flood due to observed discharge of 21820 m^3/s and finally design flood was considered as 36840 m^3/s for the Kadana Dam. However, in the year 1973 a large flood had occurred in the Mahi Basin. The observed discharge of 32986 m^3/s magnitude at

Kadana again forced to revised design flood of the Kadana Dam. The finally 46871 m^3/s discharge was considered as deign flood for the Kadana Dam and additional spillway was constructed. Nevertheless, 1973 flood caused damages to ongoing construction of the Kadana Dam (More, 1986). The effect of the 1973 flood also observed at Galiyakot (see Figure 3.2 for location of the site). Galiyakot is located on the bank of the Mahi River which was severely affected by 1973 flood. Most of the area of Galiyakot was submerged during flood. The 1973 flood caused damages to several settlements on both the banks of the Mahi River.

(ii) 1991 and 2006 floods

The flood of the year 1991 was moderate which caused road bridge constructed on the Mahi River immediate downstream of the Mahi Bajaj Sagar Dam was collapse and washout (Figure 4.47). This bridge was damaged due to sudden release of discharge from Mahi Bajaj Sagar Dam in the Mahi River. Besides, 2006 flood was severe which caused loss of properties and agriculture in the Mahi Basin. The heavy rainfall associated with low pressure circulation is the cause of the flood. One of the observed effects of 2006 flood was the damages to a weir constructed on the small stream near village Saroli in Kherwara tehsil of Udaipur district in Rajasthan (Figure 4.48). However, detailed information on these flood events has not been available.

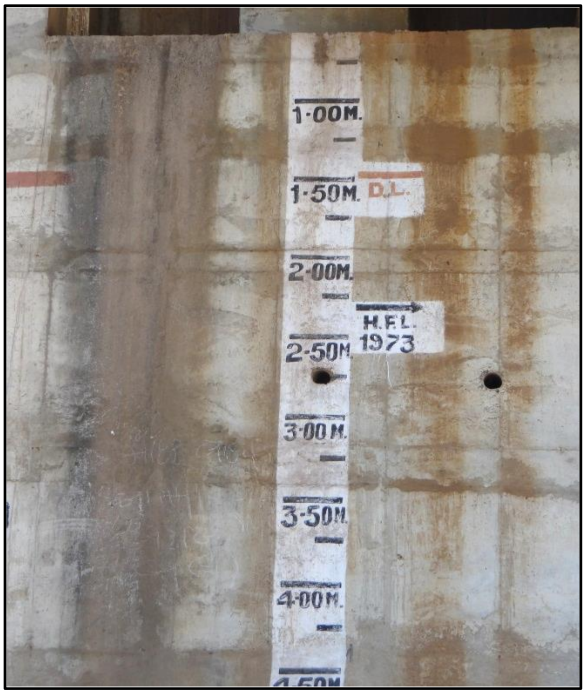


Figure 4.41: HFL mark of 1973 flood on the Mahi River on railway bridge near Timba Road railway station (Godhra, Gujarat)

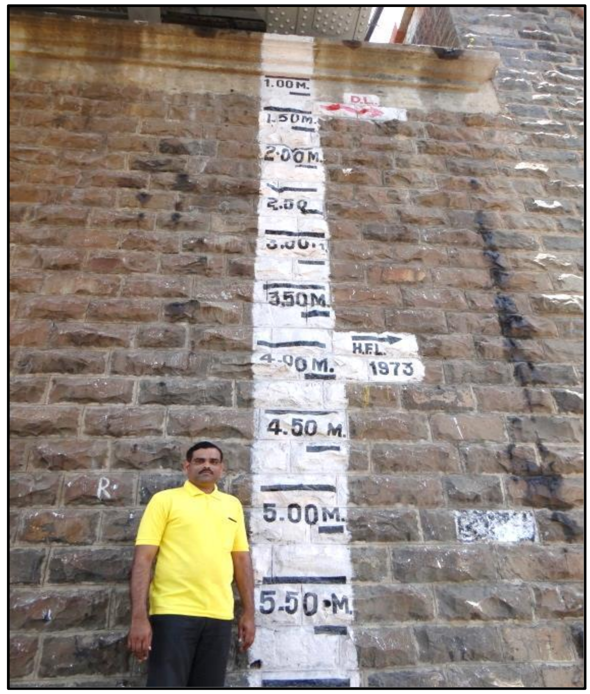


Figure 4.42: HFL mark of 1973 flood on the Mahi River on railway bridge near Vasad (Vadodara, Gujarat)

Figure 4.43: Photograph of the high flood level (HFL) mark of the 1973 flood on the bridge near Khanpur gauging site (Vadodara, Gujarat)

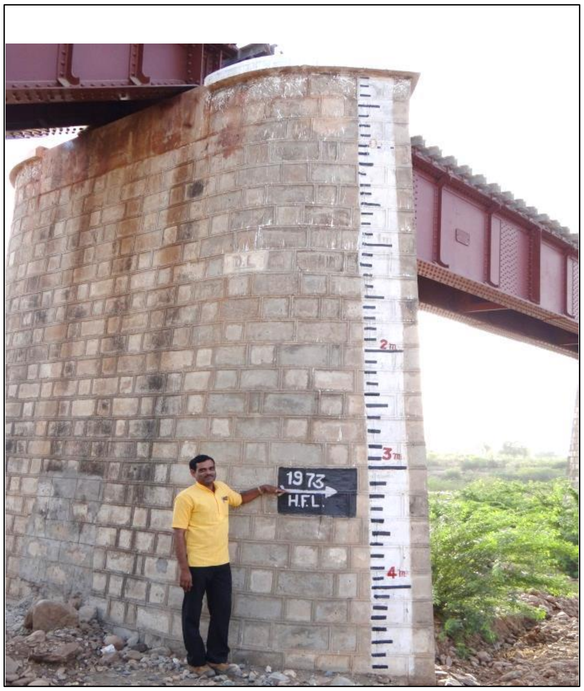


Figure 4.44: HFL mark of 1973 flood on the Som River Railway bridge near Depur (Dungarpur, Rajasthan)

Figure 4.45: HFL mark of 1973 flood on the Jakham River at Dhariawad (Dhariawad, Rajasthan)

Figure 4.46: A view of collapsed Mahi Bridge by flood on 08/09/1973 from new bridge on the Banswara-Sagwara highway near Kailashpuri (Sagwara, Rajasthan)

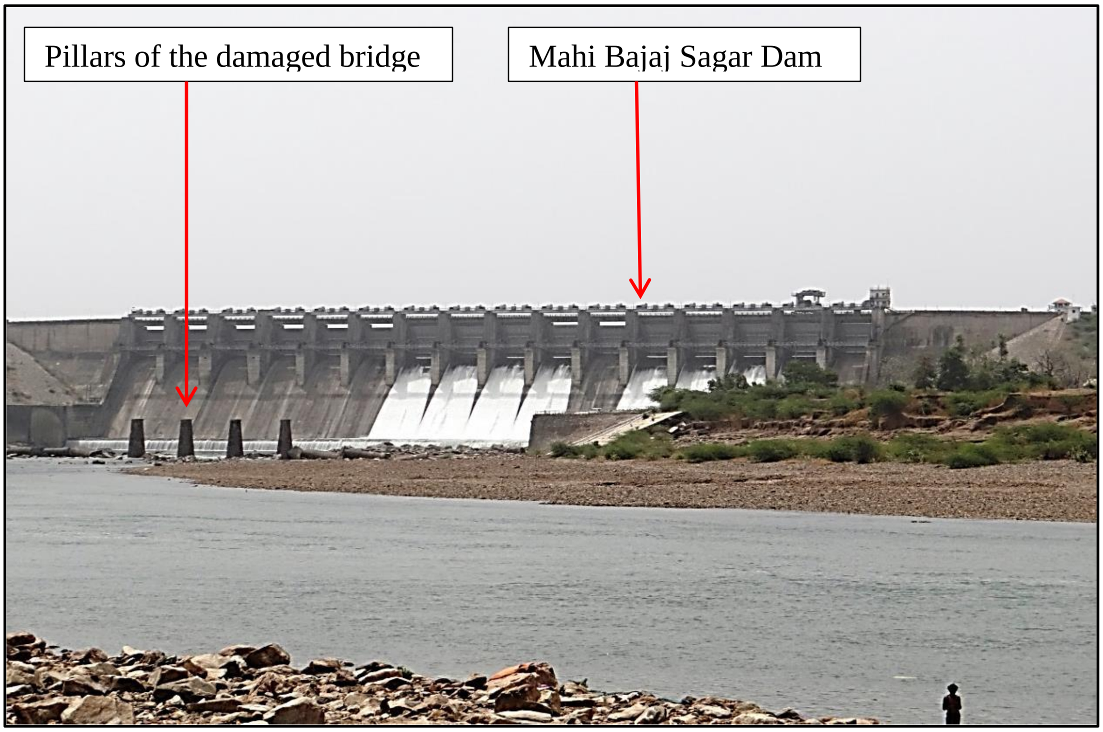


Figure 4.47: A view of damaged bridge due to 1991 flood downstream of the Mahi Bajaj Sagar Dam (Banswara, Rajasthan)

Figure 4.48: A weir on small stream of the Som River damage during 2006 flood at Saroli (Kherwara, Rajasthan)

4.2.6 Evaluation of the importance of floods

There is not a combine method or index to evaluate role of large and moderate flows which includes all the parameters of geomorphic effectiveness such as form ratio, magnitude, mean velocity, unit stream power, shear stress, etc. Therefore, ratio method has been applied and results have been mentioned in Table 4.23. The ratio is more than 1 if the quantity or value of the parameters is higher for floods and large floods, but below 1 if the quantity or value of the parameter is higher for moderate flows. The ratios for some of the parameters of effectiveness, which could be reasonably quantified are given in Table 4.23. The Qlf/Qm ratio specifies that there is an increase by a factor of 1.1 to 3.8 in hydraulic parameters in the bedrock and alluvial channels of the Mahi River and its tributaries. Besides, during maximum annual peak discharges (Qmax) there is an increase by a factor of 1.4 to 7.9 in the hydraulic parameters. Nevertheless, the form ratios show decrease by 1.1 to about 1.6 times during large floods.

Table 4.23 : Summary of the flow dynamic parameters changes from low to high discharges

River	Site	Qlf/Qm				Qmax/Qm				Qmax/Qlf			
		Q	$\bar{v}$	ω	Re	Q	$\bar{v}$	ω	Re	Q	$\bar{v}$	ω	Re
Mahi	Mataji	2.1	1.3	1.9	1.8	4.8	2.2	3.9	4.7	2.3	1.6	2.0	2.7
Mahi	Paderdi Badi	2.1	1.4	2.1	1.8	5.4	2.1	4.7	5.1	2.6	1.6	2.3	2.9
Mahi	Khanpur	2.0	1.4	2.0	2.2	4.8	2.8	4.5	6.2	2.4	1.9	2.3	2.8
Anas	Chakaliya	1.8	1.5	1.6	2.6	3.0	1.8	2.2	3.5	1.6	1.2	1.4	1.4
Som	Rangeli	2.3	1.8	2.1	3.8	6.9	2.5	5.9	7.9	3.0	1.4	2.9	2.1
Jakham	Dhariawad	2.2	1.1	2.9	1.4	5.1	1.4	5.4	2.4	2.3	1.2	1.9	1.7

River	Site	Qm/Qlf	Qm/Qmax	Qlf/Qmax	Ql/Qmax
		F	F	F	F
Mahi	Mataji	1.2	1.6	1.3	2.2
Mahi	Paderdi Badi	1.3	1.8	1.4	5.0
Mahi	Khanpur	1.6	2.2	1.4	10.6
Anas	Chakaliya	1.5	1.6	1.1	2.9
Som	Rangeli	1.3	1.7	1.3	2.9
Jakham	Dhariawad	1.1	1.2	1.1	1.4

Qmax = Maximum annual peak discharge; Qm = Mean annual peak discharges; Qlf = Large foods; Ql = Low discharge; Q = Discharge; F = Form ratio; $\bar{v}$ = Mean velocity; ω = Unit stream power; Re = Reynolds number

4.3 Flood Hydrometeorology

The analysis of flood producing conditions is one of the significant aspects in flood and fluvial geomorphology (Baker et al., 1988). Since, meteorological conditions determine the flood and fluvial characteristics of the rivers. It is essential to investigate the hydro meteorological characteristics of the river basins in association of the synoptic conditions. Indian monsoon system is complex and very erratic which results in spatio-temporal variation in the rainfall pattern and associated floods on the Indian rivers. Most of the research work has been carried out on floods at regional level. Limited research work has been conducted on floods at river basins level in association of the synoptic conditions in India.

The Mahi Basin is located in the heart of the Indian monsoon which regulates the river regime and flood characteristics of the basin. Therefore, analysis of distribution, variability and trend of monsoon rainfall over the basin is of significant aspect in this research. Besides, investigation of teleconnection of the Pacific SST to rainfall of the basin, association of the LPS(s) and rainfall over the Basin and exploration of the historical floods in the Mahi Basin is one of the objectives of this study. Therefore, an attempt has been made to understand the spatio-temporal flood hydrometeorlogical characteristics of the Mahi Basin by analyzing the rainfall data and synoptic conditions.

4.3.1 Rainfall regime characteristics

The Mahi Basin indicates significant variation in the distributional pattern of the monsoon rainfall over the basin in time and space. This variation in monsoon rainfall over the basin is caused by topographical and meteorological conditions prevailing in the basin. The Mahi, Anas and Panam Rivers originate on northern slopes of the Vindhyas over the Malwa Plateau, whilst Som River originates from eastern slope of Aravali Ranges. The upper Mahi basin comprises Malawa plateau, hills of the Aravali and Vindhya covered with forest in Madhya Pradesh and Rajasthan whereas, lower basin falls in Gujarat plain. Figure 4.49 shows the distribution of average annual rainfall and monthly rainfall pattern for seven representative rain gauge sites in the Mahi Basin.

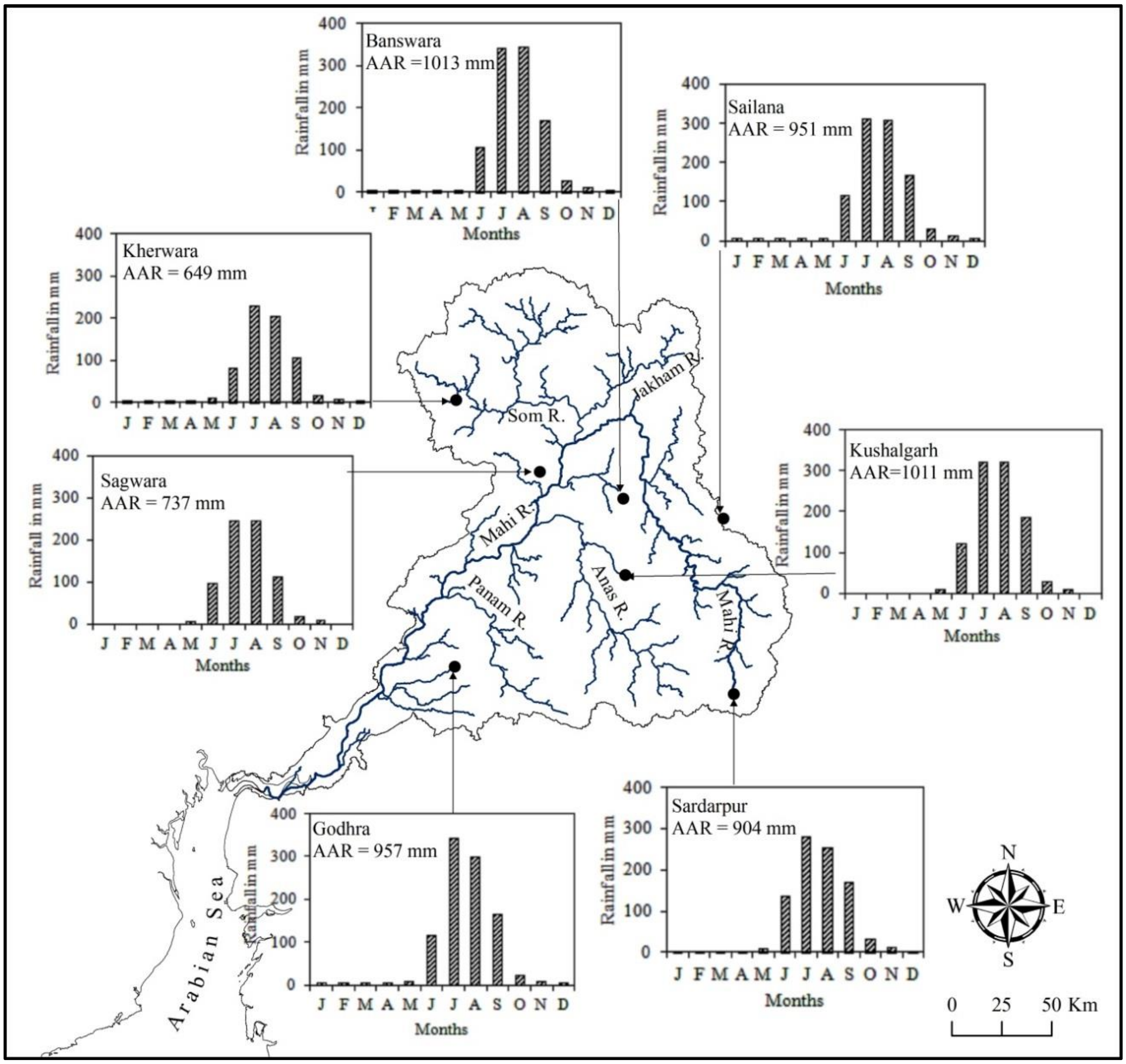


Figure 4.49: Average annual rainfall and monthly rainfall at selected sites in the Mahi Basin

The isohyetal pattern shows a marked spatial variation in the basin (Figure 1.4). Figure 4.49 indicates that the Banswara receives about 1013 mm annual average rainfall which is the highest rainfall receiving station in the Mahi Basin whereas, the Kherwara receive lowest annual average rainfall about 649 mm. More than 96% of the annual rainfall is recorded during the monsoon season. Most of the basin receives about 700 to 900 mm rainfall with average annual rainfall of 889 mm.

(I) Spatial and annual variability

The general spatio-temporal characteristics of rainfall at the selected stations in the Mahi Basin have been shown graphically in Figure 4.49 and summarized in Table 4.24. Figure 4.49 shows extensive range in seasonal rainfall distribution and annual variability in rainfall at seven rain gauge sites in the Mahi Basin. Normally, the basin gets monsoon rains from mid-June with the inception of southwest monsoon. There is significant variation in monthly rainfall during monsoon season within the basin. For example, at Sardarpur in source region of the Mahi River, about 59% of the rain falls in the month of July and August (Figure 4.49; Table 4.24). On the other hand, Banswara station located in the upper basin receives about 68% of the rainfall during the same period. Average annual rainfall is highest in the middle part of the basin.

Table 4.24: Rainfall characteristics at selected stations in the Mahi Basin
(Monthly and annual averages in mm)

Water Year	Sardarpur	Sailana	Banswara	Kushalgarh	Kherwara	Sagwara	Godhra
June	138.32	112.77	104.75	121.54	79.51	96.49	113.62
July	279.52	309.23	341.01	322.97	226.12	243.43	341.89
August	253.96	307.34	345.57	320.71	200.98	245.17	296.45
September	170.93	164.82	168.30	187.75	104.06	111.81	162.91
October	30.77	29.34	25.56	29.48	14.07	16.25	22.10
November	12.60	9.95	9.61	8.61	6.21	8.84	6.33
December	2.23	4.35	3.07	2.83	1.09	2.69	1.65
January	3.36	3.19	3.61	3.00	1.97	5.72	1.52
February	2.24	1.66	2.45	1.79	2.11	1.17	1.01
March	1.16	1.40	1.66	2.08	2.80	1.35	1.19
April	1.37	1.60	1.41	1.24	1.95	1.13	0.92
May	8.00	5.17	5.83	8.89	8.15	2.45	7.18
AAR	904.4**4**	950.8**1**	1012.8**3**	1010.88	649.0**2**	736.51	956.77
MR	873.49	923.50	985.20	982.45	624.73	713.16	936.96
NMR	30.95	27.31	27.63	28.43	24.29	23.35	19.81
% Monsoon rainfall (Jun-Oct)	96.58	97.13	97.27	97.19	96.26	96.83	97.93
% Non-monsoon rainfall (Nov-May)	3.42	2.87	2.73	2.81	3.74	3.17	2.07

Source: IMD; Based on 100-111 years of record; AAR = Average annual rainfall; MR = Monsoonal rainfall; NMR = Non-monsoonal rainfall; See Figure 3.3 for location of stations

(II) Interannual variability

The interannual and inter seasonal variation in rainfall is significant characteristics of Indian monsoon (Gadgil et.al, 2007). Spatio-temporal variations in the floods on the Indian Rivers are mainly caused by significant differences in the distributional pattern of monsoon over the Indian Territory during the south-west monsoon. Similar to other monsoon dominated rivers of India, Mahi Basin also shows significant interannual and inter seasonal variation in the rainfall and flood events. The annual rainfall characteristics at selected stations in the Mahi Basin have been summarized in the Table 4.25. The annual average rainfall is significantly high in the upper (Banswara, 1013 mm and Kushalgarh, 1011 mm) and lower basin (Godhra, 957 mm). The coefficient of variation (Cv) of annual rainfall in most part of the basin is less than 35%. However, the Cv increases to maximum 38% from middle to the lower basin.

