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MINISTRY OF WATER RESOURCES

RESEARCH ON HYDRO-MORPHOLOGICAL STUDY OF THE MAHANANDA RIVER IN BANGLADESH WITH FOCUS ON PROBLEMS AND PROBABLE SOLUTIONS OF DRY SEASON FLOW SCARCITY

TECHNICAL REPORT

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River Research Institute

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PREFACE

The technical report presents the findings for carrying out the research investigation of the Mahananda River under Chapai Nawabgonj District. This study has been carried out by the Research Team under the guidance of Director, Hydraulic Research Directorate of River Research Institute (RRI) funded by the Government of the People's Republic of Bangladesh.

We express our sincere thanks to River Research Institute (RRI) for allowing us to carry out the aforementioned study.

Special thanks are extended to Director General, River Research Institute for his guidance and encouragement for successful completion of the study.

Sincere thanks are extended to Chief Scientific Officer, Hydraulic Research for his sincere guidance, inspiration and cooperation throughout the study period.

Heartfelt thanks are also extended to Team Leader and members of the study team for their hard work throughout the study period.

Finally, profound appreciation is due to the officials and staffs of RRI who helped us directly or indirectly at different stages of the study.

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1 INTRODUCTION

1.1 Background of the Study

Mahananda river, a trans-boundary stream originating from Himalayas and spills through the southern parts of Rajshahi, Chapai Nawabganj as well as Natore district. The river has a catchment area of about 1300 sq. km. It is revealed from the recorded discharge during monsoon and lean period that the monsoon discharge is almost same in every year, whereas the lean period discharge is declined drastically from year to year. Uses of river water in various purposes have been limiting gradually due to the shortage of normal flow in the river. Mahananda is a flashy river but along the edge of Mahananda Barrage in India diverts much of its normal flow towards Bihar. The river erodes its banks during monsoon, in the Chapai Nawabganj district after re-entering Bangladesh. Its length inside Bangladesh is about 78 km. At its outfall, erosion, floods, and backwater flow of the Ganges river dominate the waterway. The major towns on the bank of Mahananda within Bangladesh territory are Tentulia, Bholahat, Gomostapur, and Chapai Nawabganj. There is a water level measuring station at Gomastapur and a discharge measuring station at Chapai Nawabganj (Haque, M. Inamul 2008). Entering back into Bangladesh at Gomostapur Upazila under Chapai Nawabganj district the Mahananda river travels 36 km through three Upazilas namely Gomostapur, Shibganj, Chapai Nawabganj Sadar. The river ultimately falls into the Ganges river at Godagari Upazila under Rajshahi district. The 36 km river reach is very important in terms of agriculture, fishery, groundwater withdrawal for irrigation and drinking purpose, transportation of different goods etc. However, due to the acute shortage of dry season flow agriculture, fishery, groundwater use and navigation have been drastically affected with direct consequences on livelihoods and environment. Depletion of groundwater table due to over withdrawal of groundwater, arsenic contamination of groundwater and inadequate recharge are some of the conceivable problems. The other problems are lack of year-round navigation facility, decreasing fish population, bank erosion and drought. All these problems are believed to be directly related to the dry season flow scarcity of the Mahananda river.

Under the above mentioned circumstance and its negative social, environmental and economic impacts the honorable Member of Parliament of 44 Chapai-Nawabganj has requested River Research Institute to take up a comprehensive study on the Mahananda river to address the issues and to find out sustainable solutions of the problem through his letter on 25 March 2016. River Research Institute is mandated to take up studies to address river-related problems and find out solutions of the same through physical and numerical model investigations as well as through field data collection and analysis. RRI conducts studies on priority of rivers and water-related problems by utilizing its own research fund. It is, therefore, decided to take up a comprehensive hydro-morphological study of the Mahananda river to identify the issues that are hindering the development and to devise feasible options to address these issues. Primarily this study has been based on primary data collected from field and secondary data available with different organizations.