All sites display very high range of annual rainfall (Table 4.25). For example, the minimum annual rainfall recorded at the Banswara site was 457 mm for the year 1918, and the maximum annual rainfall was 2591 mm for the year 2006. The values of the coefficient of skewness (Cs) are positive for the all sites, ranging between 0.32 and 1.16.

Table 4.25: Annual rainfall characteristics at selected stations in the Mahi Basin (Between 1901 and 2013).

Site	Record length in years	R max mm (year)	R min mm (year)	AAR mm	σ	Cv	Cs
Sardarpur	105	2004 (1972)	333 (1911)	904	307	0.34	0.74
Sailana	110	1732 (2006)	335 (1918)	951	317	0.33	0.32
Banswara	111	2591 (2006)	457 (1936)	1013	371	0.37	1.16
Kushalgarh	111	2045 (1946)	297 (1918)	1011	367	0.36	0.50
Kherwara	111	1332 (2006)	261 (1987)	649	210	0.32	0.50
Sagwara	103	1588 (2006)	275 (1936)	737	250	0.34	0.61
Godhra	113	2281 (1927)	193 (1911)	957	361	0.38	0.52

Source: IMD; Based on 103-113 years of record; Rmax = Maximum annual rainfall; Rmin = Minimum annual rainfall; σ = Standard deviation; Cv = Coefficient of variation; Cs = Coefficient of skewness ; See Figure 3.3 for location of sites

Figure 4.50a to Figure 4.50g reveal remarkable interannual variability in rainfall totals and subsequent floods in the Mahi Basin. Long term spatio-temporal variations in the annual average rainfall indicates some notable years when annual average rainfall was above (high) and below (low) average rainfall of the respective sites.

Examination of the graphs from Figure 4.50a to Figure 4.50g also displays that prior to 1930s rainfall was above average, but interannual variability was low. On the other hand, from 1930 to 1990s, many years recorded above average annual rainfall, but interannual variability was high. The pattern of variation in the annual rainfall is also depicted by the plots of departure from mean expressed as percentage of mean, for the Mahi Basin (Figure 4.51).

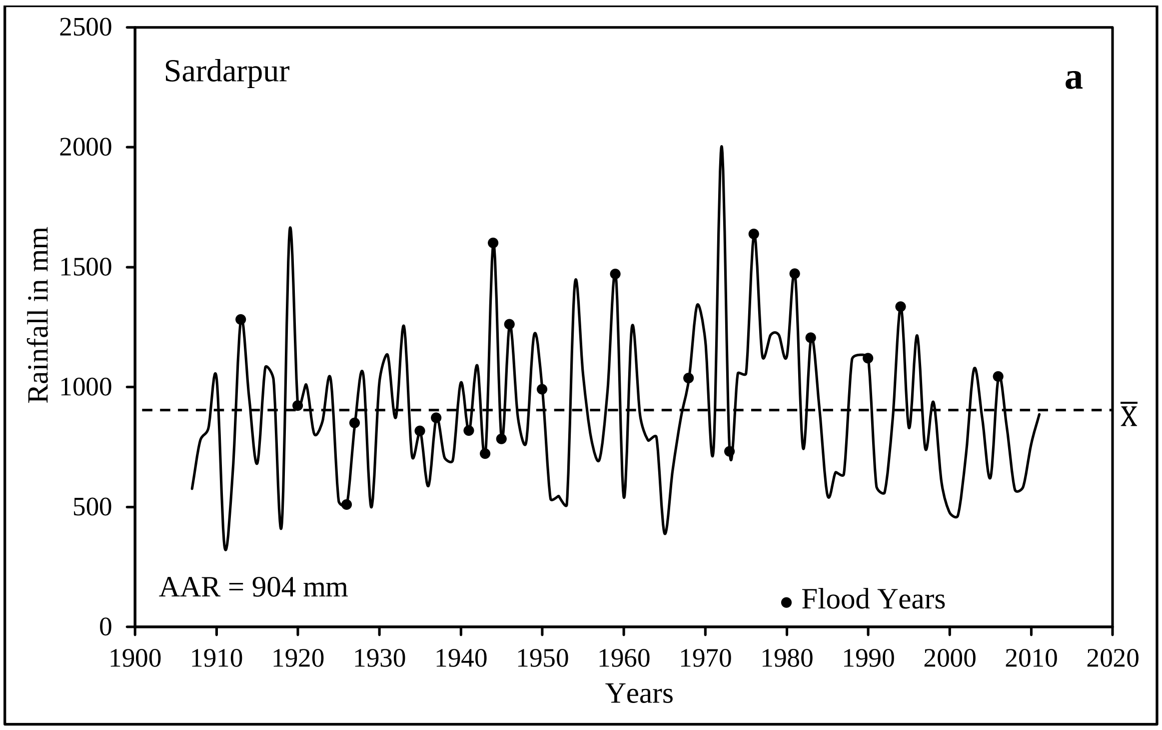


Figure 4.50a: Interannual variability of rainfall at Sardarpur station in the Mahi Basin; $\bar{X}$ = AAR; See locations of stations in Figure 3.3

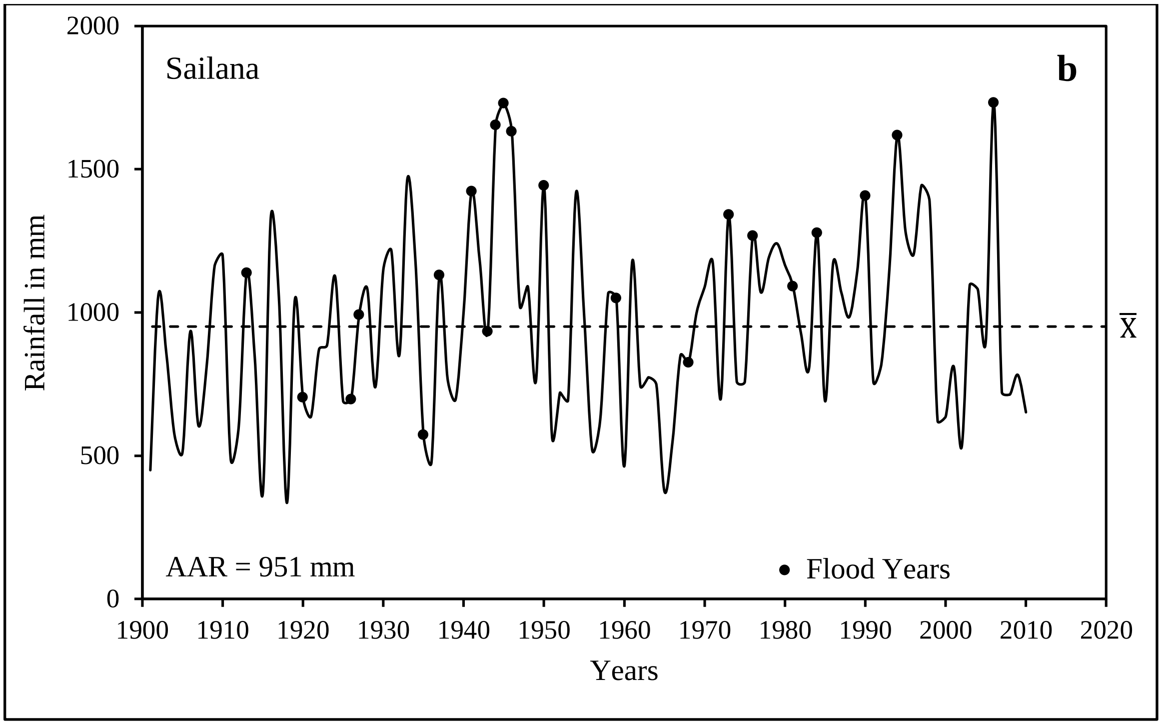


Figure 4.50b: Interannual variability of rainfall at Sailana station in the Mahi Basin; $\overline{X}$ = AAR; See locations of stations in Figure 3.3

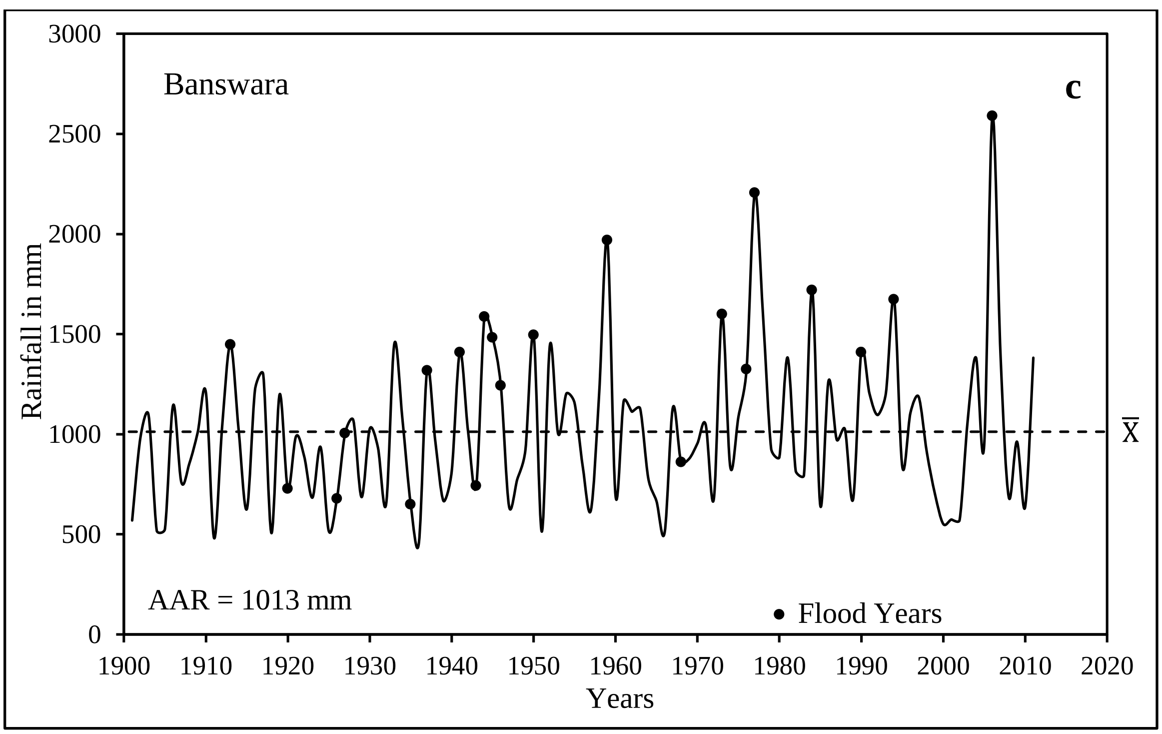


Figure 4.50c: Interannual variability of rainfall at Banswara station in the Mahi Basin; $\overline{X}$ = AAR; See locations of stations in Figure 3.3

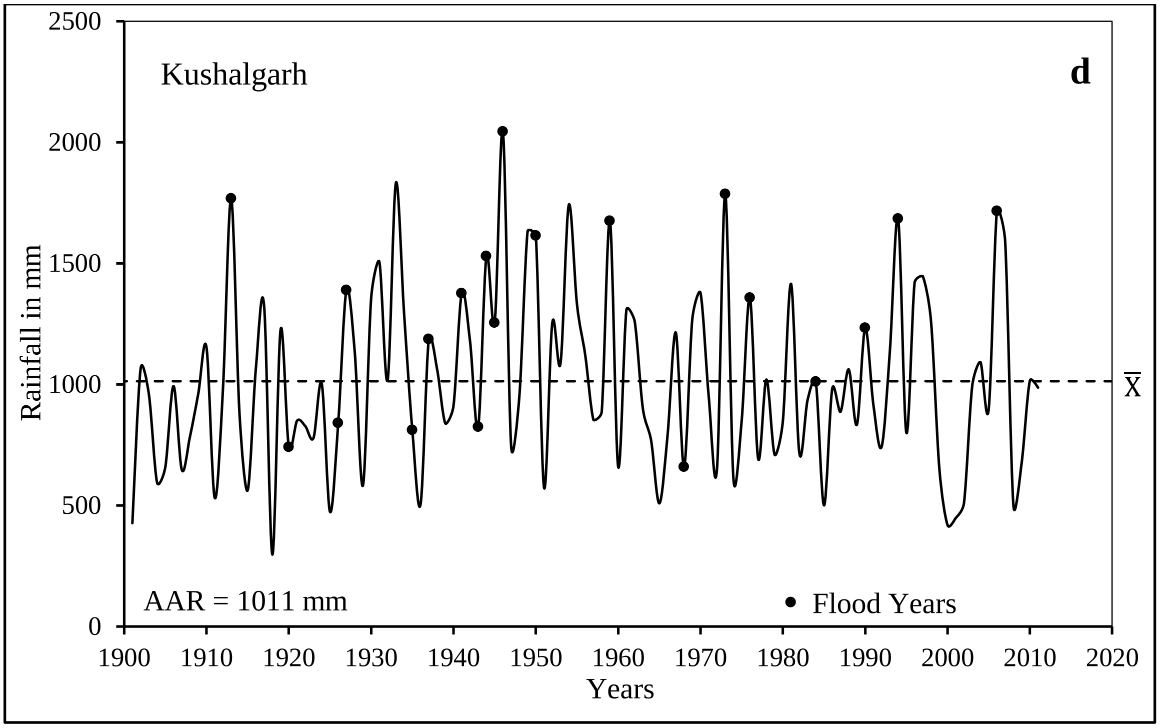


Figure 4.50d: Interannual variability of rainfall at Kushalgarh station in the Mahi Basin; $\overline{X}$ = AAR; See locations of stations in Figure 3.3

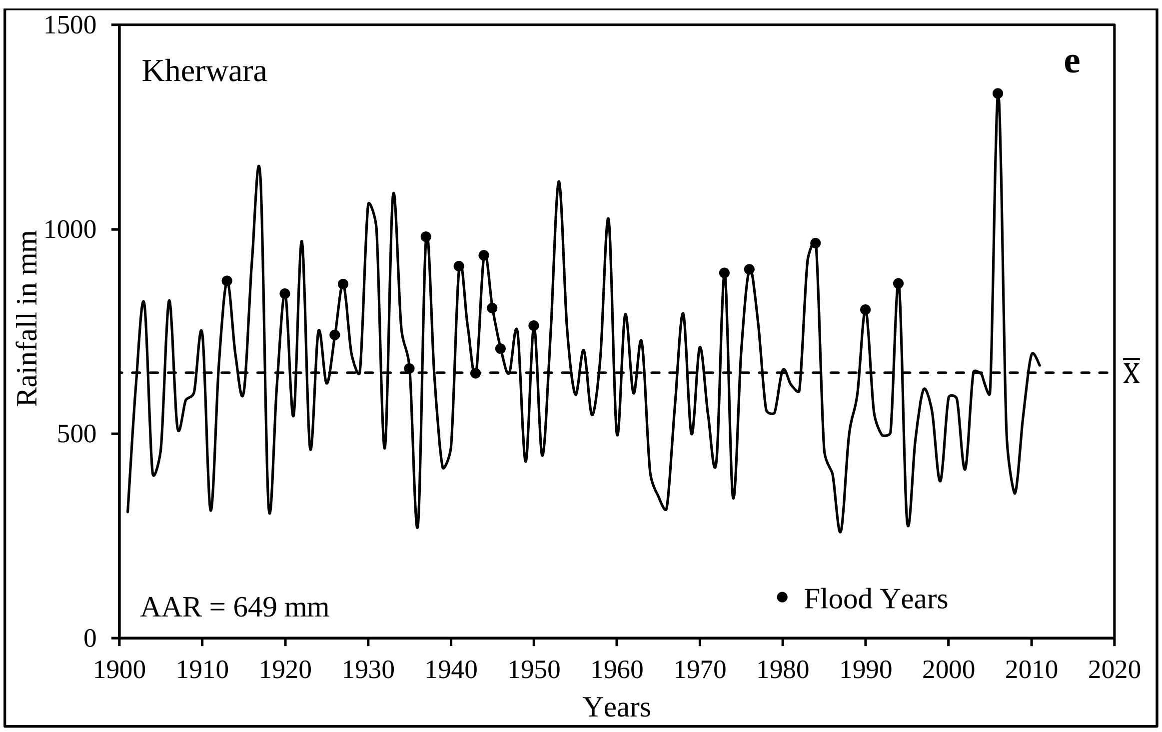


Figure 4.50e: Interannual variability of rainfall at Kherwara station in the Mahi Basin; $\overline{X}$ = AAR; See locations of stations in Figure 3.3

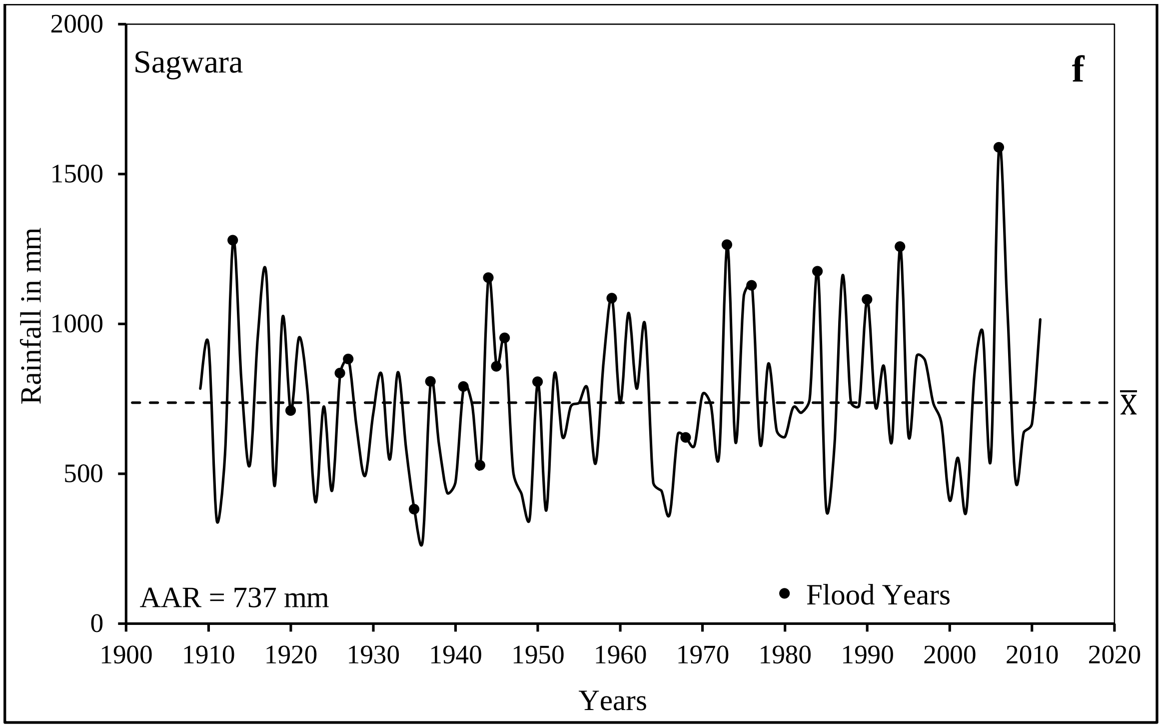


Figure 4.50f: Interannual variability of rainfall at Sagwara station in the Mahi Basin; $\overline{X}$ = AAR; See locations of stations in Figure 3.3

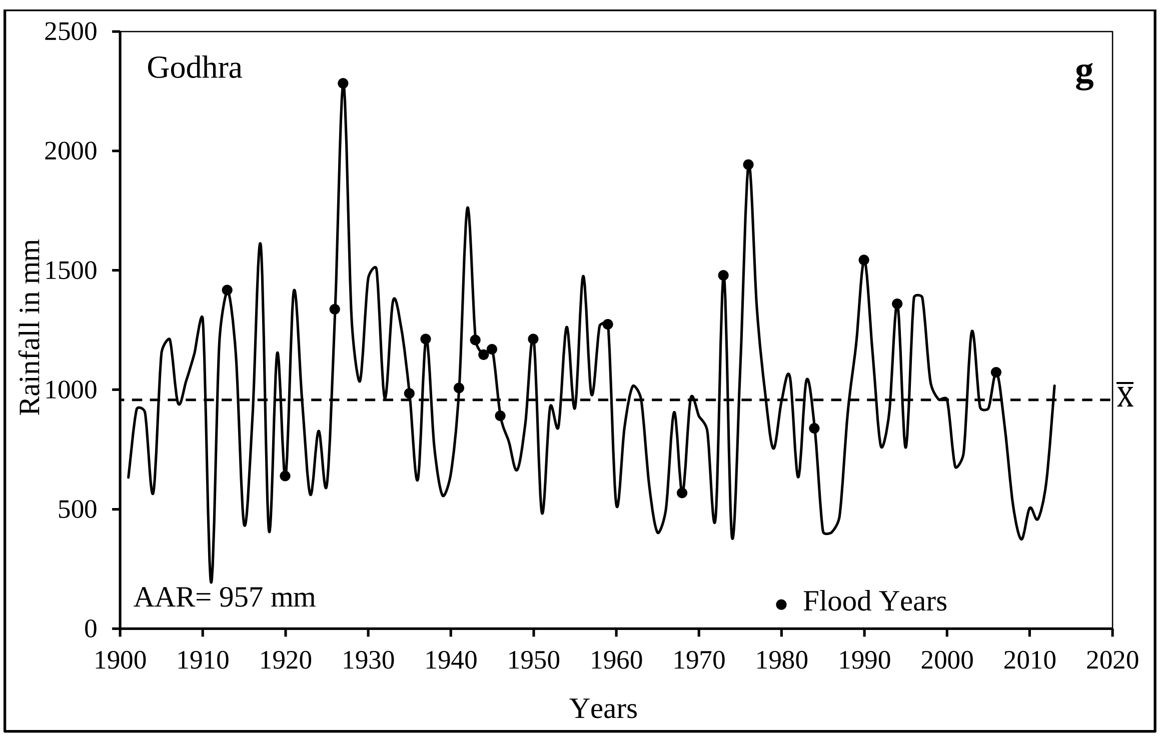


Figure 4.50g: Interannual variability of rainfall at Godhra station in the Mahi Basin; $\overline{X}$ = AAR; See locations of stations in Figure 3.3