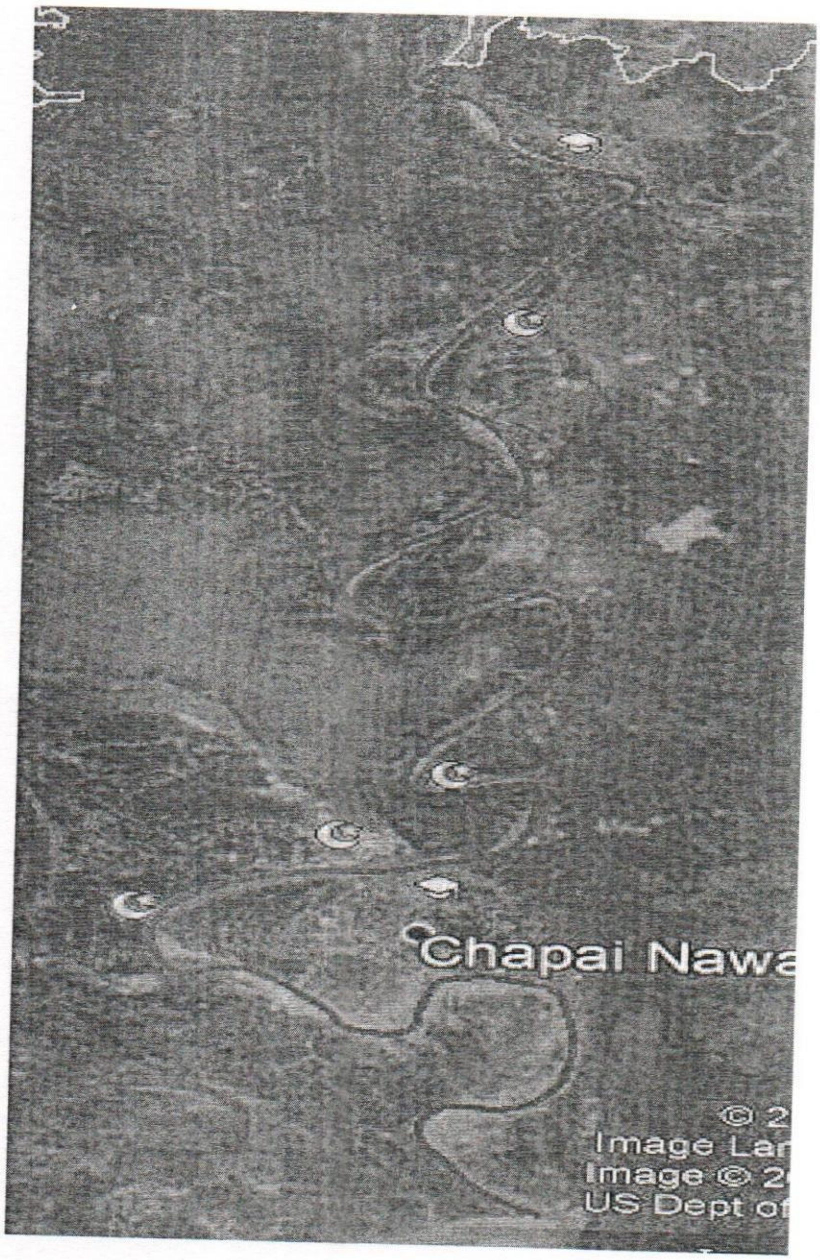

Figure 1.1 Study Reach of Mahananda River

1.2 The Mahananda River

1.2.1 Course

The Mohananda is a natural non-prismatic non-perinial mobile boundary meander river. It originates in the Himalayas: Paglajhora Falls on Mahaldiram Hill near Chimli, east of Kurseong in Darjeeling district at an elevation of 2,100 meters. It flows through Mahananda Wildlife Sanctuary and descends to the plains near Siliguri. It touches Jalpaiguri district. It enters Bangladesh near Tentulia in Panchagarh District, flows for 3 km after Tentulia and returns to India. After flowing through Uttar Dinajpur district in West Bengal and Kishanganj and katihar district in Bihar, it enters Malda district in West Bengal. The Mahananda divides the district into two regions — the eastern region, consisting mainly of old alluvial and relatively infertile soil is commonly known as Barind, and the western region, which is further subdivided by the river Kalindri into two areas, the northern area is known as "Tal." It is low-lying and vulnerable to inundation during rainy season; the southern area consists of very fertile land and is thickly populated, being commonly known as "Diara". It joins the Ganges at Godagari in Nawabganj district in Bangladesh.