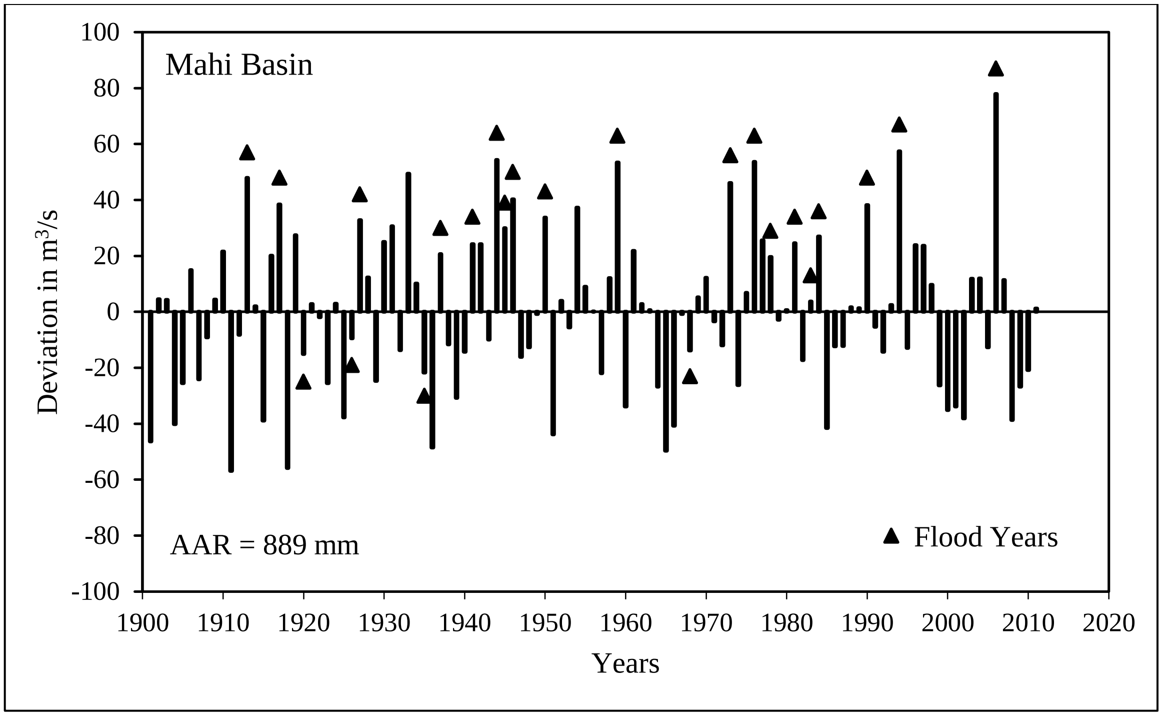


Figure 4.51: Percent departure from mean rainfall of the Mahi Basin

4.3.2 Flood-generating meteorological conditions

Synoptic events ranging from lows to cyclones are generally accompanying with extraordinary magnitude rainfall caused catastrophic floods in humid and seasonal tropics (Gupta, 1988; 1995a). Likewise, intense precipitation from LPS(s) during monsoon season is the foremost source of extraordinary floods which indicate the largest distinguished peak in a flood time series (Kale et al., 1994). The Mahi basin is lies in the western India which comes frequently under the influence of track of low pressure system originating over the Bay of Bengal, Arabian Sea and adjoining land. Therefore, severe rainstorm trigger extreme rainfall during monsoon season is the root cause of the high magnitude floods in the Mahi basin. Table 4.26 gives the significant synoptic conditions associated with the historical and modern floods in the Mahi Basin. The table reveals that some of the largest floods on record, for which data are available, were associated with the severe rainstorms, which were the result of the low pressure systems originating over the Bay of Bengal, Arabian Sea, or land.

(I) Characteristics of the flood-generating low pressure systems (LPS)

The flood records of the Mahi Basin indicates that mean track of the LPSs originating over the Bay of Bengal has a significant contribution to monsoon rainfall and floods in the Mahi Basin. However, there is no major flood in the Mahi Basin due to LPSs formed over Arabian Sea (Figure 4.52). Therefore, it is essential to explore floods that have occurred on the Mahi River as a result of monsoon disturbances. Since, the Mahi Basin is situated western part of India which recurrently affected by the monsoon disturbances formed over Bay of Bengal and moving inland northwesterly to west northwesterly direction. These rainstorms yield heavy to very heavy downpour while crossing the basin as a result floods are generated in the Mahi basin. Streamflow records available for the Mahi River and its tributaries indicate that LPS(s) have significant influence.

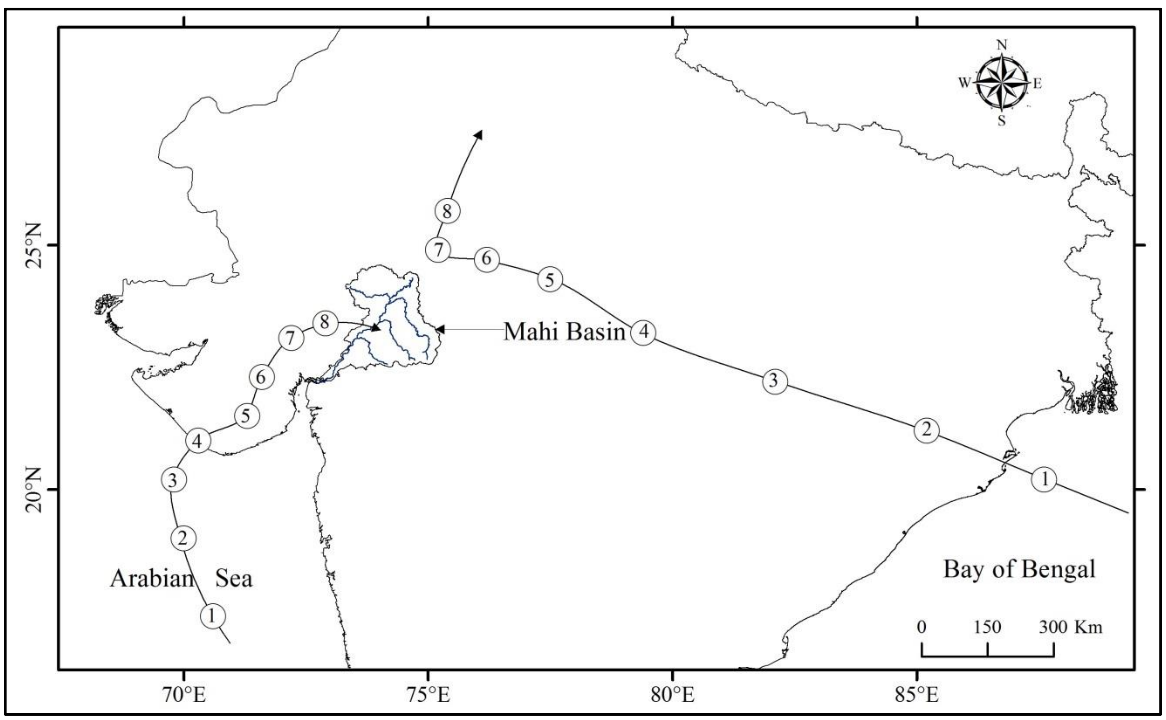


Figure 4.52: Mean tracks of the LPS affecting the Mahi Basin

(i) LPS(s) that passed through the Basin

The flood records of Mahi Basin have shown spatio-temporal variation of occurrence of floods within the basin. The basic reason behind this is LPS(s) that pass through the basin or traversed a part of the basin. The magnitudes of flood caused by LPS(s) vary over different reaches of the Mahi Basin. The tributaries of the Mahi River such as Anas, Panam and Som have source in the Vindhyas and the Aravalli Ranges respectively. The basins of these tributaries come under the influence of Bay Depressions that travels northwest. Therefore, high magnitude floods in these river basins are associated with the LPS(s) such as floods of the year 1927, 1959, 1986, 1973, 1976 and 2006. Major floods of the Mahi Basin have been discussed in the following section (Figure 4.53).

The catastrophic flood that had occurred in the Mahi Basin in the year 1927 was associated with LPS. The severe rainstorm of July 26-28 passes through lower Mahi Basin. The centre of this rainstorm was at Dakor in Gujarat which is adjacent to the Mahi Basin. This rainstorm caused 1-day maximum rainfall in the Mahi Basin was recorded at Godhra on July 26 which was 401 mm whereas, Kalol station recorded about 1003 mm rainfall during storm period. However, such a catastrophic flood event, no discharge record is available.

The rainstorm formed over Bay of Bengal in the year 1952 caused large flood in the Mahi Basin. However, flood levels are found only in the Anas and Panam Basins. The centre of the rainstorm was at Jhalod in Gujarat on July 30-31. The rainstorm recorded 538 and 581 mm of rainfall on respective days at Jhalod. Besides, 1-day maximum rainfall of 300 mm recorded at Banswara on July 30 in the middle Mahi Basin. Nevertheless, no records of this flood also available in terms of discharges and geomorphic effectiveness of the floods. In the same decade, the severe rainstorm of September 14-15, 1959 had produced flood in the Mahi Basin. Besides this storm, antecedent moisture conditions prevailed in the basin is one of the causes of 1959 flood. In the same monsoon season on July 23, 1959, Banswara station receives 559 mm rainfall in a day which the highest ever recorded one day rainfall at Banswara and in the Mahi Basin also. As a result of rainstorm of September 14-15, maximum flood discharge of 20839 m^3/s magnitude was observed at Wanakbori on September 15, 1959.

The cyclonic depression formed over Bay of Bengal on July 29-31, 1968 which caused widespread heavy rainfall in the lower Mahi Basin. The maximum flood discharge was 19149 m^3/s recorded at Wanakbori on August 1, 1968. The major rainstorm of August 30, 1973 produced largest ever recorded flood in the entire Mahi Basin. The rainstorm centred at Modasa which is very close to the Mahi Basin. However, the antecedent moisture condition prevailed in the upper Mahi Basin due to land depression of August 14-18 is also accountable for large flood of 1973. This flood even recorded highest flood discharge 40,663 m^3/s at Wanakbori on September 7, 1973. The geomorphic effects of 1973 flood have been discussed in flood geomorphology section in detailed. The second largest flood the centenary in the Mahi Basin was associated with land depression of 1976 formed near Raipur in Chhattisgarh. The land depression centered over Sallopat in Banswara on August 29 where 1-day maximum rainfall of 339 mm was recorded. This rainstorm had created large flood with the maximum observed discharge of 26534 m^3/s magnitude at Wanakbori on August 30, 1976.

The flood of 1990 had occurred due to rainstorm of August 24 whose center was Halol in Gujarat. The 1-day maximum rainfall was recorded at Halol was 476 mm on August 24. The maximum discharge of 29295 m^3/s magnitude was also recorded on the August 24 at Wanakbori. The recent flood of the year 2006 was the largest flood in the Mahi Basin after 1973. There are several synoptic conditions as mentioned in the Monsoon - 2006 Report published by India Meteorological Department, Pune. These conditions are as follows;

(a) Monsoon trough was south of its normal position by 3-4^o

(b) A low pressure area formed over North Bay on 28 July and moved west north westwards. This low pressure was over west Rajasthan on 1 August and became less marked on August 2.

(c) An upper air cyclonic circulation merged with the cyclonic circulation lay over west Madhya Pradesh and neighbourhood on July 29.

(d) A Deep Depression during August 2-5 declining into a well-marked low pressure area over southwest Madhya Pradesh on August 6. It lay as low pressure area over north west Madhya Pradesh and adjoining east Rajasthan on August, 8 and weakened over southeast Rajasthan and neighbourhood on August 12.

These synoptic conditions caused heavy to very heavy rainfall over the Mahi Basin. As a result, more inflow of water in the major dams located on the Mahi River and its tributaries. Consequently, water was released from Mahi Bajaj Sagar Dam on the Mahi River, Jakham Dam on the Jakham River, Som-Kamala-Amba Dam on the Som River in

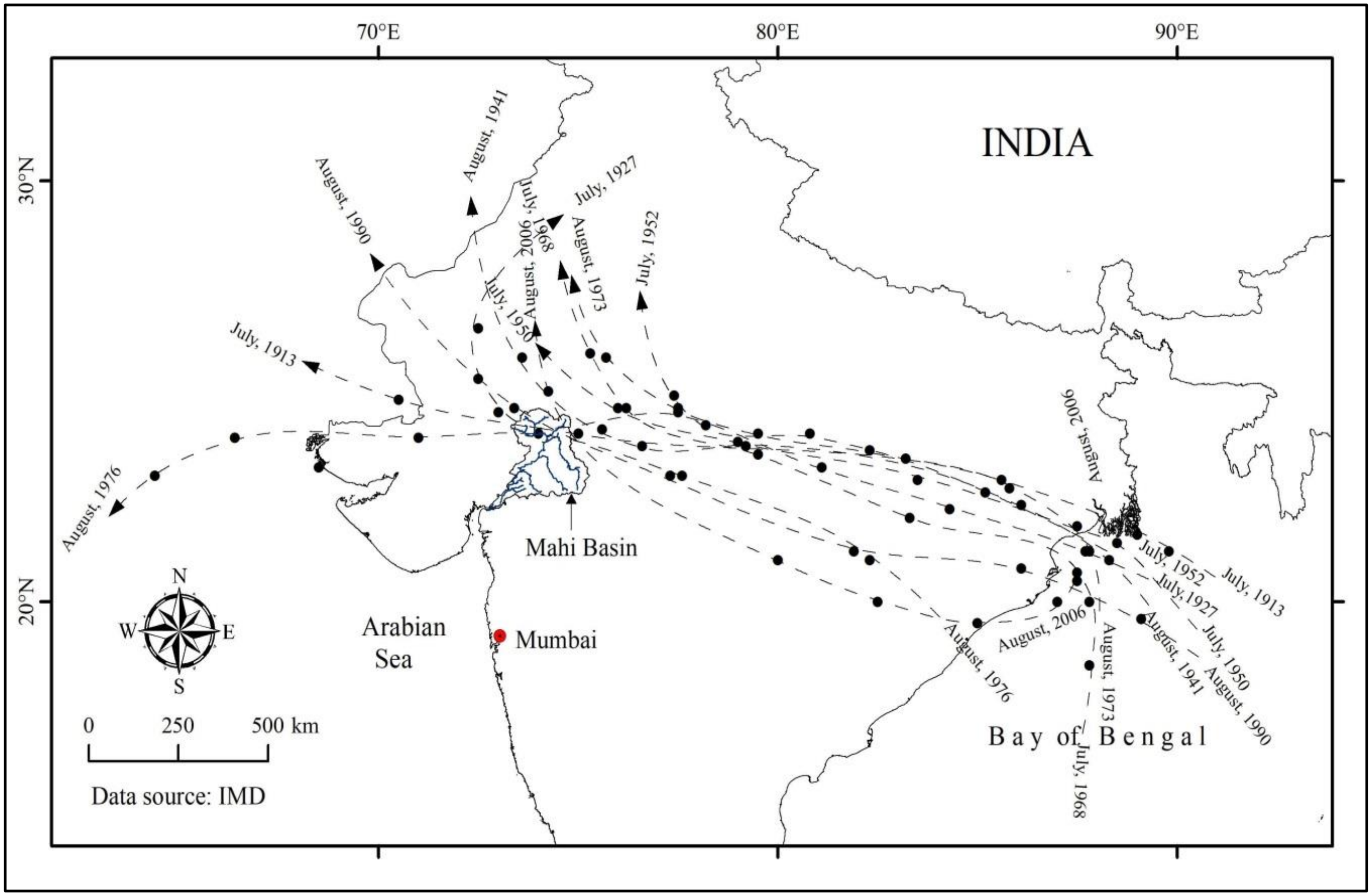


Figure 4.53: Tracks of major LPS(s) affecting the Mahi Basin

Table 4.26: Synoptic conditions associated with major floods in the Mahi Basin

Month, date and year of flood	Annual rainfall of the basin (mm)	Monsoon rainfall of the basin (mm)	Associated LPS	El Niño or La Niña year	Remark
July 27, 1913	1107.57 (+24.63%)	1072.43 (+24.27%)	Bay Depression	-	Passed through basin
June, 1920	650.97 (-26.77%)	565.57 (-34.46%)	-	La Niña	-
September, 1926	805.40 (-9.40%)	793.09 (-8.10%)	-	-	-
July 27, 1927	1180.81 (+32.85%)	1143.57 (+32.51%)	Bay Depression	-	Passed through basin
September, 1933	1329 (+49.49%)	1278.40 (+48.13%)	Bay Depression	Following severe El Niño	Passed through basin
July, 1935	695.97 (-27.71%)	690.37 (-20.00%)	-	-	-
June, 1937	1072.20 (20.61%)	1067.19 (23.66%)	-	-	-
July, 1941	1105 (+24.30%)	1078.33 (+24.95)	Bay Depression	El Niño	Passed through basin
July, 1943	800.66 (-9.94%)	793.17 (-8.09%)	Bay Depression	-	Passed through basin
August, 1944	1372.16 (+54.33%)	1347.11 (+56.10%)	Bay Depression	Following El Niño	Passed through basin
September 24, 1945	1154.71 (+29.92%)	1148.41 (+33.07%)	Bay Deep Depression	-	Passed through basin
August 5, 1946	1247.11 (+40.28%)	1184.27 (+37.23%)	Land Depression	-	Passed through basin
July, 1950	1188.90 (33.73%)	1188.90 (37.76%)	-	Weak La Niña	-
September 15, 1959	1363.81 (+53.43%)	1352.49 (+56.72%)	-	Following severe El Niño	-
August 1, 1968	643.18 (-27.65%)	635.20 (-26.40%)	Land Depression	Weak El Niño	Passed through basin
September 6, 1970	997.19 (+12.17%)	995.85 (+15.39%)	Land Depression	Moderate La Niña	Passed through basin
September 7, 1973	1298.90 (+46.12%)	1287.94 (+49.24%)	-	Strong La Niña	Passed through basin
August 30, 1976	1365.51 (+53.66%)	1247.81 (+44.59%)	Bay Depression	Weak El Niño	Passed through basin
August 30, 1978	1063.01 (+19.57%)	1025.24 (+18.80%)	Bay Depression	La Niña	Passed through basin
August 16, 1981	1107.77 (+24.61%)	1066.10 (+23.53%)	-	-	-
August 20, 1984	1128.58 (+26.95%)	1128.58 (+30.77%)	-	-	-
August 24, 1990	1227.93 (+38.13%)	1180.06 (+36.74)	Bay Depression /Deep Depression	-	Passed through basin
August 2, 1994	1399.30 (+57.37%)	1369.06 (+58.64%)	-	Weak El Niño	-
August, 2006	1582.09 (+77.95%)	1580.94 (+83.19%)	-	Weak El Niño	-

the upper reaches of the Mahi Basin. A huge runoff from upstream catchment resulted in an increase in the water level of Kadana Dam due to this water also released from Kadana Dam. The Wanakbori Weir located upstream of the Khanpur gauging site also overflown. A large flood was observed with a maximum discharge of 32557 m3/s magnitude at Wanakbori and on August 12, 2006.

(II) Rain spells and large flood

The Mahi River is notable for flash floods which occurred due to high precipitation in a span of 1 to 3 days spells of rainfall associated with rainstorms. Therefore, it is essential to understand the highest 1-day or 24-hr rainfall and floods in the Mahi Basin. Table 4.27 shows the result of highest 24-hr rainfall at selected sites in the Mahi Basin. It is important to note that point rainfall do not necessarily reflect basinwide precipitation.