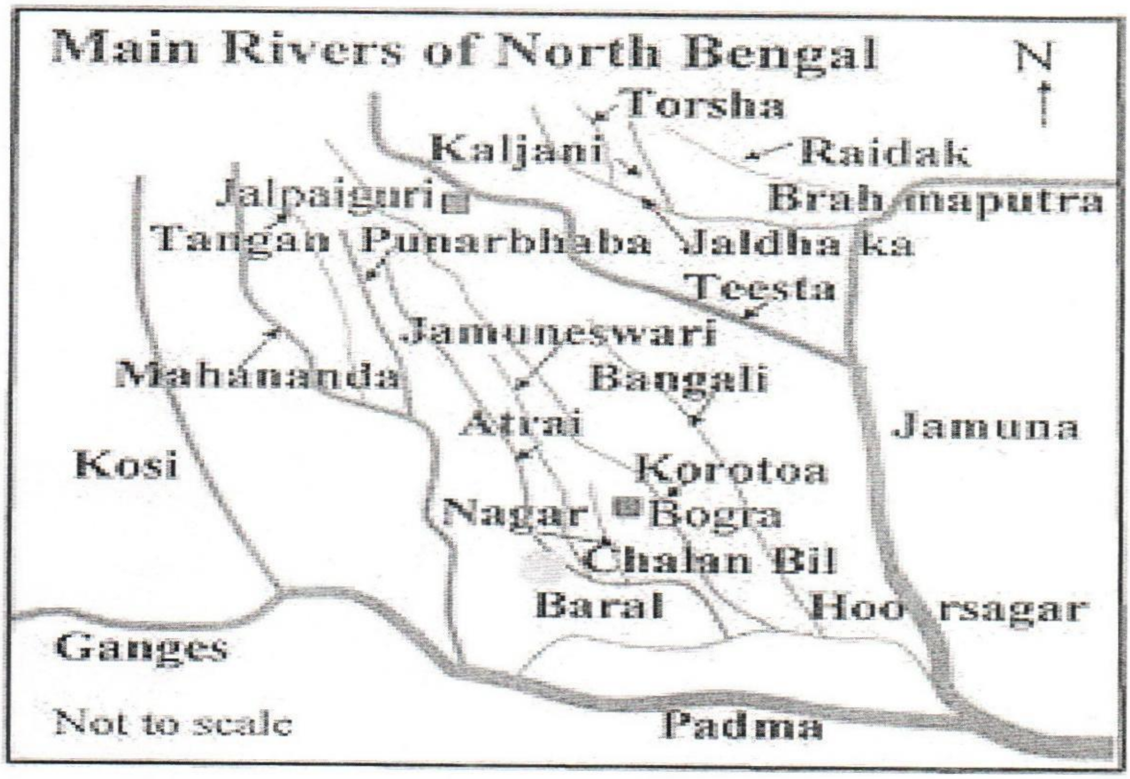

Figure 1.2: Main rivers of North Bengal

1.2.2 Tributaries

The main tributaries of the Mahananda are Balason, Mechi, Ratwa, Kankai. In the Siliguri area it has three tributaries called the Trinai, Ranochondi and the pair of Chokor and Dauk taken as a single tributary. The main tributaries of the Mahananda in Bangladesh are Pugla and Punarbhaba.

1.2.3 History

The Mahananda river passes through North Dinajpur, Purnea, Katihar, and Maldah district. In Maldah district, it receives the Kalindi river and the Nagor and Kulik rivers those originate in the Dinajpur district of Bangladesh. The Mahananda river then reaches international border near Bholahat of the Chapai Nawabganj district. Here, following the international borderline, the river receives another tributary on its left bank named the Tangon river. Following a length of about 12 km along the border, the Mahananda river finally enters into Bangladesh territory. At Gomastapur, it meets with another tributary the Punarbhaba river on its left bank. The Mahananda river then flows south and falls in the Ganges river near Godagari of Rajshahi district. Just before its outfall, it meets with a tributary on its right bank called the Pagla river. This river enters into Bangladesh from India near the Sona Masjid of Shibganj Upazilla. Presently, the Ganges river has advanced further north by eroding its bank. As a result, the Pagla river now directly falls into it. This will eventually cause environmental degradation in the Nawabgani district. This watercourse has a large catchment area in Indian states of West Bengal, Bihar along with Nepal and Bangladesh. The Mahananda river is embanked all along its margin. The right bank of Mahananda is protected by 3.1 km embankment from Poladanga to Munshiganj ghat and 2.1 km embankment at Gilabari under Bholahat thana. At Poladanga BGB camp under Bholahat thana, the river is protected by 1.52 km embankment while the left bank is sheltered by 1.6 km embankment at Sadarghat of Chapai Nawabganj district. There is a bridge named Birshresto Captain Mohiuddin Jahangir on the Mahananda river at Chapai Nawabganj Sadar. The Mahananda river passes through North Dinajpur, Purnea, Katihar, and Maldah district. In Maldah district, it receives the Kalindi river, and the Nagor and Kulik rivers those originate in the Dinajpur district of Bangladesh. The Mahananda river then reaches international border near Bholahat of the Chapai Nawabganj district. Here, following the international borderline, the river receives another tributary on its left bank named the Tangon river. Following a length of about 12 km along the border, the Mahananda river finally enters in to Bangladesh territory. At Gomastapur, it meets with another tributary the Punarbhaba river on its left bank. The Mahananda river then flows south and falls in the Ganges river near Godagari of Rajshahi district. Just before its outfall, it meets with a tributary on its right bank called the Pagla river. This river enters into Bangladesh from India near the Sona Masjid of Shibganj upazilla. Presently, the Ganges river has advanced further north by eroding its bank. As a result, the Pagla river now directly falls into it. This will eventually cause environmental degradation in the Nawabgani district. This watercourse has a large catchment area in Indian states of West Bengal, Bihar along with Nepal and Bangladesh. The Mahananda river is embanked all along its margin. The right bank of Mahananda is protected by 3.1 km embankment from Poladanga to Munshiganj ghat and 2.1 km embankment at Gilabari under Bholahat thana. At Poladanga BGB camp under Bholahat thana, the river is protected by 1.52 km embankment while the left bank is sheltered by 1.6 km embankment at Sadarghat of Chapai Nawabganj district. There is a bridge named Birshresto Captain Mohiuddin Jahangir on the Mahananda river at Chapai Nawabganj Sadar.

1.3 Geometry and Sinuosity of the Channel

Channel pattern is used to describe the plan view of a reach of river as seen from an airplane and includes meandering, braiding, or relatively straight channels. Natural channels characteristically exhibit alternating pools or deep reaches and riffles or shallow reaches, regardless of the type of pattern. The length of the pool or distance between riffles in a straight channel equals the straight line distance between successive points of inflection in the wave pattern of a meandering river of the same width. The points of inflection are also shallow points and correspond to riffles in the straight channel. This distance, which is half the wavelength of the meander, varies approximately as a linear function of the channel width.