Table 4.27: Highest 24-hr rainfall at selected stations in the Mahi Basin

Station	Highest 24-hr rainfall in mm	Date of occurrence	Annual rainfall in mm	% of annual rainfall
Sardarpur	266	August 22, 1919	1659	16
Sailana	360	August 11, 1941	1422	25
Banswara	559	July 23, 1959	1970	28
Kushalgarh	409	July 26, 1913	1768	23
Kherwara	221	July 05, 1930	1060	21
Sagwara	384	August 26, 1987	1162	33
Godhra	401	July 26, 1927	2281	18

Source: IMD

This highest daily rainfall ranges between 221 mm at Kherwara and 559 mm at Banswara. The second and third highest 24-hr rainfall of 406 mm at Kushalgarh and 401 mm at Godhra respectively was associated with rainstorm and major floods in the Mahi Basin. The highest one day rainfall at Sailana was 360 mm which had occurred because of LPS. This storm event produced flood in the upper reaches of the Mahi River.

The rainfall and flood series in the Mahi Basin are characterized by large year-to-year variability. Therefore, monsoon rainfall magnitude index (MRMI) also has been calculated in order to understand the monsoon rainfall magnitude and floods in the Mahi Basin (Table 4.28).

Table 4.28: Monsoon rainfall magnitude index (MRMI) of the Mahi Basin

SN	Site	Record length	MRMI
1	Sardarpur	105	0.18
2	Sailana	110	0.21
3	Banswara	111	0.22
4	Kushalgarh	111	0.20
5	Kherwara	111	0.20
6	Sagwara	103	0.22
7	Godhra	113	0.22
	Mahi Basin		**0.21**

Source: IMD; See Figure 3.3 for location sites

The MRMI value of the Mahi Basin is 0.21 which is greater than MRMI values of the other river basins of India. This shows remarkably high rainfall variability in the Mahi Basin. This variability also reflected in the floods of the Mahi Basin.

Figure 4.54a to Figure 4.54g illustrates the plots of return period of highest 24-hr rainfall of the seven sites namely Sardarpur, Sailana, Banswara, Kushalgarh, Kherwara, Sagwara and Godhra. However, the recurrence intervals of rainfall associated with some of the major flood events are given in the Table 4.29. The results demonstrate that although highest 24-hr rainfall values are associated with large floods on the Mahi River in the upper reaches (Sailana, 1941), Middle reaches (Banswara, 1959) and (Kushalgarh, 1913), but not necessarily the highest flood on record for instance the 1973 and 2006 floods.

Table 4.29: Return period of daily rainfall associated with major floods

Site	Flood Year	Month and date	24-hr Rainfall in mm	Return period (yr.)
Sardarpur	1959	June 30	235.7	35
	1973	September 06	173.5	10
	1976	July 31	118.1	03
	2006	August 06	128.0	03
Sailana	1973	August 31	176.5	07
	1976	August 29	137.2	03
	2006	September 07	160.0	04
Banswara	1959	July 23	558.8	113
	1973	September 07	185.3	04
	1976	August 29	132.0	02
	2006	July 22	379.0	38
Kushalgarh	1944	August 22	229.9	08
	1959	September 15	234.9	09
	1973	September 07	180.0	04
	1976	August 29	160.0	03
	2006	September 07	164.0	03
Kherwara	1944	July 27	080.8	02
	1959	September 14	087.6	02
	1973	September 01	153.0	10
	1976	September 13	095.0	02
	2006	August 16	182.0	18
Sagwara	1959	August 27	135.9	03
	1973	September 08	161.0	06
	1976	November 23	168.0	07
	2006	September 07	191.0	09
Godhra	1927	July 26	400.8	109
	1973	August 31	176.0	04
	1976	August 29	205.0	07
	2006	July 29	127.0	02

Source: IMD

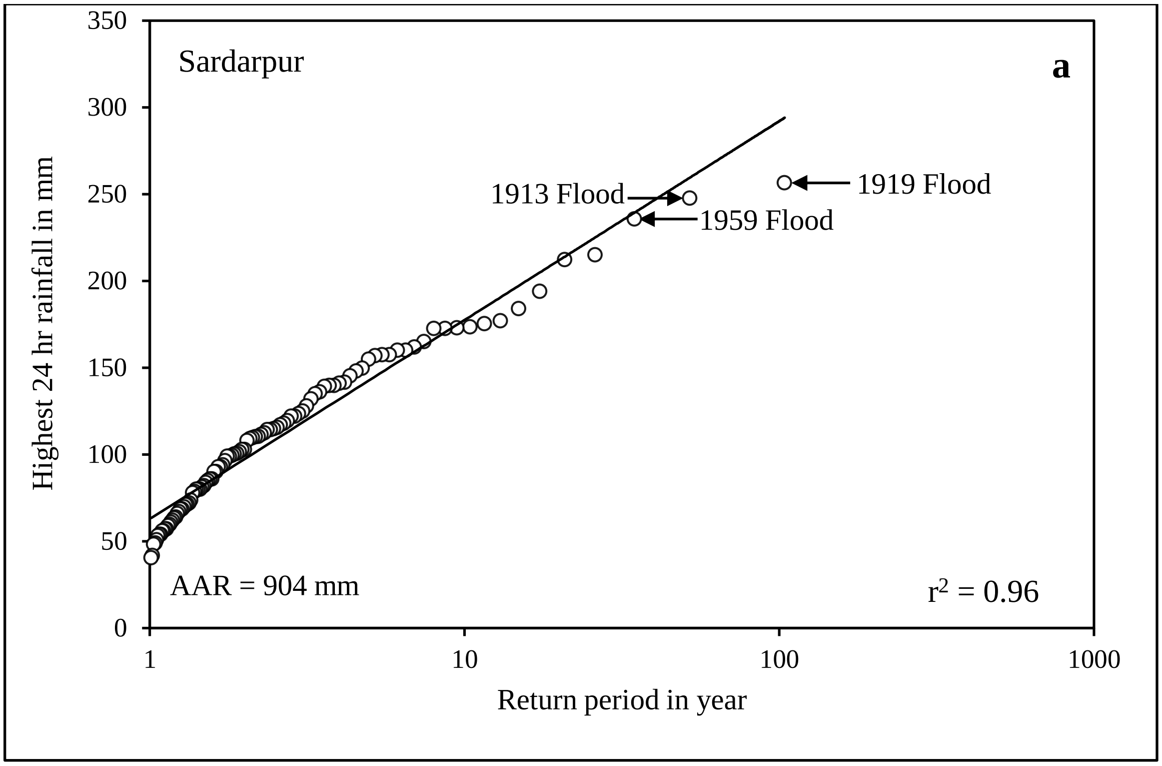


Figure 4.54a: Return period of highest 24-hr rainfall of Sardarpur station in the Mahi Basin; See locations of stations in Figure 3.3

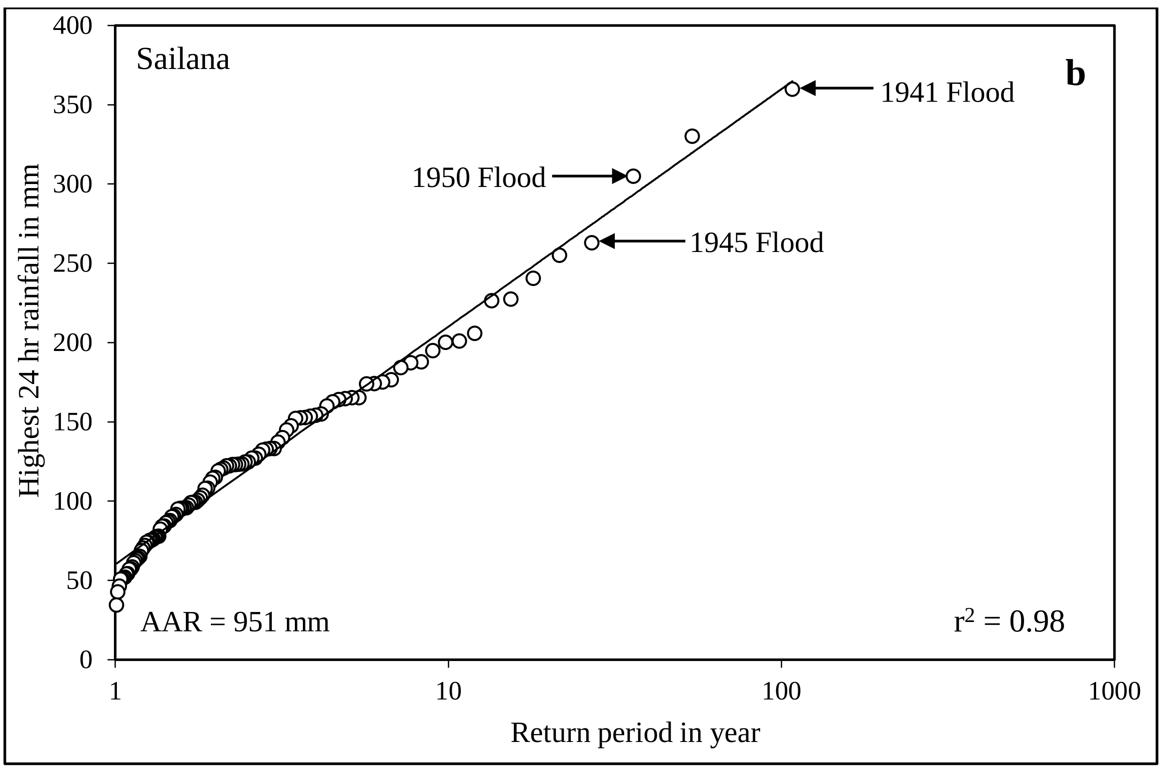


Figure 4.54b: Return period of highest 24-hr rainfall of Sailana station in the Mahi Basin; See locations of stations in Figure 3.3

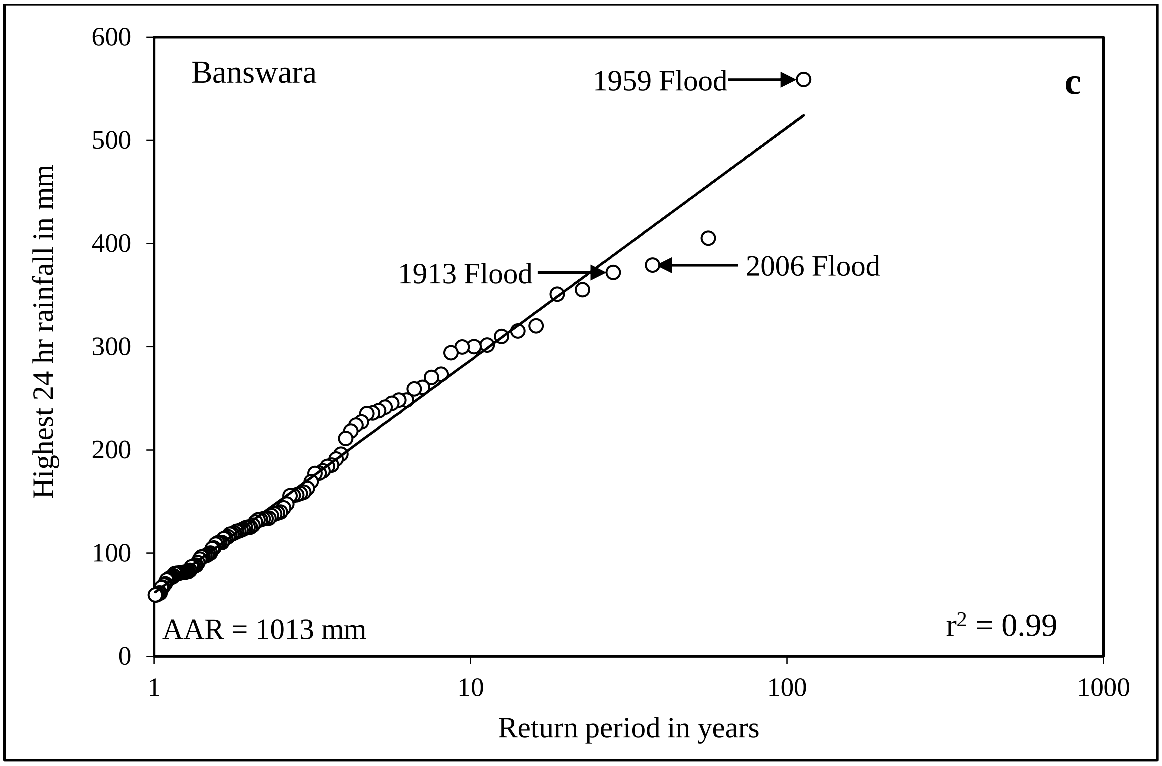


Figure 4.54c: Return period of highest 24-hr rainfall of Banswara station in the Mahi Basin; See locations of stations in Figure 3.3

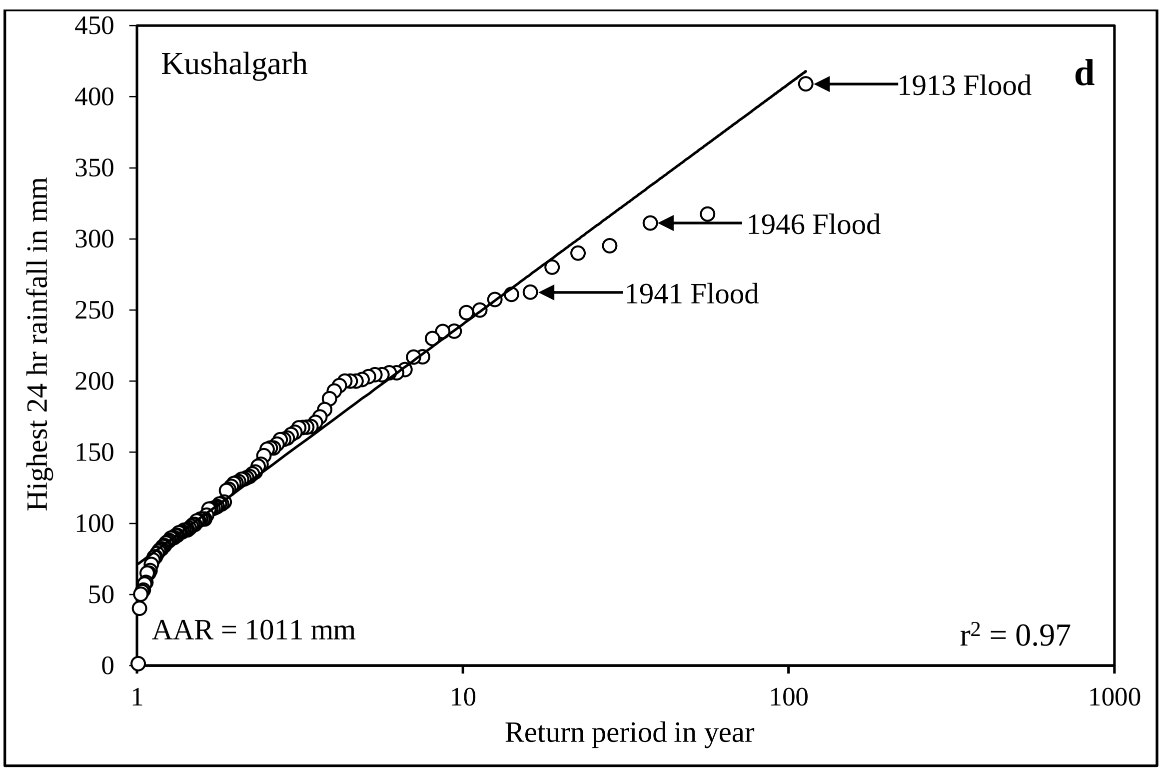


Figure 4.54d: Return period of highest 24-hr rainfall of Kushalgarh station in the Mahi Basin; See locations of stations in Figure 3.3

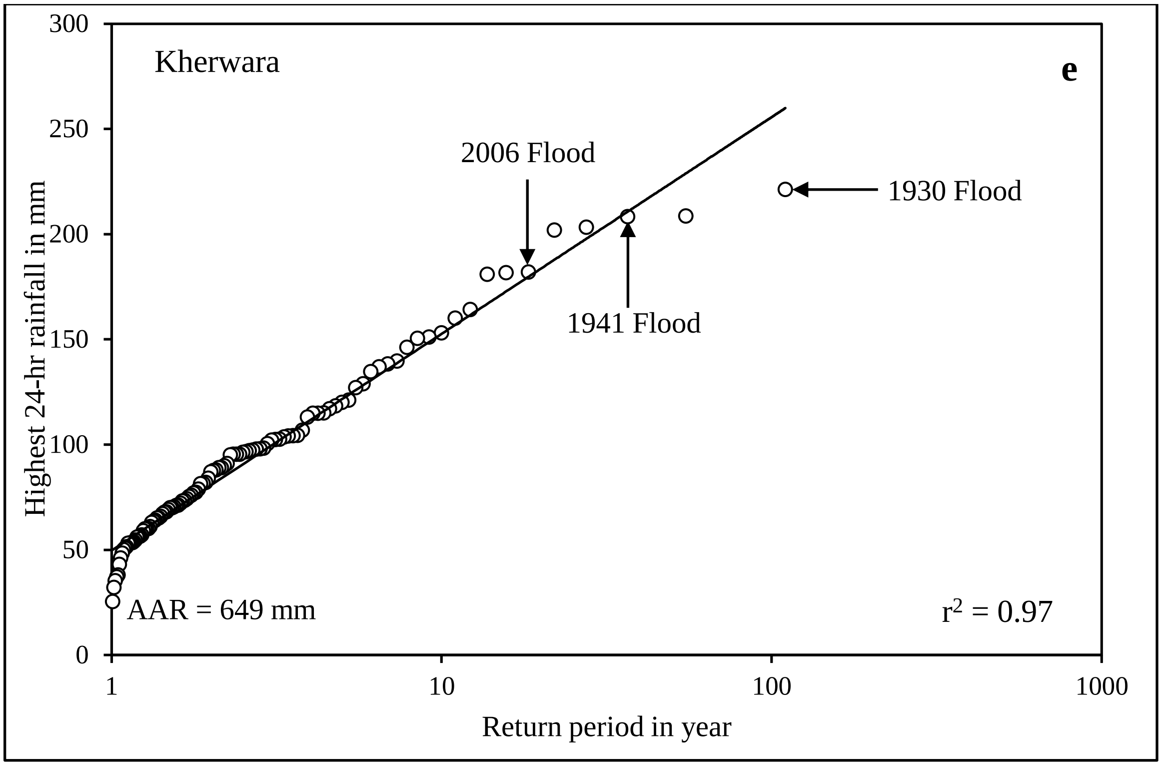


Figure 4.54e: Return period of highest 24-hr rainfall of Kherwara station in the Mahi Basin; See locations of stations in Figure 3.3

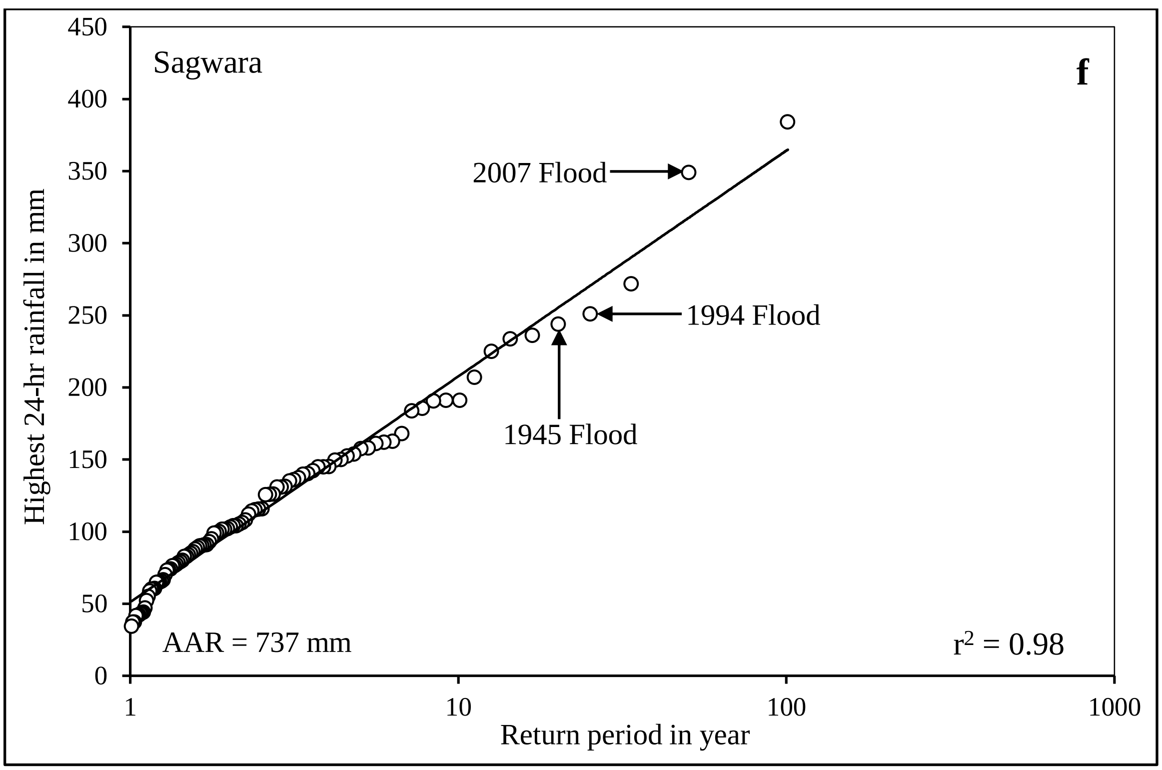


Figure 4.54f: Return period of highest 24-hr rainfall of Sagwara station in the Mahi Basin; See locations of stations in Figure 3.3

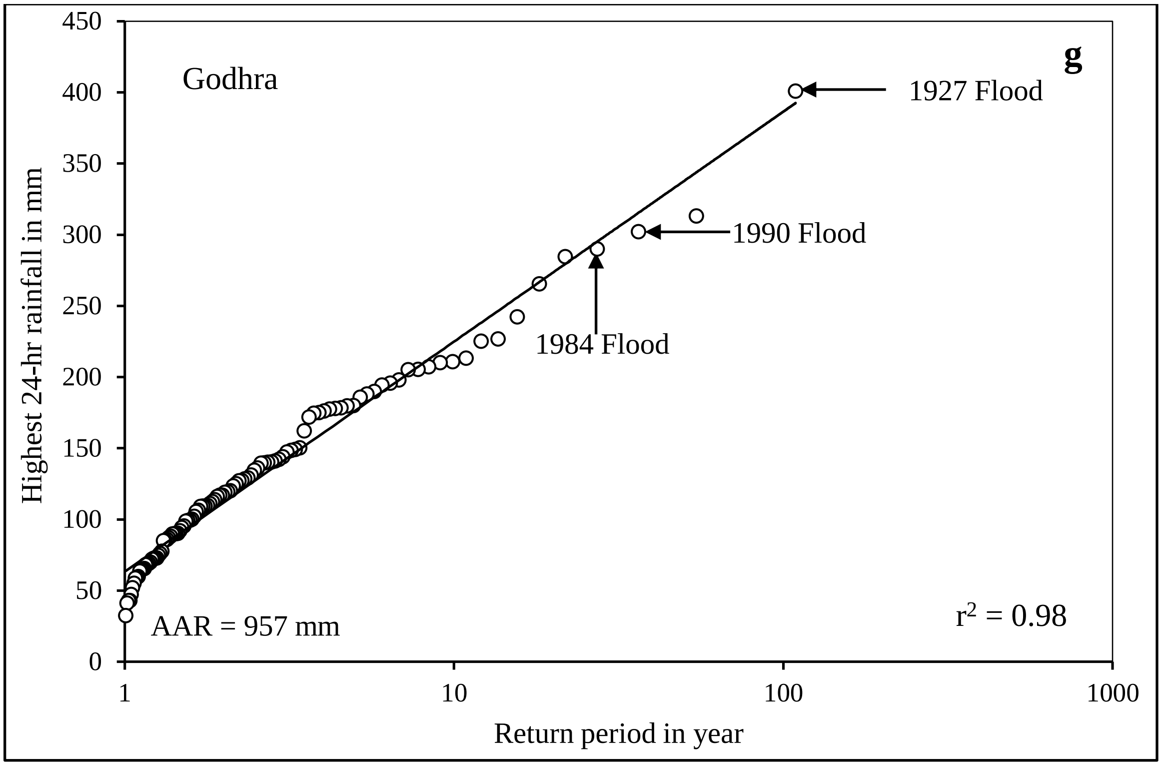


Figure 4.54g: Return period of highest 24-hr rainfall of Godhra station in the Mahi Basin; See locations of stations in Figure 3.3

In addition to this, highest one day rainfall for Sardarpur (266 mm), Kherwara (221 mm) and Sagwara (384 mm) sites did not produce large or largest flood in the Mahi Basin. Therefore, it is evident from the above discussion that though the magnitude of 24-hr rainfall is more at particular station. Furthermore, it is essential to understand the duration and areal coverage of high intensity rainfall.

(III) LPS produced flood events and Depth-Area-Duration (DAD) analysis

The DAD curves were developed only for large flood generating LPS which occurred over the basin during the period of 1901 to 2011. Therefore, storm isohyetal maps of 1927, 1973 floods (Figure 4.55a and Figure 4.56a respectively) and 2006 flood events have been considered and DAD curves up to 3-day duration of rainstorm have been obtained (Figure 4.55b, Figure 4.56b and Figure 4.57).

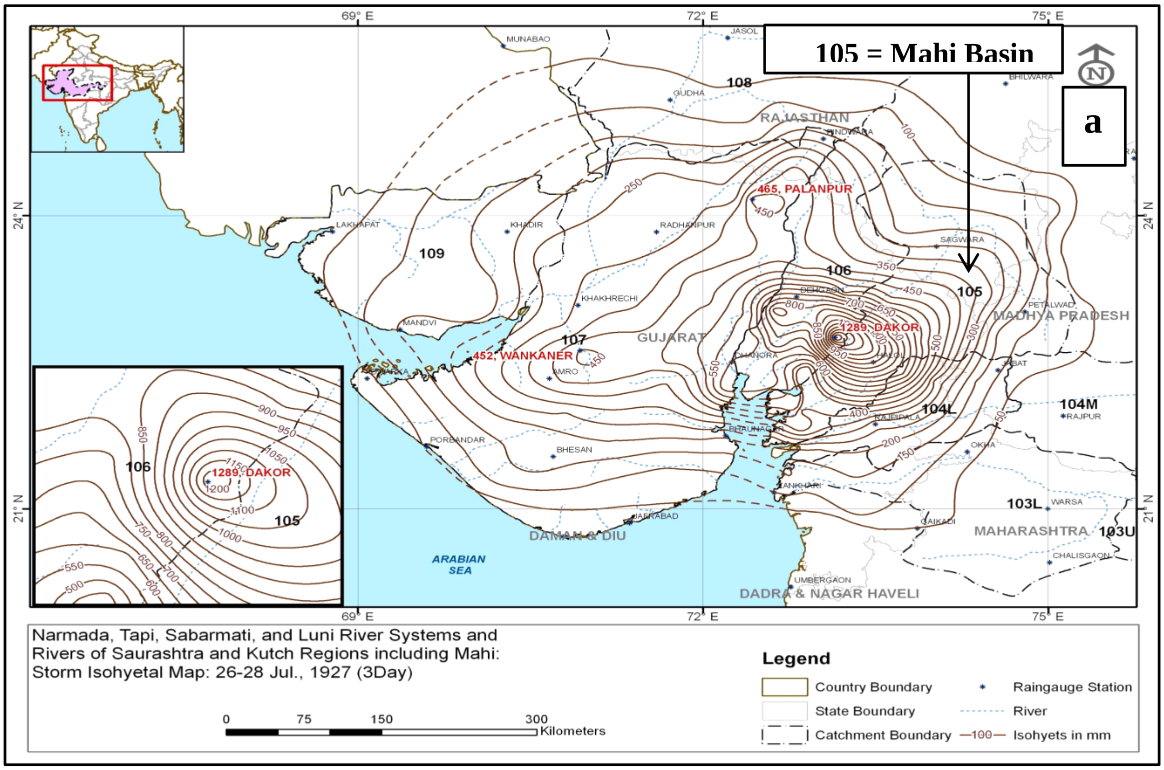


Figure 4.55a: Storm isohyetal map: 26-28 July 1927 (3-day)
Source: PMP Atlas for Narmada, Tapi, Mahi and other adjoining river basins, Volume - I; IMD

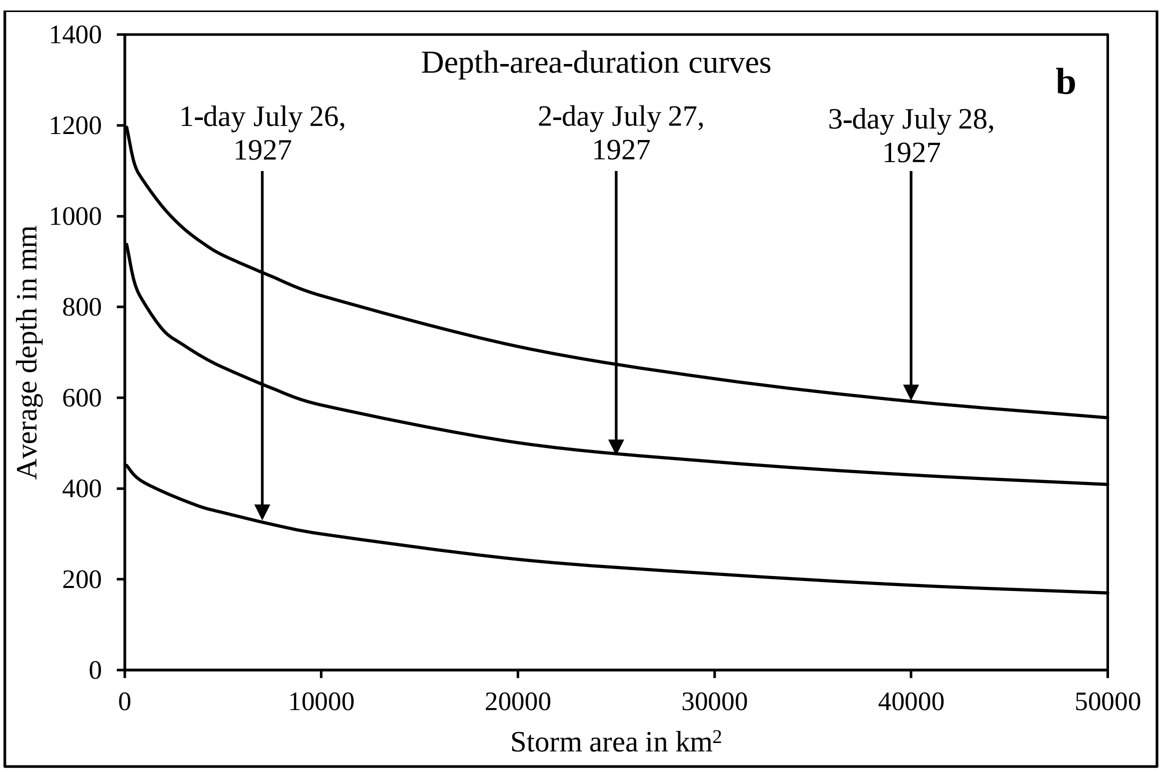


Figure 4.55b: Depth-Area-Duration Curve of rainstorm 1927 affecting the Mahi Basin

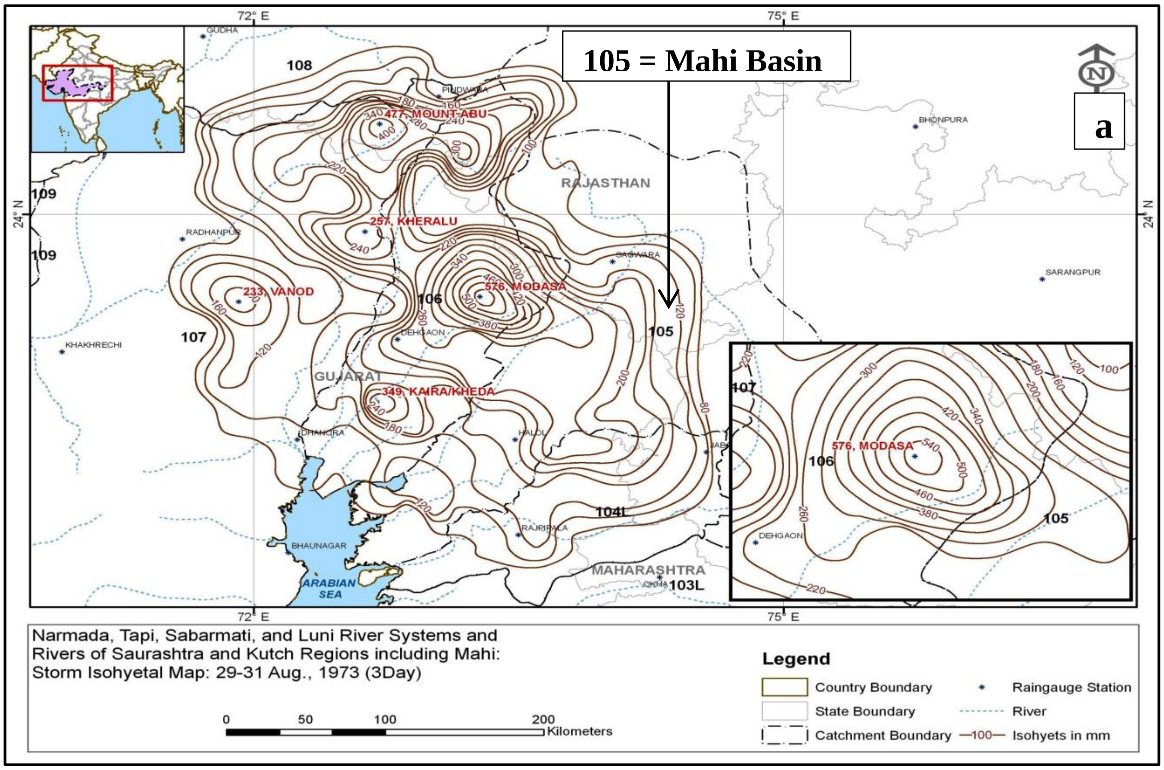


Figure 4.56a: Storm isohyetal map: 29-31 August 1973 (3-day)
Source: PMP Atlas for Narmada, Tapi, Mahi and other adjoining river basins, Volume - I; IMD

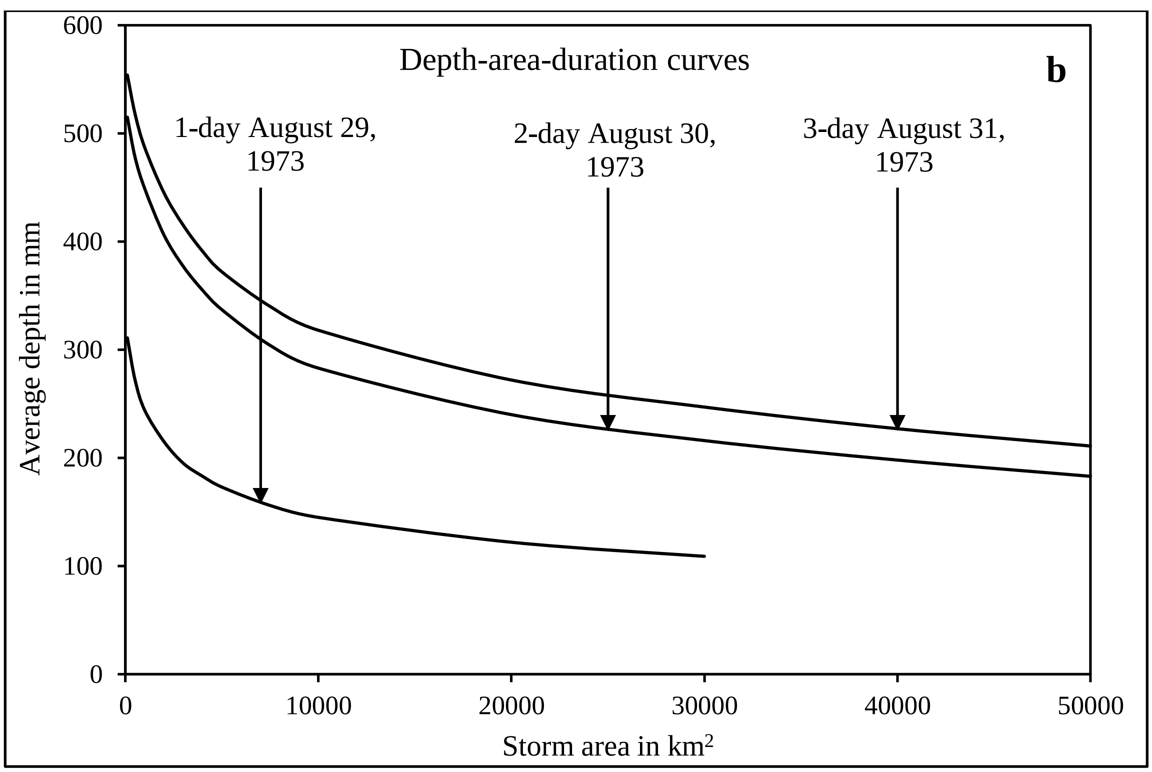


Figure 4.56b: Depth-Area-Duration Curve of rainstorm 1973 affecting the Mahi Basin

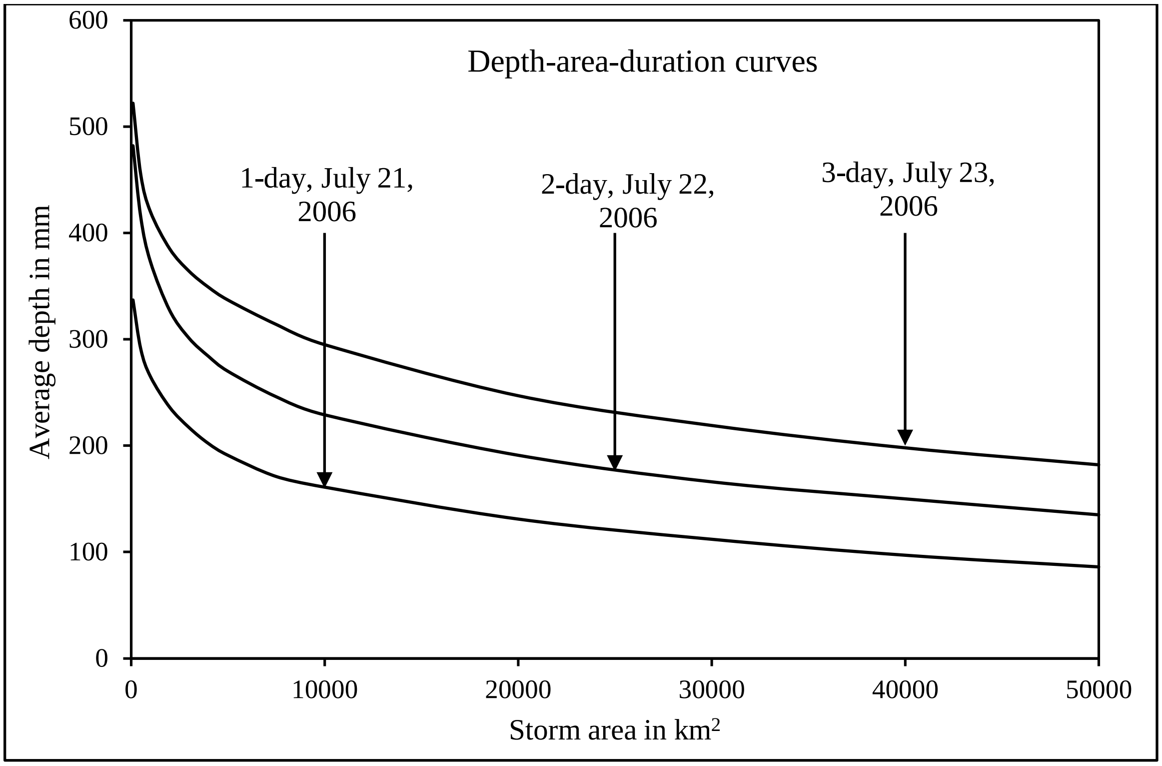


Figure 4.57: Depth-Area-Duration Curve of rainstorm 2006 affecting the Mahi Basin

The Figure 4.55a and Figure 4.55b indicates that the depth-duration curve of 26-28 July 1927 storm has contributed the highest average depth of 650 mm rainfall for 3 days in the lower Mahi Basin in Gujarat because rainstorm center was at Dakor which is adjacent to the Mahi Basin. Although storm of the 1973 has produced highest flood in the Mahi Basin on record, but did not produce highest average rainfall depth in the basin (Figure 4.56a and Figure 4.56b). However, no storm event produced higher maximum average rainfall depth over the Mahi Basin after 1927 during period of 1901 to 2017. Besides, the Rainstorm of July 21-23, 2006 has also been responsible for generating flood in the entire Mahi Basin. However, rainfall depth over the Mahi Basin for 3 day duration was less as compared to the 1927 and 1973 flood (Figure 4.57).

4.3.3 Relationship between annual rainfall totals and flood occurrences

Figure 4.58 indicates discharge (Wanakbori Site) and rainfall (Mahi Basin) departure from their respective averages. The graph clearly reveals that out of eight large floods (from 1959 to 2009) seven floods have occurred during the years of above-average annual rainfall of the Mahi Basin. The largest floods of 1973 and 2006 were associated with positive departure from mean rainfall of the Mahi basin. However, the 1968 flood had occurred during below-average rainfall year and is caused by LPS. The 1959, 1976, 1990 and 1994 floods also associated with the low pressure system which results in significant increase in the average annual rainfall of the Mahi Basin.