River braiding is characterized by channel division around alluvial islands. The growth of an island begins as the deposition of a central bar which results from sorting and deposition of the coarser fractions of the load which locally cannot be transported. The bar grows downstream and in height by continued deposition on its surface, forcing the water into the flanking channels, which, to carry the flow, deepen and cut laterally into the original banks. Such deepening locally lowers the water surface and the central bar emerges as an island which becomes stabilized by vegetation. Braiding was observed in a small river in a laboratory. Measurements of the adjustments of velocity, depth, width, and slope associated with island development lead to the conclusion that braiding is one of the many patterns which can maintain quasi-equilibrium among discharge, load, and transporting ability. Braiding does not necessarily indicate an excess of the total load.

Channel cross-section and pattern are ultimately controlled by the discharge and load provided by the drainage basin. Channel width appears to be primarily a function of near-bankfull discharge, in conjunction with the inherent resistance of bed and bank to scour. Excessive width increases the shear on the bed at the expense of that on the bank and the reverse is true for very narrow widths.

Channel roughness, to the extent that it is determined by particle size, is an independent factor related to the drainage basin rather than to the channel. Roughness in streams carrying fine material, however, is also a function of the dunes or other characteristics of bed configuration.

1.4 Mahananda Barrage and its salient Features

The Mahananda barrage was constructed in 1986. The barrage is situated near the city Siliguri of West Bengal state. Some salient features are shown in table below.

Table 1.1 Salient features of Mahananda Barrage

Sl. No.	Attribute	Measuring units	Value
1	Year of commencement	YYYY	1979
2	Year of completion	YYYY	1986
3	Length of barrage and anicut	m	182.88
4	No. of bays	-	06
5	Width of bay	m	18.288
6	Design flood discharge	cumec	2265
7	No. of spillway gates	-	06
8	Size of spillway gate	m x m	18.288 x 3.75
9	No. of under sluice gates	-	04
10	Size of under sluice gate	m x m	18.29 x 4.63
11	Maximum discharge of canal	cumec	345.26

1.5 Objectives of the Study

The main objectives of the proposed investigation are as follows:

- To develop an understanding of the hydro-morphological processes of the river Mahananda from a historical perspective and to assess the impacts of changes in flow
- Identification of issues that are hindering development and development of likely options to address these issues.

The specific objectives of the proposed investigation are as follows:

- To assess the past hydro-morphological developments of the Mahananda river and to predict possible future developments;

- To assess the impacts of natural changes and human interventions in the river and floodplain on flow;
- To analyze time series satellite images and to develop interrelationships among planform parameters;
- To appraise the socio-economic impact of flow scarcity in riverbank people;

2 LITERATURE REVIEW

2.1 General

In the recent past, many researchers put efforts for developing a proper understanding of the bank shifting processes and mechanisms of the alluvial rivers. Fluvial geomorphology studies the ways in which streams alter landforms, geomorphic and hydrologic function classification of stream networks, longitudinal profiles of streams, geologic controls, floodplains and terraces, and general types of channels are components of fluvial geomorphology. First, geomorphic and hydrologic functions need to be understood. The processes of erosion, transportation, and deposition of sediments are most relevant in fluvial geomorphology. Stream systems generally erode material in the steeper upper reaches. This material is transported via stream channels and eventually deposited in the lower reaches of a stream system, and ultimately into oceans. Whether a given stream reaches is emotional transportation, or depositional depends on several hydraulic characteristics. A number of important studies have been done by various researchers in this regard. Their works have led to valuable insights into bank erosion mechanisms. Some of these studies have reported the erosion rates and rate law governing bank erosion. Classification of stream networks is based on stream orders and on hierarchical classification. Stream order is a measure of the number of tributaries feeding any given fluvial system. Hierarchical classification considers stream network patterns, stream reach, and stream channel units. A single, small channel with no tributaries is classified as a first-order stream (Strahler, 1946). A second-order stream is formed by the juncture of two first order streams. Two second-order streams combine to form a third order stream, and so on.

Three general channel types occur, although most streams have reaches belonging to more than one channel type. The three types are straight single channel, meandering channel, and braided channel. Straight single channels are typical of mountain streams and typically lie on bedrock or coarse (cobble and boulder) substrates. High gradient and low sinuosity are characteristic of straight, single channels. During periods of very low flow, the streams may develop meandering thalwegs within the bankfull channel. However, once the median flow is restored, the low flow thalweg is washed out and the stream fills the less sinuous median flow channel. Meandering channels are more characteristic of lower gradient streams and rivers. Meandering streams have higher sinuosity and higher form roughness. Braided channels contain complexes of bars and islands and can shift channels often. Abundant bed load and variable discharge are among the factors that produce braided channel patterns. Findings of those research works and the theoretical approaches of the researchers can be very useful for the engineers and researchers who are involved in the implementation of various river engineering projects and engaged in the same field of study. Hereafter some of those studies have been reviewed briefly.

2.2 Review of Past Studies on Mahananda

According to Sarkar et al (2003), the Ganges rises from the Godagari glacier on the southern slope of the Himalayas at an elevation of above 7000m west of Nanda Devi range in Himachal Pradesh and northernmost Uttar Pradesh, west of Nepal. The river comes out of the Himalayan and Siwalik range near Dehradun and enters the plains at Haridwar. The river enters into Bangladesh through the northwest district of Chapai Nawabgonj. It flows about 95km between India-Bangladesh borders before entering fully into Bangladesh. From this point, river flows in southeastern direction for another 120 km and confluences with the Jamuna River upstream of Aricha. The total length of the river upto Aricha is 2200 km. Mahananda is one of its tributary which meets the Ganges at Godagari of Rajshahi District.

The Mahananda originates in the Himalayas Paglajhora Falls on Mahaldiram Hill near Chimli, east of Kurseong in Darjeeling district at an elevation of 2,100 meters (Sharad et al, 2010). It enters Bangladesh near Tentulia in Panchagarh District, flows for 3 kilometres after Tentulia and returns to India. After flowing through Uttar Dinajpur district in West Bengal and Kishanganj and katihar district in Bihar, it enters Malda district in West Bengal. The Mahananda divides the district into two regions - the eastern region, consisting mainly of old alluvial and the western region, relatively infertile soil is commonly known as Barind. It joins the Ganges at Godagiri in Nawabganj district in Bangladesh.

Mohananda River is a trans-boundary river. Mohananda enters Bangladesh at Bholahat Upazila of ChapaiNawabganj district and then flows towards the south and meets with the Ganges near Sultanganj under Godagari Upazila. It has two main tributaries: Punorbhaba and Pagla. Punorbhaba meets with Mohananda near Mokarrampur and Pagla meets with Mohananda at further downstream near Char Mohanpur (IWM, 2015)

Rahman et.al, 2011 studied the geographical position and aquatic resources of Mohananda River. According to the study, the Mahananda River is one of the major rivers of the Northern region of Bangladesh. The Mahananda, a river of fair size during rainy season, joins the Ganges just west Godagari town. About sixteen miles further downstream, the river washes the southern tip of Rajshahi town. It is a major tributary of the Padma. The lowest water level recorded was 12.32 meter in April and the highest water level recorded was 19.50 meter in September. The fisheries resources of Nawabganj are quite good.

2.3 Hydraulic Parameters

Critical parameters in river channel hydraulics include roughness, valley, bank, floodplain, and stream channel slopes, sinuosity, mean velocity, top width, mean depth, bankfull depth, bankfull width, width of valley floor. Roughness is the ability of a given surface to slow the flow of water. Roughness can be divided into form roughness and skin friction for any given channel. Form roughness includes stream channel units such as pools, riffles, and meanders. Skin friction roughness relates to the type of material comprising a channels substrate. Manning's roughness coefficient is a numerical assignment expressing skin friction roughness, and is higher for floodplains and channels with large rocks and vegetation, and lower for smooth channels. Velocity is related to Manning's n, to the hydraulic radius (R), and to channel slope (S).

Width of a stream is measured from bank to bank in a direction perpendicular to the direction of flow. The gradient of a stream is important to the stream's ability to erode or deposit material. Valley width can determine how much area is available for flood plains, and can determine whether a stream is constrained or unconstrained. Depth of a stream is usually defined as mean depth. Depths are taken at regular spacing along 'a line perpendicular to the direction of flow and are related to other hydraulic parameters of flow, and these depths are averaged to find a mean depth.

Depth measurements, similar to width measurements, are different for different póints. Q = W * D * V. These hydraulic parameters vary at any given point on a stream through time. Stream channel parameters are mathematically related through a series of equations. Depth and width define other parameters as well. Cross-sectional area (A), wetted perimeter (P) and hydraulic radius (R) are related to width (W) and depth (D).

$$A=W*D \qquad P=2*D+W \qquad R=A/P$$

Whether a stream has an erosional or depositional character depends on a number of factors. These factors include stream discharge, of minimal precipitation, gradient, sediment load, and nature of streambed. The amounts of suspended, saltated, and bed loads play critical roles in determining the erosional or depositional character of any stream. Discharge fluctuations, stream gradient, amount of material available for transport, and character of streambed all crucially affect the erosional or depositional character of streams. Many previous workers have studied erosional versus depositional regimes. Concepts describing these relationships include stable channel balance (Lane, 1955), a complex response concept (Schumm, 1977), and degrees of freedom (Beschta and Platts, 1986).

2.4 Channel Geometry and Cross Section

2.4.1 Pools and crossings in Bends

There is a concentration of flow due to centrifugal forces. This causes the depth to increase at the outside of the bend, and this area is known as a pool. As the thalweg again changes sides below a bend, it crosses the centerline of the channel. This area is known as the riffle or crossing. At the point of tangency between adjacent bends, the velocity distribution is fairly consistent across the cross-section, which is approximately rectangular in shape. The concentration of flow in the bends lost and the velocity decreases accordingly, thus causing deposition in the crossing.