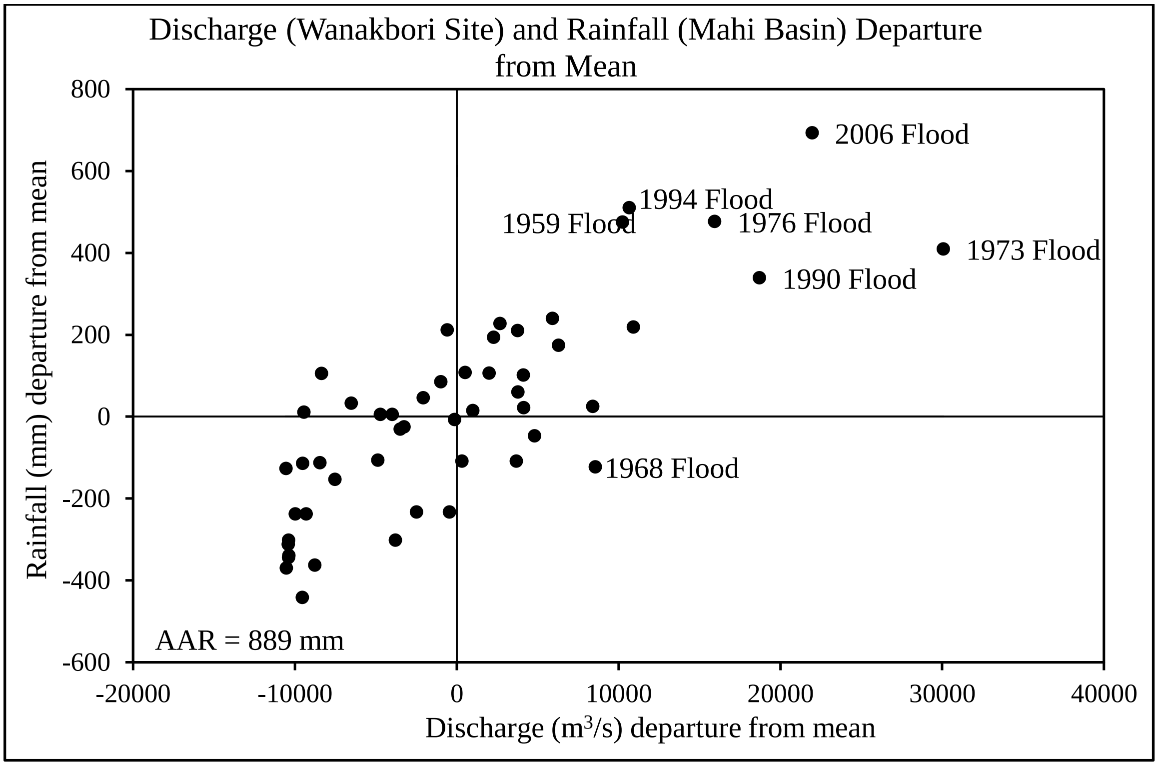


Figure 4.58: Discharge (Wanakbori) and Rainfall (Average annual rainfall of the basin departure from mean)

4.3.4 Long-period fluctuations in monsoon rainfall and floods

(I) Normalized accumulated departure from mean (NADM) and floods in the Mahi Basin

The NADM graph of Mahi Basin shows a period of below-average rainfall from 1900s to1930s and above-average rainfall between 1930s and 1990s followed by a period of fluctuation conditions. A comparison of the NADM graph with the plot of large floods in Mahi Basin illustrates that the period of below-average annual rainfall was associated with low frequency of floods and above-average annual rainfall (1930s to 1990s) was associated with high frequency and large magnitude of floods in the Mahi Basin (Figure 4.59)

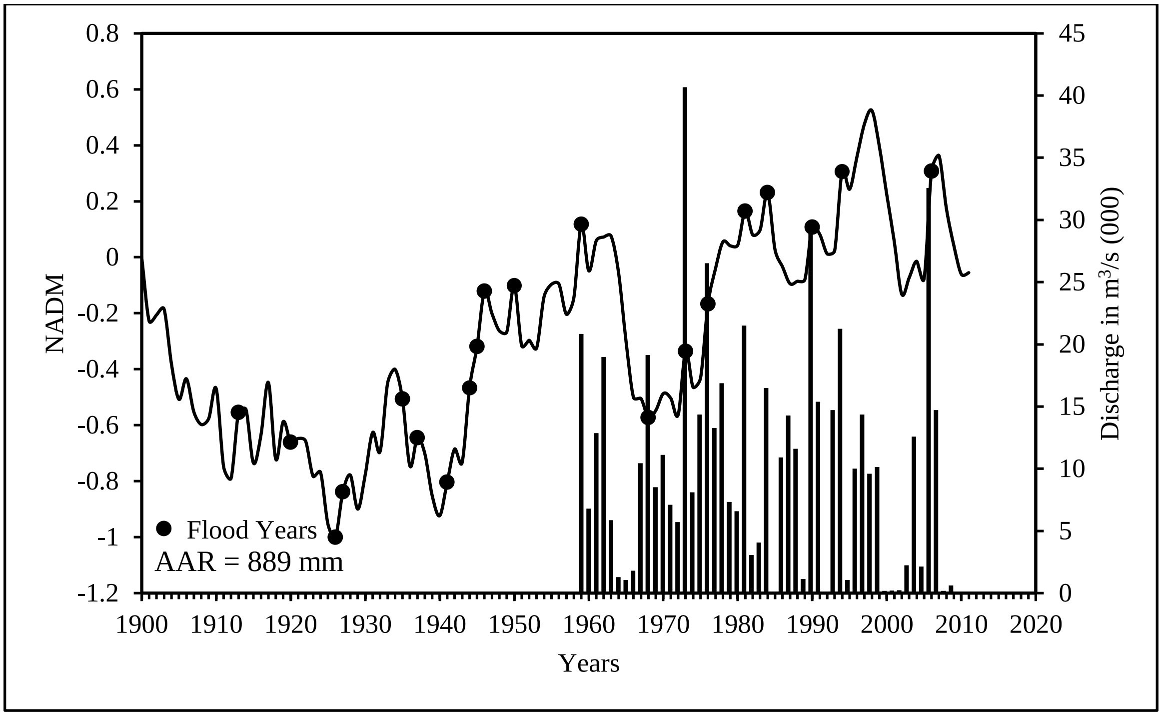


Figure 4.59: Normalized Accumulated Departure from Mean (NADM) and Discharge (Wanakbori)

(II) El Niño and Southern Oscillation (ENSO) and floods in the Mahi Basin

The Indian monsoon circulation has teleconnections with global phenomena such as El Niño and Southern Oscillation (ENSO). Therefore, analysis of El Niño-Southern Oscillation (ENSO) is of great significance from the flood hydro-meteorological point of view. Berlage (1966) and Ropelewski and Halpert (1987) had also shown significant connection between ENSO and precipitation around the world. Therefore, it is necessary to understand connection between ENSO and rainfall while studying floods in the Mahi Basin. Figure 4.60 indicates association of the floods in the Mahi Basin with ENSO and annual rainfall of the Mahi Basin.

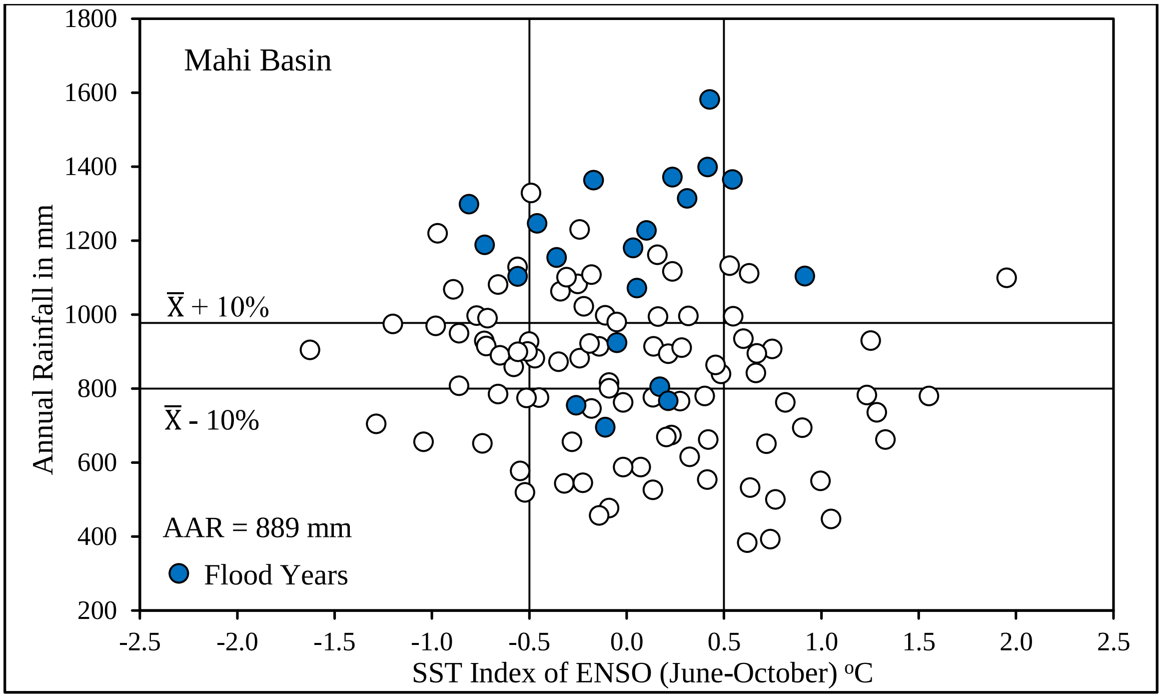


Figure 4.60: Categories of annual rainfall and ENSO index of the Mahi Basin; AAR = Average annual rainfall; **Source:** IMD

Table 4.30: Conditional probability of the monsoon rainfall over Mahi Basin, given the SST index of ENSO (n = 111 years)

Basin	AAR	SST		
		Cold	Normal	Warm
Mahi Basin	High	0.32	0.39	0.25
	Normal	0.43	0.24	0.21
	Low	0.25	0.37	0.54

Low < 10% and High > 10%

Table 4.31: Occurrence of floods and its relation with the annual rainfall and SST index of ENSO

Basin	Rainfall	Cold	Average	Warm
Mahi Basin	Above Normal	1950, 1973, 1984	1913, 1926, 1927, 1937, 1944, 1945, 1946, 1959,1990, 1994,2006	1941, 1976,
	Normal	-	1952	-
	Below Normal	-	1920, 1926, 1935,	1968

Below-normal < 10% and above-normal >10%

Table 4.30 indicates that the probability of having high monsoon rainfall in the Mahi Basin is more during cold and normal conditions (32% to 39%) and very low during warm ENSO conditions (54%). Table 4.31 shows that the frequency of occurrence of floods is generally high during the normal or above-normal rainfall years.

(III) Detection of changes in the annual rainfall

The Mann-Kendall's test is mainly proposed to understand the rainfall change/trend over the Mahi Basin. Accordingly, Mann-Kendall's (Tau) τ and z scores are obtained for the Mahi Basin and have been summarized in Table 4.32. The positive (negative) sign of τ indicates increasing (decreasing) trend. Therefore, the positive value of τ i.e. 0.0143 (Table 4.32) for the Mahi Basin suggests, the rainfall trend for the given period is increasing. Nevertheless, the trend is statistically significant or not is projected by testing the significance of τ and result has been summarized in the Table 4.32. However, the important question to basin wise rainfall studies in India is whether the future is likely to see the condition of rainfall decreased, unchanged or exacerbated.

Table: 4.32: Nature of changes/trends in annual rainfall records based on Mann-Kendall test

Basin	Period	N	Tau (τ)	Z score	Trend/change
Mahi Basin	1901-2011	111	0.0143	0.0225	No specific change

N = number of observations

(IV) Detection of future changes in the rainfall

The result of an application of the Students t test to the statistical parameters of rainfall data of the Mahi Basin have shown in Table 4.33. It is observed that 18% change in the average annual rainfall is required for next 10 years to deem it different than the available rainfall record in the Mahi Basin. Likewise, to establish the significant change in the rainfall of the next 20 and 50 years, the average annual rainfall should differ by 13% and 8% respectively than the present mean of the rainfall. While, to declare the average annual rainfall of the present century (21st century) considerably different than the previous century (20th century), 6% change is required in the long-term mean of the rainfall of the basin.

Table: 4.33: Percent change required to identify statistically significant change in average annual rainfall (AAR) of the Mahi Basin

Basin	N	AAR (mm)	σ	Percent change required in the AAR at 95% of confidence level, Years.			
				10	20	50	100
Mahi Basin	111	889	247	18	13	8	6

Source: IMD; N = Number of observation

4.4 Palaeoflood Hydrology

Among different palaeostage indicators the slackwater deposits (SWD) provide accurate evidence about the palaeoflood stages. Mouths of small tributaries and bends in bedrock channels are the most suitable sites for SWD. A continuous stratigraphic record is produced by frequently occurring high magnitude flood events in succession. According to Baker (1987) and Baker and Kochel (1988), on the basis of sudden variations in texture, colour and composition individual flood units are identified.

4.4.1 Estimation of palaeoflood magnitude

The upper catchment stream area of the Kothada and Mahudi ka Mal sites has no well-documented records of historical floods or gauge data. However, available records (HFL) on the Mahi river railway bridge at Bhairaogad (downstream of Kothada) and Mataji gauging site located downstream of the Mahudi ka Mal at 13 km indicate that the two most extraordinary floods on the upper Mahi Basin were recorded in August 1973 and August 2006. In the absence of flood records at Kothada, Mahudi ka Mal and Bhungda, discharges were calculated with respect to the palaeostage indicators (PSI) i.e. scour line, shrub line and slackwater deposits (see Figure 3.2 for location of sites). The palaeoflood discharge of the Kothada site was calculated based on the scour line at left bank of the Mahi River (Figure 46.1a).

Therefore, Kothada site is included in the palaeoflood hydrology section and also in the modern flood records. The palaeoflood levels at Mahudi Ka Mal and Bhungda sites are also determined relating to PSI (Figure 4.62a and Figure 4.63a). The estimated past discharges for the Kothada , Mahudi ka Mal and Bhungda sites are 7251m^3/s, 14,101

m^3/s and 10591m^3/s magnitudes respectively (Figure 4.61b; Figure 4.62b; Figure 4.63b). Nevertheless, the estimated discharge of the 2006 flood at the Bhungda was of 25049 m^3/s magnitude and much greater than palaeofloods. Table 4.34 indicates flood power of the extreme event in the past on the Mahi River.

Table 4.34: Boulder dimensions in the channel of the Mahi River and its tributaries and the associated theoretical entrainment values

River	Site	I axis cm	$\bar{v}$ m/s	τ N/m^2	ω W/m^2	W's T Shear stress τ	W's T Stream power ω	W's T Velocity $\bar{v}$
Mahi	Kothada	120	7.97	326	2985	2.25	204	643
Mahi	Mahudi ka Mal	120	5.99	153	1061	2.25	204	643
Mahi	Bhungda	226	3.90	97	452	3.09	384	1437

I-axis = Intermediate axis; $\bar{v}$ = Mean velocity in m/s; τ = Boundary shear stress in N/m^2;
ω = Unit stream power in W/m^2; W's T = William's Threshold value of entrainment;
See figure 3.2 for location of sites

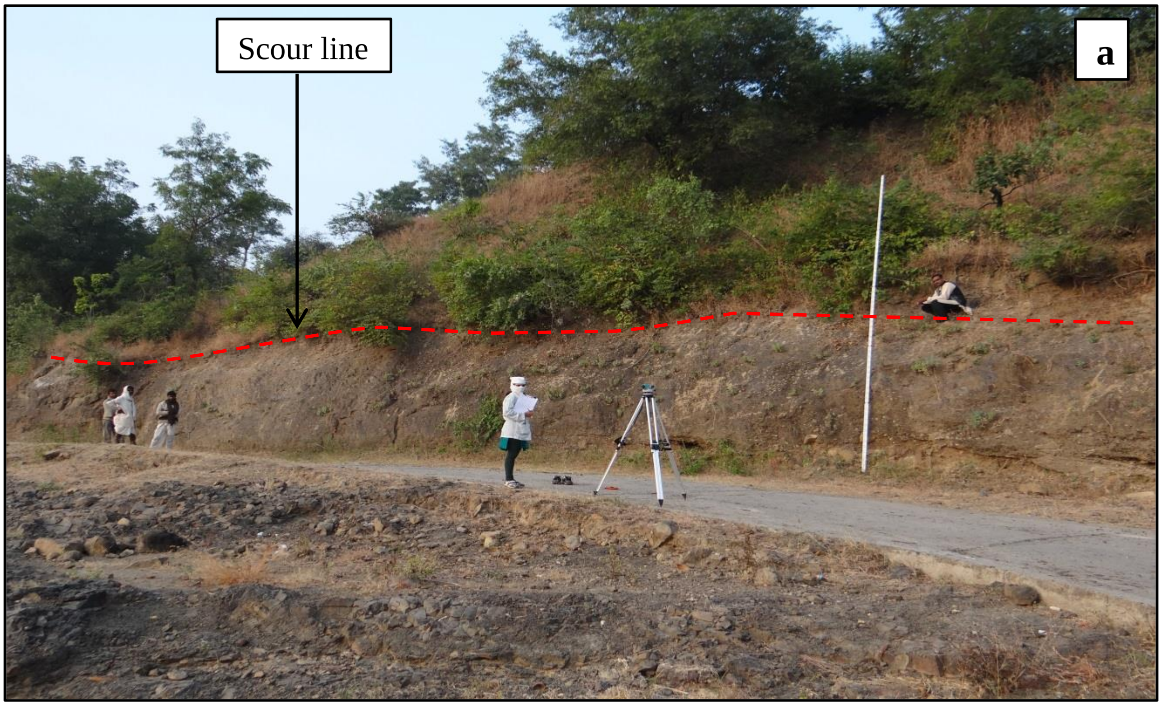


Figure 4.61a: Location of the palaeostage indicator site on the Mahi River near Kothada (Dhar, Madhya Pradesh)

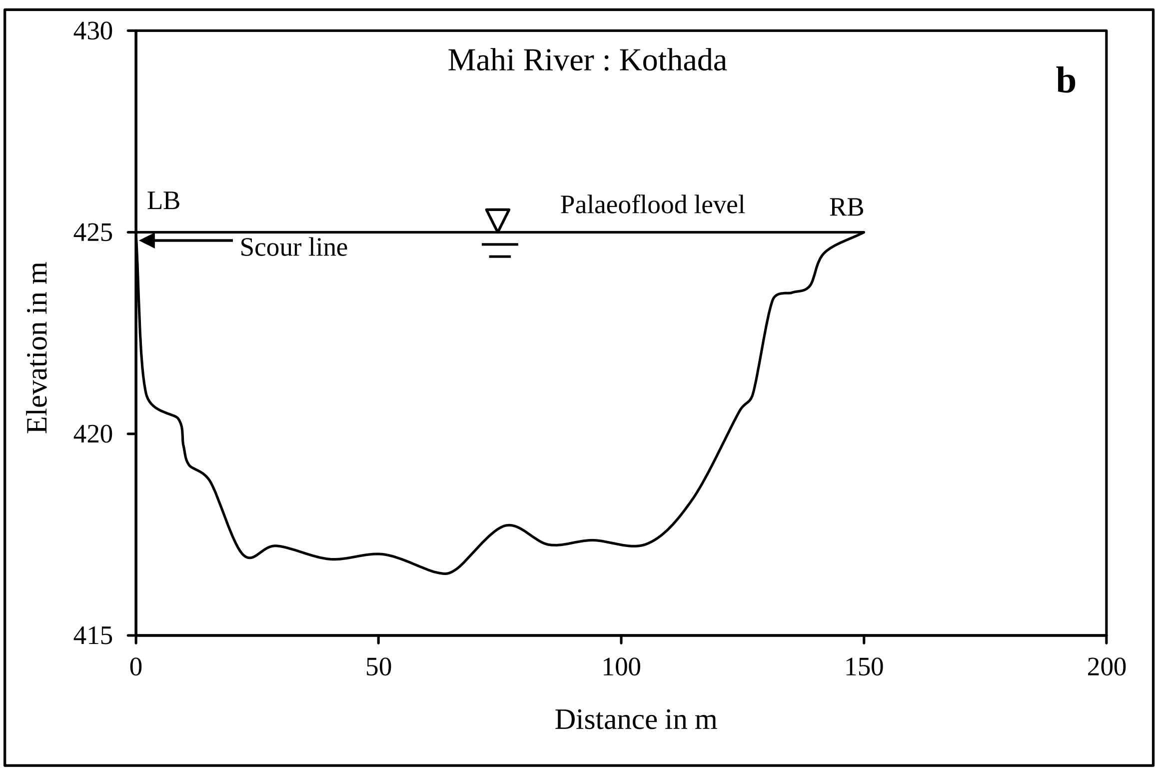


Figure 4.61b: Cross section of palaeoflood site near Kothada on the Mahi River; LB = Left bank; RB = Right bank