2.4.2 Cross-Section Shape

The shape of a cross-section in a stream depends on the point along the channel with reference to the plan geometry, the type of channel, and the characteristics of the sediment forming and transported within the channel. The cross-section in a bend is deeper at the concave (outer bank) side with a nearly vertical bank, and has a shelving bank as formed by the point bar on the convex side. The cross-section will be, more trapezoidal or rectangular in a crossing. Cross-section shape can be described by a number of variables. Some of these such as the area, width, and maximum depth are self-explanatory. However, other commonly used parameters warrant some explanation. The wetted perimeter (P) refers to the length of the wetted cross section measured normal to the direction of flow. The width-depth (w/d) ratio is the channel width divided by the average depth (d) of the channel. The average depth is calculated by dividing the cross section area by the channel width. The hydraulic radius (r), which is important in hydraulic computations, is defined as the cross sectional area divided by the wetted perimeter. In wide channels with w/d greater than about 20 times of the hydraulic radius and the mean depth are approximately equal. The conveyance or capacity of a channel is related to the area and hydraulic radius and is defined as $AR^{2/3}$.

2.4.3 Channel Bars

Channel bars are depositional features that occur within the channel. The size and location of bars are related to the sediment transport capacity and local geometry of the reach. The enlargement of a bar generally results in caving of the opposite banks in order to maintain conveyance of the discharge. The primary types of bars are point bars, middle bars, and alternate bars. Point bars form on the inside (convex) bank of bends in a meandering stream. The size and shape of the point bar are determined by the characteristics of the flow. The development of a point bar is, partially due to the flow separation zone caused by centrifugal forces in the bend, and secondary flow. Middle bar is the term given to areas of deposition lying within, but not connected to the banks. Middle bars tend to form in reaches where the crossing areas between bends are excessively long and occasionally in bends due to the development of chutes. Alternate bars are depositional features that are positioned successively down the river on opposite sides. Alternate bars generally occur in straight reaches and may be the precursor to a fully developed meander pattern.

2.5 Planform Geometry

Sinuosity is a commonly used parameter to describe the degree of meander activity in a stream. Sinuosity is defined as the ratio of the distance along the channel (channel length) to the distance along the valley (valley length). The meander wavelength (M_L) is twice the straight-line distance between two consecutive points of similar condition i.e. pools or crossings) in the channel. This is sometimes referred to as the axial meander wave length to distinguish it from the channel length between inflection points which is also sometimes referred to as the meander wave length. The meander amplitude (M_B) is the width of the meander bends measured perpendicular to the valley or straight line axis. The ratio of the amplitude to meander wave length is generally within the range 0.5 to 1.5. It should be noted that the meander amplitude and the width of the meander belt would probably be unequal. The meander belt of a stream is formed by and includes all the locations held by a stream during its development history. In many cases, this may include all portions of the present flood plain. Meander wave length and meander width are primarily dependent on the water and sediment discharge, but may also be modified by confines of the material in which the channel is formed. The effects of bank materials are shown by the irregularities found in the alignment of natural channels. If the material forming the banks was homogeneous over long distances, a sinusoidal alignment having a unique and uniform meander wavelength would be expected although this rarely occurs in nature. The radius of curvature (r_m) is the radius of the circle defining the curvature of an individual bend measured between adjacent inflection points. The arc angle (e) is the angle swept out by the radius of curvature between adjacent inflection points. The radius of curvature to width ratio (r/w) is a very useful parameter that is often used in the description and comparison of meander behavior, and in particular, bank erosion rates. The radius of curvature is dependent on the same factors as the meander wavelength and width. Meander bends generally develop a radius of curvature to width ratio (r_m/w) of 1.5 to 4.5, with the majority of bends falling in the 2 to 3 range.

2.6 Relationships among Meander Parameters

One interesting aspect of meandering rivers is the similarity in the proportion of planform characteristics. Various empirical relationships have been developed which relate the radius of curvature and meander wavelength to channel width and discharge. Brice (1984) suggested that these similarities regardless of size, account for the fact that the meandering planform is sensibly independent of scale.

Investigation by Lane (1957) and Leopold and Wolman (1957) showed that the relationships between discharge and channel slope could define thresholds for indicating which rivers tend to be braided or meandering. Rivers that are near the threshold lines may exhibit segments that transition between the two planforms. Another set of empirical relationships is related to meander geometry. Leopold et al. (1964) reported the relationship between meander wave-length (ML) and channel width (W), meander amplitude (Ms) and channel width (w), and meander wave length (ML) and radius of curvature (rm) as defined by Leopold and Wolman (1960). The relationships are:

$M_L = 10.9\ W^{1.01}$ $\qquad$ $M_B = 2.7\ W^{1.1} M_L = 4.7\ r_m^{0.98}$

All of the parameters are measured in feet. Leopold et al. (1964) stated that the exponents for the relationships are approximately unity, and these relationships can be considered linear. In that case, it can be written as;

$$r_m = 2.4\ W$$

That indicates the approximate maximum curvature for meander bends, found by Leopold and Wolman. Also, they pointed out that channel meander form is affected by the cohesiveness of the channel boundaries. Dury (1964) found that meander wavelength is related to the mean annual flood (Q_{ma}):

$$M_L = 30\ Q_{ma}^{0.5}$$

Inglis (1949) correlated the meander wavelength and meander amplitude analyzing the huge amount of field data, with the maximum discharge and the channel width as

$M_L = 6.06$ $\qquad$ $W = 29.6 Q_{max.}^{0.5}$
$M_B = 17.38$ $\qquad$ $W = 64.7$
$Q_{max.}^{0.5}$

Based on the experimental analysis in Poona laboratory (1945) it was found that;

$M_L = 36.5\ Q^{0.5}$ and $M_B = C_b Q^{0.5}$

Where, C_b = 11.5 to 17 and Q = dominant discharge or constant discharge in laboratory flume.

2.7 Review of Past Studies on River Bank Erosion

D. J. Hagerty (1991)

The author in his paper "piping/sapping erosion 1: Basic considerations" reported erosion of river banks by infiltrating seepage which is a very widespread and significant bank erosion mechanism, but is rarely recognized. Such erosion is not consistent with common theories of tractive force and can occur long after periods of high stage and in locations where deposition would be anticipated. The major cause of such unanticipated erosion is an outflow of seepage with attendant removal of soil particles in the exfiltration zone, and consequent instability of undercut strata located above the zone of soil loss. It is seen at the site that seepage flow out of a sandy layer carries sand out of the river bank, and the overlying more cohesive upper bank layer is undermined and collapsed. Such piping in river banks is most commonly noticed in alluvial soil deposits where the natural layering associated with alluvium favours concentration of flow in more pervious strata, and more cohesive layers tend to bridge over cavities, allowing conduits to form. For internal erosion to produce cavities there must be a free face or external plain from which seepage outflow can remove soil particles. The slabs or blocks of soil displaced during those failures will accumulate on the lower portions of the bank, together with the soil removed by piping directly. In order for the erosion process to continue, the accumulated failure materials must be removed. In the absence of continued river transport of the material eroded by piping away from the bank eventually reach equilibrium slopes, become vegetated, and remain stable.

Hickin and Nanson (1984)

The paper of the authors Lateral Migration Rates of River Bands' presented channel bend migration data for a range of meandering rivers in western Canada and assessment of the factors that control these rates. Channel migration rates transformed to a reference bend curvature *(r/w* =2.5) are shown to be a simple function of stream power, outer bank height, and a co-efficient of resistance to lateral migration.

The rate of channel migration (M) can be expressed by the qualitative statement:

$$M = f(C_D, Y_b, h, r, w)$$

Where, C_D = stream power per unit bed area, Y_b = the opposing force per unit boundary area resisting migration, h = bank height, r = bend radius and w = channel width.

An earlier study of the authors on the Beatton river showed that channel migration rates are strongly controlled by bend curvature. Similar data analysis was made for all the rivers taken into consideration and a curve was developed displaying the same basic form. Then the entire data set where M>o was transformed into a reference curvature ratio. The curvature ratio adopted in the study was r/w =2.5 which represents the crest of the envelope curve. It permits the relatively simple transformation of the data points on both limbs of the distribution using the follow equation:

$$M(r/w) = M25.f(r/w)$$

Where, $f(r/w) = 2/3\ (r/w - 1)$ if $1 < r/w < 2.5$

f(r/w) = 2.5 (r/w) if r/w <2.5

Klaassen and Masselink (1992)

The authors studied the bank erosion of the Jamuna River of Bangladesh and reported the findings in their paper entitled' Planform Changes of a Braided River with fine sand as a bed and bank material'. The river is a large braided sand bed river. The number of braids varies between 2 to 3 and the total width of the braided Channel pattern varies between 5 and 17 Km. The yearly erosion rates were studied based on cross-sectional data and planform data derived from LANDSAT imageries. The bank erosion rates along curved channels for four different periods were observed. Information about the average number of occurrences for the four different periods has been plotted. It shows in most of the cases erosion rate along the curved channels is between 0 and 500 m/year. The bank erosion rate might be up to 1000 m/year under exceptional conditions. With respect to the influence of vegetation on erosion rate, it was found from the study that influence of vegetation is negligible. It was also found that rotation and extension type of erosion mechanism was active in the Jamuna river. Translation type of erosion mechanism was absent because the chars and flood plain deposits exhibit hardly any cohesion. The bank erosion rates were analysed within the framework similar to the work of Nanson and Hickin (1985) for meandering rivers. The expression of bank erosion gives by Hickin and Nanson was reduced to the following assuming that Chezy coefficient and overall bank resistance coefficient don't vary along the river.

$M = f\,(\mathrm{w}, \mathrm{r/w})$

The values of the relative curvatures (r/w) for the two years were averaged. However, if one value of r/w was smaller than 5 and the other was greater than 5, then the value of the bend with the smallest relative curvature was used. This is because it was considered that this bend was most active in the eroding process. A plot of M/w versus r/w shows that low relative curvatures lead to relatively fast erosion rates and vice versa. The value of "w" used in the study corresponds to low flow width. No sharp bend was found to have smaller erosion rates, as was observed by Hickin and Nanson for meandering rivers. Another important finding from the study was large channels (w >1000m) demonstrated relatively smaller erosion rates whereas there was no significant difference in relative erosion rates between the smallest (w <500m) and the intermediate (500< w < 1000m) channels.