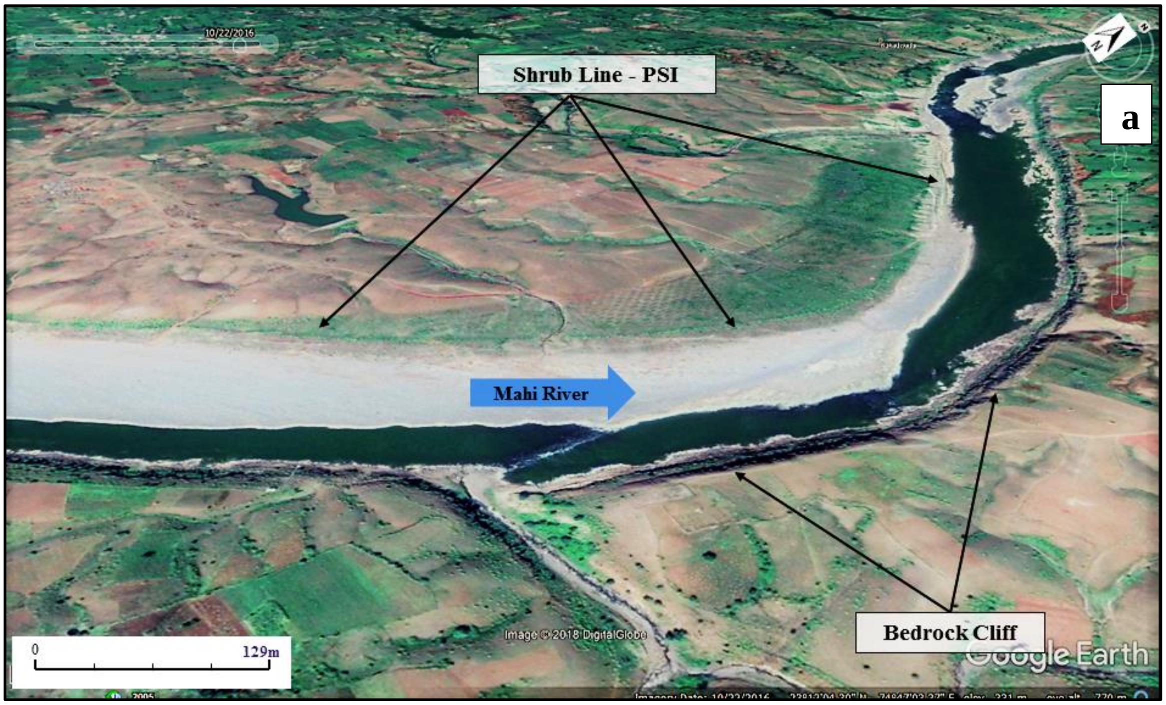


Figure 4.62a: Location of the palaeostage indicator site on the Mahi River near Mahudi ka Mal (Ratlam, Madhya Pradesh)

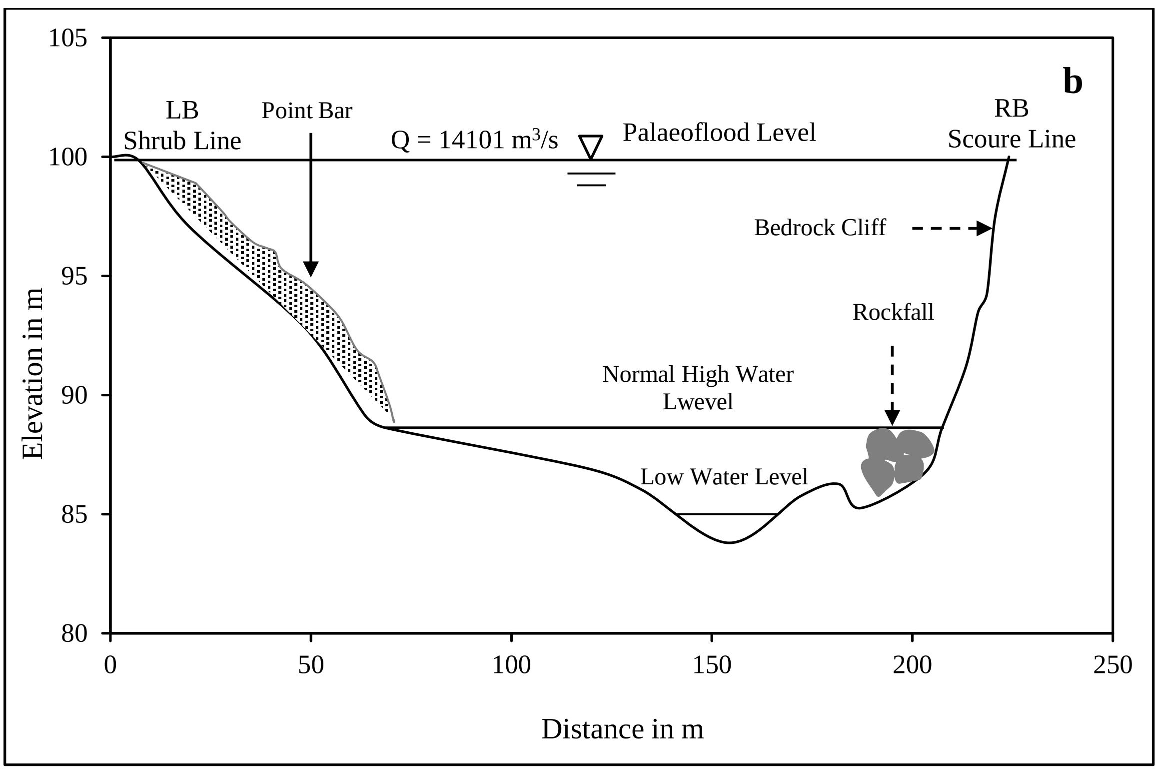


Figure 4.62b: Cross section of palaeoflood site Mahudi ka Mal on the Mahi River; LB = Left bank; RB = Right bank; HFL = High flood level

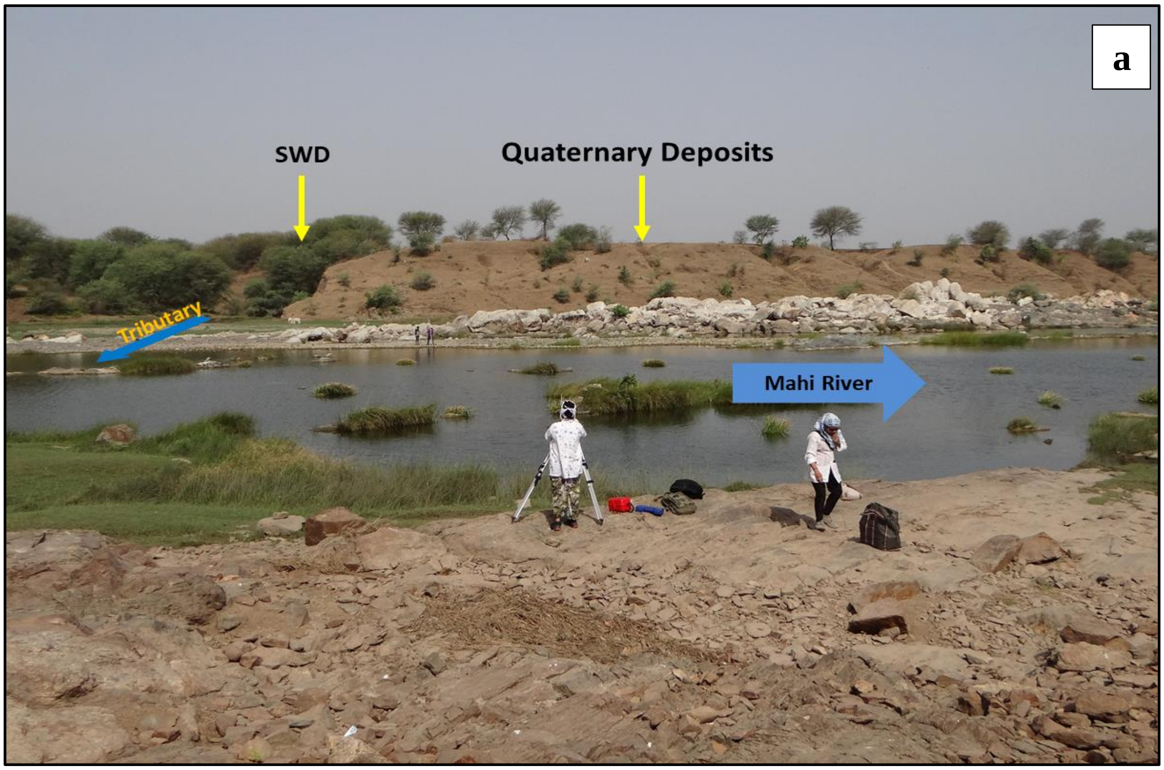


Figure 4.63a: Cross section survey at palaeoflood site on the Mahi River at Bhungda (Banswara, Rajasthan); SWD = Slack water deposits

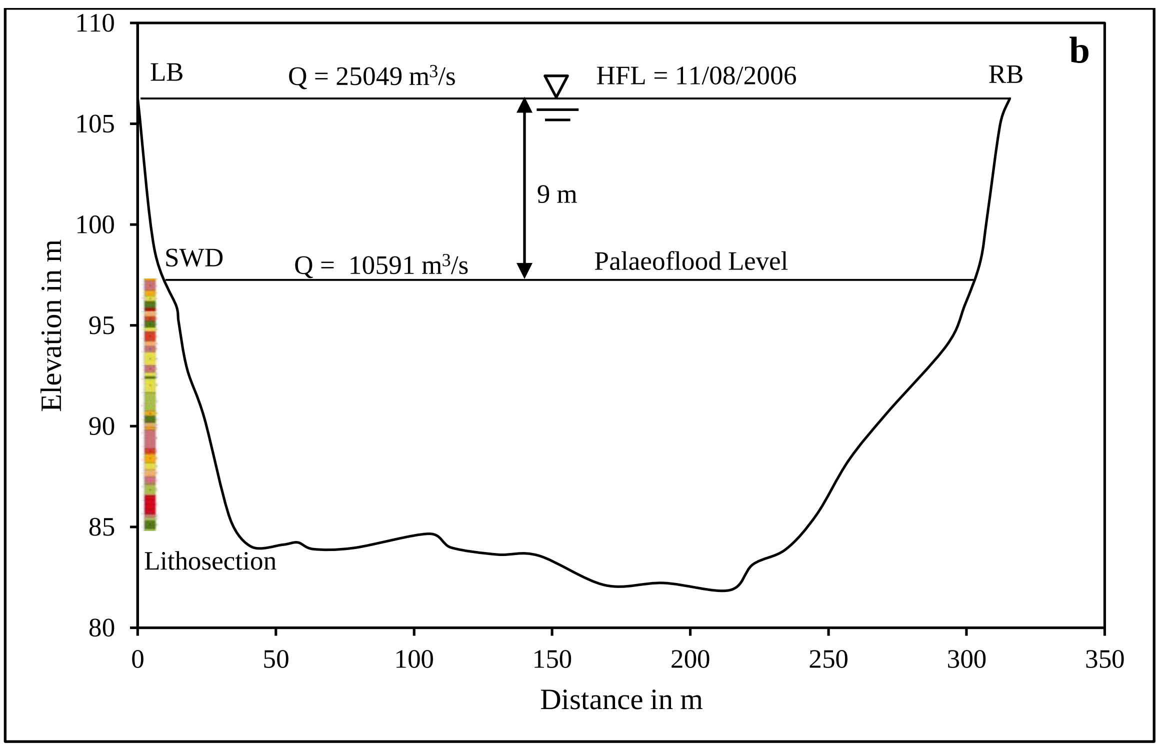


Figure 4.63b: Cross section of palaeoflood site Bhungda on the Mahi River; the lithosection is not exactly on the profile but 15 meters upstream; LB = Left bank; RB = Right bank; HFL = High flood level;

4.4.2 Sedimentological analysis

The results of textural characteristics of the sediments have been obtained by analyzing 17 soil samples selected from 37 flood units of the SWD from the lithosection on the left bank tributary of the Mahi River and summarized in the Table 4.35 (Figure 4.64). The result of sedimentology analysis shows that there are significant variations in particle size of each unit. Besides, stratigraphic studies of the slackwater deposit at Bhungda also indicate that the site of the flood deposit contain about 37 stratigraphic flood units of 9.97 m thick section (Figure 4.65).

Table 4.35: Textural properties of slackwater flood deposits

Sample No.	Mean φ	Median φ	Sorting Index	Skewness	Kurtosis
S1	1.73	2.00	0.58	-0.59	0.41
S2	1.70	2.00	0.68	-0.61	0.54
S3	1.92	2.10	0.50	-0.54	0.68
S4	1.33	1.30	0.69	0.02	0.38
S5	1.59	1.63	0.52	-0.10	0.39
S6	1.47	1.50	0.64	-0.09	0.36
S7	1.70	1.90	0.59	-0.44	0.36
S8A	1.92	2.10	0.51	-0.52	0.58
S8	1.72	1.95	0.59	-0.50	0.37
S9	1.97	2.10	0.47	-0.47	0.78
S10A	1.80	2.05	0.58	-0.58	0.45
S10	1.65	1.80	0.59	-0.33	0.34
S11	1.51	1.55	0.63	-0.12	0.38
S12	1.67	1.85	0.61	-0.39	0.39
S13	1.82	2.05	0.53	-0.58	0.50
S14	1.81	2.03	0.57	-0.55	0.51
S14A	0.83	0.75	0.55	0.25	0.83

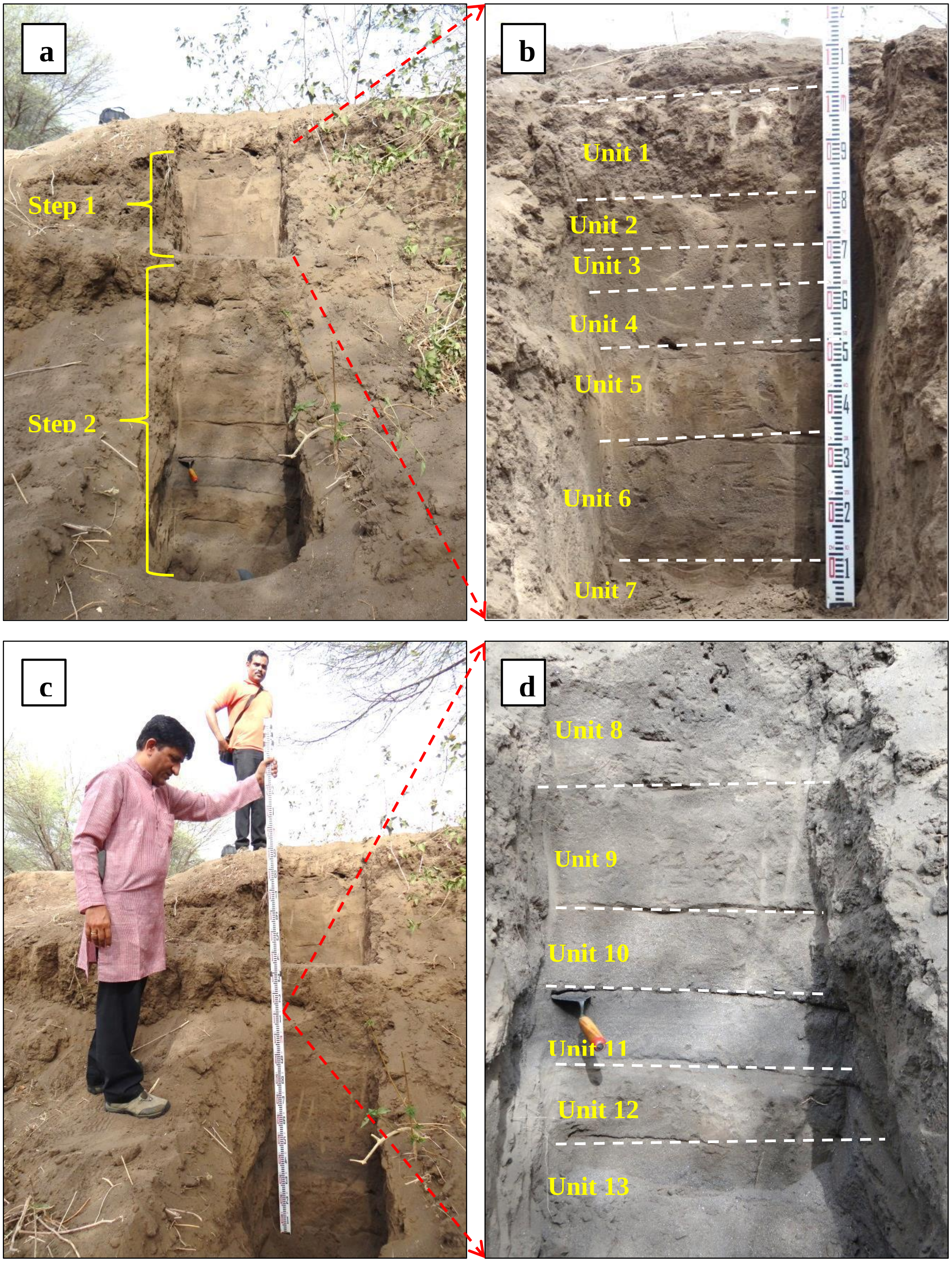


Figure 4.64: Various units of the elevated slack water deposit in the step 1 and step 2 at Bhungda palaeoflood site; (Banswara, Rajasthan)

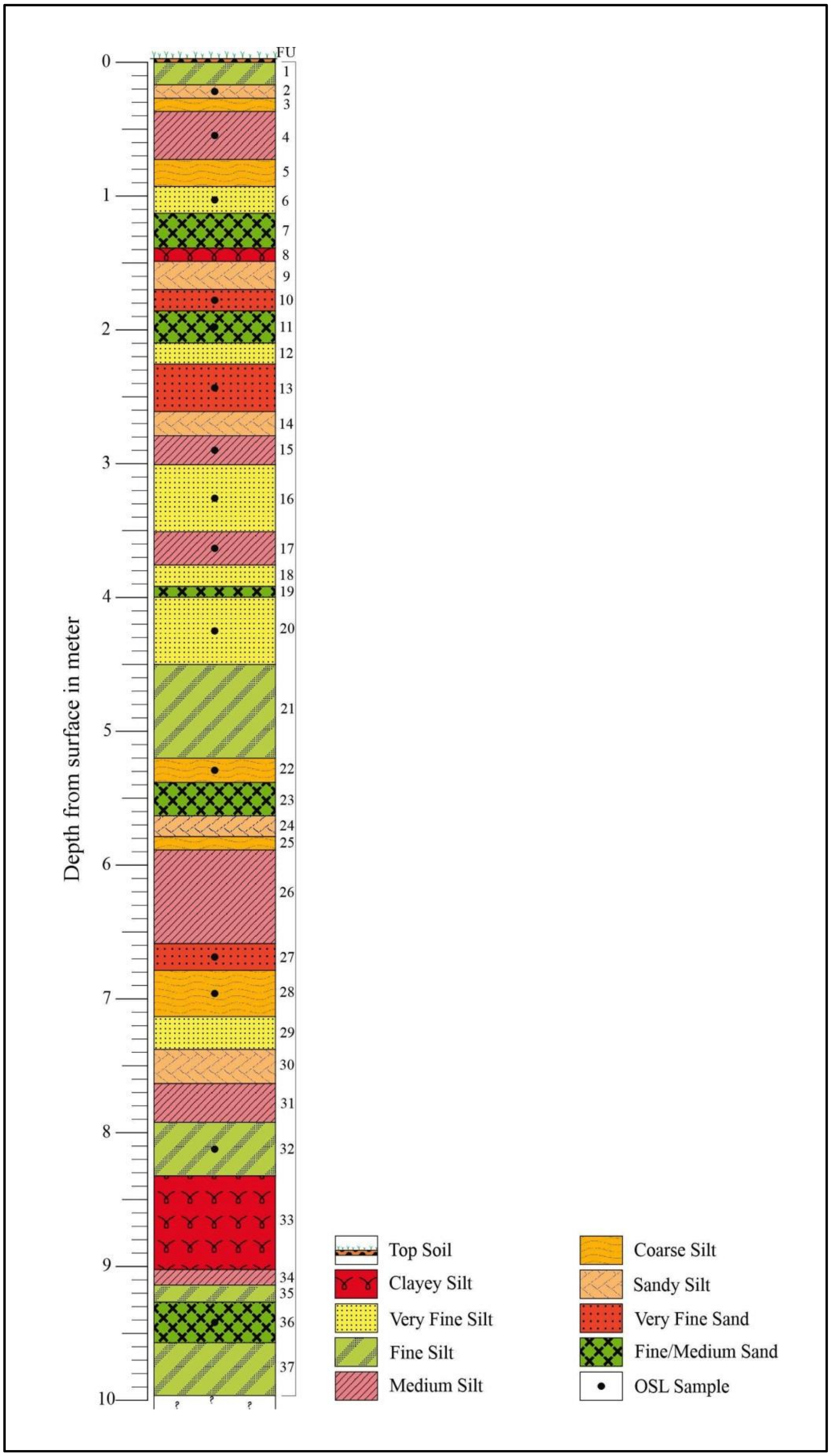


Figure 4.65: Sedlog of the slack water deposits of palaeoflood at the Bhungda

4.4.3 Hydraulic modelling

The cross sectional data and the elevations of the SWD occurring at the Bhungda site have been used for the Hydraulic modelling of the palaeodischarges. The result of hydraulic modelling shows that the highest palaeoflood deposits at the Bhungda site was associated with discharge of 10591 m^3/s magnitude (Figure 4.66). The above discussion leads to the following observations regarding the palaeofloods in the upper Mahi Basin;

1. The river has preserved evidence of 37 palaeofloods.
2. A modern flood had occurred due to sudden release of dam water in 2006.
3. The estimated discharge associated with 2006 flood stage was 25,770 m^3/s and was much greater in magnitude than the palaeofloods.

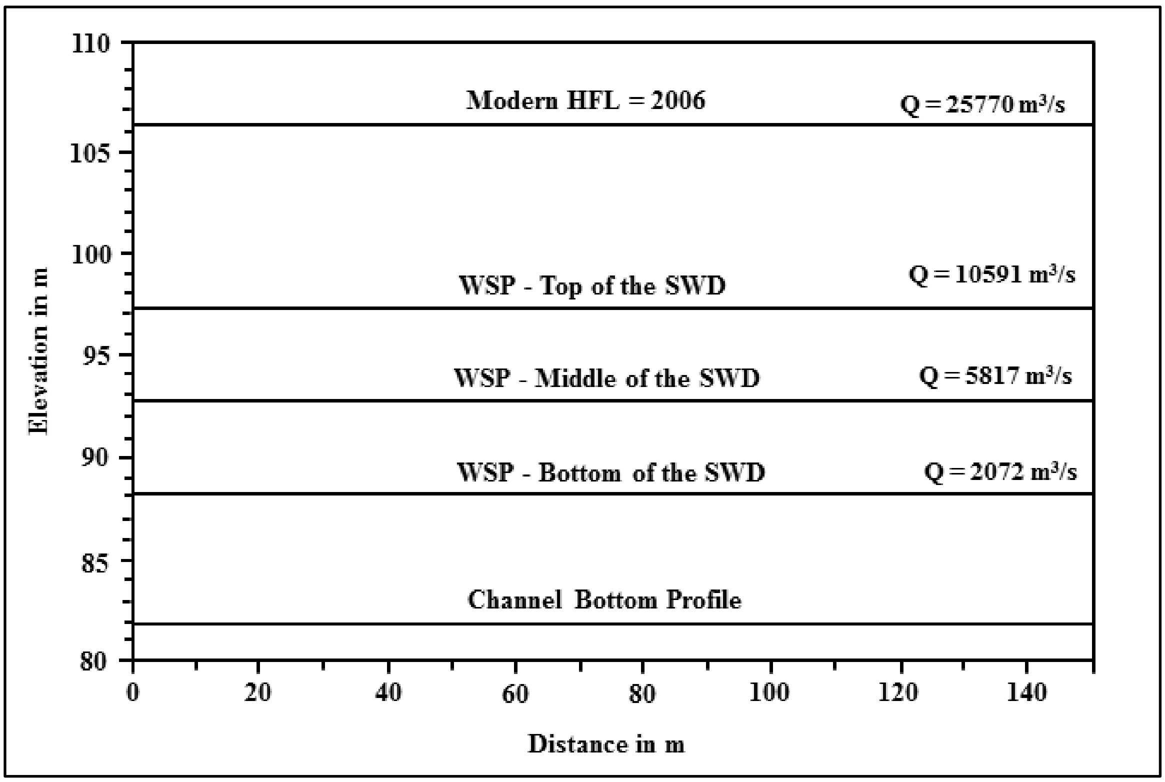


Figure 4.66: Water surface profiles (WSP) associated with different discharges at Bhungda palaeoflood site; SWD = Slackwater deposits; Q = Discharge in m^3/s

Chapter 5

Conclusions and Major Findings

5.1 Conclusions

5.1.1 Flood Hydrology

1) The spatio-temporal fluctuation in the southwest monsoon rainfall over the Mahi Basin is the prime cause of significant variations in the interannual and interseasonal variations in the streamflows of the Mahi Basin.
2) The mean annual hydrographs indicate a single peak of discharge in the mid of the August. This reveals the simple river regime characteristic of the Mahi Basin. However, steep rising limbs and falling limbs of the mean annual hydrographs indicates greatest concentration of flows in the mid of the monsoon season. Besides, it also shows the flashy nature of the streamflows in the Mahi River and tributaries in a short duration.
3) The maximum streamflows (>93%) in the Mahi Basin are recorded during the monsoon season. Consequently, most of the geomorphic work of erosion and sediment transportation has been completed during monsoon season by the Mahi River and its tributaries.
4) The Mahi River and its tributaries show high interannual variability in the annual peak discharges with two or three extreme events such as floods of the year 1973, 1994 and 2006.
5) The Qmax/Qm ratio indicates that observed maximum annual peak discharges (Qmax) are 3 to 7 times higher than average peaks (Qm). Moreover, the result of the coefficient of variation specify that the Som River shows significant variations (1.24 or 124%) in the annual peak discharges than other rivers in the Mahi Basin.
6) The plots of the variability of peak discharges indicates that high intensity rainfall associated with monsoon low pressure systems is the root cause of the extreme fluctuations in the streamflows in the Mahi Basin. This shows that mean annual streamflows are intensely exaggerated because of few extreme flows.

7) The comparatively high flash flood magnitude index of the Mahi Basin (0.57) clearly indicates flashy and variable nature of floods. Furthermore, the index also specifies that there is higher probability of significant geomorphic work during large and infrequent floods.
8) The positive values of the coefficient of skewness (Cs) show occurrence of one or two or a few very large magnitude flows during the gauge period in the Mahi Basin.
9) The higher unit discharges in the upper reaches of the Mahi River particularly at Rupakheda (32.76) and Kothada (10.13) indicate that upper reaches are capable of producing large floods.
10) The estimated discharges by Gumbel Extreme Value type I (GEVI) for various recurrence intervals are fairly close to the observed mean annual discharges, large flows and annual peak flows on record. Normally, estimated discharges for the return period 50 and 100 yr return period are considered for designing hydraulic structures in India.
11) The Gumbel Extreme Value type I (GEVI) probability distribution shows return period of 2.33 yr for mean annual peak discharges and 6.93 yr for large floods. However, the Rangeli site on the Som River has the highest recurrence interval (720 yr) for the observed maximum annual peak discharge. These suggest that largest flood are infrequent and have maximum recurrence interval based on hydrometeorological conditions of the basin.
12) The magnitude frequency curve obtained by using Gumbel Extreme value type I (GEVI) shows that curves best fit to the annual maximum series data of the all sites on the Mahi River and its tributaries. Therefore, GEVI probability distribution is best fit for the flood frequency analysis of the Mahi River and tributaries.
13) The envelope curve developed for the Mahi Basin is below the envelope curve of the world. However, peak flows observed in source catchment of the Mahi Basin for instance, at Rupakheda and Bhungda are higher than the world envelope curve. This reveals potential of Mahi River to produce high discharges in the upper reaches.

14) The flow duration curves significantly indicate that at Khanpur site flows are relatively higher than Mataji and Paderdi Badi site because of its downstream location. However, the large-magnitude flows (>5000 m^3/s) on the Mahi River generally occur for less than 2% of the time.
15) The steepness of the rising limb and falling limb of the flood hydrographs of the 2006 flood indicates flash flood characteristics of the Mahi River. However, flood of the year 2006 flood was associated with heavy rainfall in the upper catchment area of the major dams and release of discharge from dams in the Mahi Basin. This results in flash flood in the Mahi River and its tributaries in downstream reaches.

5.1.2 Flood Geomorphology

1) The channel of the Mahi River is bedrock in the upper and middle reaches with quaternary alluvium deposition on the banks. However, in the alluvial plain of Gujarat, Mahi River has alluvial meandering channel with depositional features such as point bars, sand bars, etc. Besides, badland topography due to headward erosion by smaller streams is one of the features in the lower reaches of the Mahi River.
2) The tributaries of the Mahi River have deeply incised valleys and gorges in their upper reaches in the bedrock channel. Therefore, the channel fill discharges rarely occur, and most high monsoon flows are confined within the channel.
3) The average channel width of the Mahi River increases from upper reaches to middle reaches e.g. at Chikhali. However, due to presence of the Kadana ridges across the Mahi River, channel becomes narrow and depth significantly increases. As a whole, despite of the local controlling factors on channel width of the Mahi River, there is gradual increase in channel width from upstream to downstream.
4) The maximum value of the hydraulic radius is 21 m at Kadana which reflects the high efficacy of the channel of the Mahi River. Similar to the channel depth, as the distance from the source and catchment area increases, the hydraulic radius also goes on increasing.

5) The values of form ratio for most of the sites are less than 39. It shows that the Mahi River channel is deep and narrow. The variation in the width-depth ratio with respect to discharges indicates high hydraulic efficiency of the Mahi River during high flows.
6) The exponent values (b, f and m) and the plots of hydraulic geometry specify that the rate of change in the mean depth (f) is higher than the rate of change in the width of all the sites on the Mahi River and its tributaries. The b/f ratios denote that rate of change in width is always lower than the rate of change in mean depth. Besides, the higher value of the m/f ratio suggests more rapid sediment load transportation with increase in discharge.
7) The increase in the hydraulic parameters and the decrease in the form ratio with discharges of lower to higher recurrence interval shows that the hydraulic effectiveness and the energy per unit area increases significantly during infrequent large magnitude floods. Therefore, these suggest that infrequent and high magnitude floods are capable to perform geomorphic work of erosion of bed and bank material and transportation of coarse sediments.
8) Generally, sediment concentrations and discharge are zero during the non-monsoon season and measurable only during the monsoon season. However, the time series analysis of the Mahi River shows zero to negligible concentration of suspended sediment in the early part of the monsoon season. Further, total amount of annual sediment load carried by the Mahi River is less than large rivers of the central India such as Narmada River, Tapi River, Godavari River and Mahanadi River. Besides, flood hydrograph shows equal time of suspended sediment concentration and peak discharge of the Mahi River at the Mataji and Paderdi Badi sites. Nevertheless, the greater concentration of suspended sediment has been observed on the rising phase than the falling.
9) The strong hysteresis suggests discontinuous supply and removal of fine-grained sediment from the basin. During the rising limb of the hydrographs, the high flows remove easily entrained sediments left by falling stage of overland or streamflows of the previous event. This supply is exhausted after the peak flow, and so sediment concentration decreases. This implies that the concentrations

should be higher during the early monsoons season and during high flows immediately following long dry spells. This effect is particularly pronounced at Khanpur.

10) Since there is a positive relationship between discharge and suspended sediment load in the study area, it would be logical to infer that maximum load is transported during floods than during low discharges. Besides, the bedload sediment transport analysis shows that infrequent and large flood on the Mahi River which occur at an interval of several decades are more significant and effective than frequent events of lower magnitude.

11) The high values of the unit stream power and bed shear stress indicate ability of the Mahi River and its tributaries to erode and transport coarse sediment. Besides, high values of Reynolds number also indicate that the flood discharges could be extremely turbulent, and thus, are capable of accomplishing a variety of geomorphic activities.

12) The Mahi River had experienced some of the large floods in the year 1927, 1968, 1973, 1976, 1994 and 2006. However, there are no remarkable changes in the Mahi River channel. The analyses of the evaluation of flood show that ratios for all the hydraulic variables such as discharge, mean velocity, stream power and Reynolds number are more than 1.

5.1.3 Flood Hydrometeorology

1) The annual rainfall of the Mahi Basin has mainly confined to southwest monsoon months; whilst 96% to 98% occurs in the monsoon months. July is the rainiest month throughout the basin which accounts for 31% to 36% of the total annual rainfall. The mean annual rainfall in the Mahi Basin at various stations varies between 1013 mm (Banswara) and 649 mm (Kherwara). However, mean annual rainfall of the Mahi Basin is 889 mm.

2) The coefficient of variation (Cv) indicates that interannual variability of rainfall within the Mahi Basin is not significantly high. However, positive values of the coefficient of skewness (Cs) suggest the occurrence of a few very wet years during the gauged period. Since the skewness values have been obtained on the basis of more than 100 years data, they are all statistically significant.

3) The time series plots reveal that interannual variability was characterized by increased frequency and magnitude of floods on the Mahi River. The plots show that the rainfall sometimes varies by as much as ± 60% to 80%.
4) The analysis of flood generating LPS(s) shows that almost all the large floods that have been recorded in the Mahi Basin in the last century and recent years were associated with extraordinarily heavy rainfall triggered by Bay or land depressions. For example, floods of the year 1927, 1968, 1973, 1976 and 2006. However, the path and duration of LPS(s) over the basin determine rainfall depths and consequently magnitude of floods.
5) This highest daily rainfall of 559 mm at Banswara received on July 23, 1959 which gives 28% of annual rainfall in a day. Although, the highest 24-hr rainfall in the Mahi Basin was associated with rainstorm and floods, it may not be always associated with large floods such as 1973, 1976 and 2006. The highest 24-hr precipitation totals do not necessarily indicate the occurrence of an extreme flood, since they do not reflect basinwide precipitation. Nevertheless, wet spells that are widespread, of a longer duration (2-day or 3-day) are responsible for the high-magnitude floods in the Mahi Basin.
6) The analysis of the DAD indicates that long duration rainfall events such as 1927 and 1973, which are widespread and capable of producing large floods in the Mahi Basin even if the daily precipitation totals are not the highest and record breaking.
7) The analysis of the NADM reveals that three largest floods of the 20th century (1973, 1976 and 1990) had occurred when rainfall of the Mahi Basin was above average. Therefore, it implies that floods in the Mahi Basin are not randomly spaced, but follow a pattern directed by long-term changes in the monsoon rainfall.
8) The analysis of ENSO indicates that out of the 21 floods in the Mahi Basin 17 floods have occurred during normal and La Niña conditions when annual average rainfall of the Mahi Basin was normal or above normal. Whereas, only four floods were observed during warm ENSO conditions when annual average rainfall of the Mahi Basin was below normal.

9) The Mann Kendall test applied for the annual rainfall of the Mahi Basin indicates increasing trend of the rainfall. However, testing the significance of Tau (τ) indicates that annual rainfall trend/change over a Mahi Basin does not show any specific trend during 1901 to 2011. The analysis of the t test also denotes that the monsoonal rainfall of the Mahi Basin is highly regular and reliable. Consequently, it is probable to be the same in this as well as in the next century.

5.1.4 Palaeoflood Hydrology

1) The presence of large boulders along the Mahi River provides evidences to the competence of large palaeo flows. The palaeodischarges of the Mahi River had high ability to transport coarse sediment such as pebbles, cobbles and boulders.
2) The results of sediment analysis shows that the sediments of slack water deposit are dominated by very fine silts to medium sands (0.0039 to 0.30 mm), which are strongly negatively skewed and well sorted to moderately well sorted. Besides, stratigraphic analysis of the Bhungda site shows 0.1 and 0.7 m. variation in thickness of units.
3) The result of the hydraulic modelling also denotes that the palaeoflood discharges were lower in magnitude than the modern floods such as 2006 flood. However, unit discharges with respect to palaeoflood discharge at Kothada and Bhungda sites are 10.13 $m^3/s/km^2$ and 6.59 $m^3/s/km^2$ respectively.

5.2 Limitations of the study

An attempt has been made to study all characteristics of flood hydrology, flood geomorphology, flood hydrometeorology and palaeoflood hydrology of the Mahi Basin. Therefore, data have been collected through extensive field surveys, central water commission (CWC), India Meteorological Department (IMD), Survey of India (SOI), a number of research publications and reports. However, the study is not complete in all respects. Some of the major limitations of the present study have been outlined below.

1) The analytical research and findings about the flood hydrological characteristics of the Mahi Basin are based upon inadequate hydrological data (discharge), which is of very short duration. Besides, most of the tributaries of the Mahi River does have discharge gauging sites.

2) The data regarding suspended sediment are available only for the gauging sites on the Mahi River and that too for very short period (2000-2005). During this period no mega-flood had occurred. Therefore, the dynamic of suspended sediment transport during catastrophic floods such as 1973, 1976, 1990 and 2006 floods could not be evaluated. Therefore, results derived from such short data are not very reliable and meaningful.
3) There is not sufficiently long stage and historical record of floods for the Mahi River and its tributaries. Besides, annual maximum series data are not available for long period for all sites in the Mahi Basin. However, there are several tributaries of the Mahi River such as the Panam River, the Bhadar River and the Moran River for which hydrological gauging sites are not available. Consequently, whole picture about the flood hydrology of the Mahi Basin could not be very clear.
4) Flood frequency analysis based on such limited data is not very reliable and meaningful. However, the Wanakbori station has sufficient length of the data from which some constructive outcomes could be obtained.
5) The channel morphological study of the Mahi River and its major tributaries was mainly based on only 19 cross sections. In order to understand the downstream variations in the channel morphological parameters, several such cross sections at closer interval are essential. However, major dam has been constructed on the Mahi River and its tributaries due to which most of the part of channels of the Mahi River and its tributaries are under water even during summer season.
6) Flood plays an important role in shaping the stream channel and landforms. In relation to this, the erosional and depositional features of the Mahi River and its tributaries could not be studied very well due to submergence under backwater of the dams. Besides, all the dams in the Mahi Basin have constructed at very ideal sites. These sites are also significant for fluvial and flood geomorphological analysis. However, due to inaccessibility upto these sites geomorphic effectiveness of the floods could not studied in depth.

7) The evaluation of geomorphic impact of floods on the Mahi River and its tributaries was based on very limited data of the floods of the 1973, 1991 and 2006. The catastrophic flood of the year 1927 for which information is not available. No systematic records of erosion, sediment transport or deposition during large floods are available. Besides, in order to understand changes in the river channel, the cross sectional data of available gauging sites before and after recent floods of the 1990, 1994 and 2006 also not available.
8) There is sufficient and long meteorological data to understand the causes of large floods during the last 110 years However, most of the raingauge stations in the Mahi Basin have not rainfall data from the year 1901 to 2015. Besides, there is not continuous record of the daily rainfall data, some of the years data are missing. Therefore, estimated rainfall data might influence the results regarding hydrometeorology of the Mahi Basin.
9) The relationship between monsoon rainfall, large-scale systems, and its teleconnections with large-scale phenomena such as the ENSO is extremely complex. This will require further research.
10) The palaeoflood deposits well-preserved sites on the Mahi River and its major tributaries are very limited. Only Bhungda site in the Banswara district of the Rajasthan has very well-preserved slack water deposits. Many ideal sites might have been submerged under backwater of the major dams in the Mahi Basin. It would be helpful if better and longer records of palaeofloods are discovered on the main river as well as its tributaries.

5.3 Major findings of the study

The major findings and contributions that have emerged from this study are as follows;

1. The Mahi River exhibits all the hydrological, geomorphological and meteorological characteristics of a flood-dominated river. Large floods are common and frequently occurring events at the decadal interval. Interventions of man, mainly due to construction of dams, have made the recent floods more destructive, for instance 2006 flood.

2. The channel perimeter lithology has played significant role in determining efficacy of the floods on the Mahi River. The channel of the river is mainly confined into bedrock particularly in the upper reaches. The channel in middle reaches is comprised of thick Quaternary alluvium with bedrock exposures on the bed and banks. The perimeter in the lower reaches is characterized thick Quaternary alluvium with sandy bed. Since the bank resistance is high, only infrequent large magnitude floods that occur at the interval of several decades or century, are capable to erode the banks and determine size and shape of the cannel of the Mahi River. Thus, the channel morphological characteristics of the bedrock as well as the alluvial reaches of the Mahi River are maintained by infrequent but large magnitude extreme floods such as the 1927, 1973 and 2006 flood events that occur at an interval of several decades or hundreds of years. Apart from transporting the fine-grained sediments in suspension or moving sandy/pebbly bedload or modifying the channel bedforms, the frequently-occurring moderate flows have little effect on the mobility of coarse sediments and on the morphology of the channels.
3. Floods on the Mahi River are not randomly spaced, but follow a pattern dictated by long-term changes in the monsoon rainfall over the basin. Thus, the temporal distribution of geomorphologically effective floods is strongly influenced by long-term changes in the monsoon conditions and the rainfall regime. Examination of the synoptic conditions associated with the flood-generating low pressure systems reveals that majority of floods are the result of either Bay of Bengal or adjoining land depressions.

The present study sharply contrasts with numerous studies, primarily of humid region, which indicate that frequent, moderate flow events are more important in the transportation of maximum suspended sediment load and in maintaining the stream morphology (Wolman and Miller, 1960). The conclusions of this study are more in agreement with the inferences drawn by Pickup and Warner (1976) for semi-arid regions, and by Gupta (1995a) and Hire (2000) for tropical/monsoonal environments, that a series of flows rather than a single flow determine the channel characteristics. The low or moderate magnitude flows transport most of the fine-grained sediment such as clay, silt and sand and modify the channel bedforms to some extent. However, the channel size and shape is maintained by large magnitude floods, such as the 1927, 1973 and 2006 floods that occur at long intervals.

Investigations of hydrological, geomorphological and meteorological characteristics of floods on the Mahi River have facilitated us to understand the distinctiveness of monsoonal rivers that are categorized by frequent floods of high magnitude. This study has revealed that monsoonal rivers preserve numerous prerequisites for disastrous flood responses.

The inferences regarding the hydrological, geomorphological and meteorological significance of floods accomplished in the present investigation have been discussed only for one medium-sized basin. Nevertheless, the geology, topography, climate and tectonic setup within the monsoonal/tropical region are varied, the conclusions cannot be applied directly to all the basins within the monsoonal/tropical region. Nonetheless, such studies are beginning to provide a database and discuss the significance of the infrequent large magnitude floods in monsoonal environments.

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