D. J. Hughes (1976)

The author investigated the rates of erosion around the meander arcs in relation to peak discharges, based upon the analysis of data recorded at meander locations in the river Cound catchment. Bank erosion was measured and discharge variations were monitored form January 1972 to September 1974 for a reach of the river having a length of 1 Km. Erosion rates around the eroding arcs were monitored by using 92 bank pegs and measurement of the distance from peg to channel margin was recorded at monthly intervals and more frequently during periods of high discharge. Profiles of the channel margin were measured every six months at 15 sites to show the nature of bank retreat in relation to the rates of erosion recorded at the pegs. A series of cross sections were taken at profile sites for indicating the total morphological changes of both bed and bank of the river in response to the discharges experienced. The discharge was monitored at the downstream end of the study reach.

It was seen from the study that the pattern of period rates of erosion is similar for each of the three individual arcs. The values of mean loss per site for each arc were also similar. During the study period two major peak discharges occurred.

Recorded data showed that two floods together caused the greatest amount of erosion and contributed some 52%, 78%, and 47% of total erosion recorded in three arcs studied. Thus discharge magnitude appears to represent a threshold for major channel changes along the reach of the river. Of equal importance is the discharge required for a threshold of minimum activity below which little channel change takes place. From the study, a range of discharges representing the erosion threshold for the reach as a whole was recognized and three erosional classes based on erosion rates were indicated. The discharges representing the lower erosion threshold have a long term frequency of 10 to 12 times per year whereas the discharge presenting the higher erosion threshold associated with widespread channel erosion occurs once in a period of 1.5 years.

2.8 Review of Past Studies on Sediment Transport

Sediment transport is the movement of solid particles (sediment), typically due to a combination of gravity acting on the sediment, and/or the movement of the fluid in which the sediment is entrained. Sediment transport occurs in natural systems where the particles are clastic rocks (sand, gravel, boulders, etc.), mud, or clay; the fluid is air, water, or ice; and the force of gravity acts to move the particles along the sloping surface on which they are resting. Sediment transport due to fluid motion occurs in rivers, oceans, lakes, seas, and other bodies of water due to currents and tides. Transport is also caused by glaciers as they flow, and on terrestrial surfaces under the influence of wind. Sediment transport due only to gravity can occur on sloping surfaces in general, including hill slopes, scarps, cliffs, continental shelf and the continental slope boundary.

Sediment transport is important in the fields of sedimentary geology, geomorphology, civil engineering and environmental engineering. Knowledge of sediment transport is most often used to determine whether erosion or deposition will occur, the magnitude of this erosion or deposition, and the time and distance over which it will occur.

By the sediment transport rate, also called the sediment discharge mean the mass of sedimentary material, both particulate and dissolved, that passes across a given flow-transverse cross section of a given flow in unit time. (Sometimes the sediment transport rate is expressed in terms of weight or in terms of volume rather than in terms of mass.) The flow might be a unidirectional flow in a river or a tidal current, but it might also be the net unidirectional component of a combined flow, even one that is oscillation-dominated. Only in purely oscillatory flow in which the back-and-forth phases of the flow are exactly symmetrical is there no net transport of sediment. Here we focus on the particulate sediment load of the flow, leaving aside the dissolved load, which is important in its own right but outside the scope of these physics-based notes.

Over the past hundred-plus years, much effort has been devoted to accounting for or predicting, the sediment transport rate. Numerous procedures, usually involving one or more equations or formulas, have been proposed for prediction of the sediment transport rate. These are commonly called "sediment-discharge formulas". No single formula or procedure has gained universal acceptance, and only a few have been in wide use. None of them does anywhere near a perfect job in predicting the sediment transport rate—which is understandable, given the complexity of turbulent two-phase sediment-transporting flow and the wider range of joint size–shape frequency distributions that are common in natural sediments. Prediction of the sediment transport rate is one of the most frustrating endeavors in the entire field of sediment dynamics.

2.8.1 Critical Shear Stress

The Shields diagram empirically shows how the dimensionless critical shear stress (i.e. the dimensionless shear stress required for the initiation of motion) is a function of a particular form of the particle Reynolds numbers or Reynolds number related to the particle. This allows us to rewrite the criterion for the initiation of motion in terms of only needing to solve for a specific version of the particle Reynolds numbers, which we call.

$\tau_b *= \int (Re_p *)$

This equation can then be solved by using the empirically derived Shields curve to find as a function of a specific form of the particle Reynolds number called the boundary Reynolds number. The mathematical solution of the equation was given by Dey.

2.8.2 Particle Reynolds Number

In general, a particle Reynolds Number has the form:

$$Re_p = \frac{UpD}{\vartheta}$$

$$= \frac{UpD}{\vartheta}$$

Where Up is a characteristic particle velocity, D is the grain diameter (a characteristic particle size), and $\vartheta$is the kinematic viscosity.

2.8.3 Rouse Number

The location in the flow in which a particle is entrained is determined by the Rouse number, which is determined by the density ρs and diameter d of the sediment particle, and the density ρ and kinematic viscosity ν of the fluid, determine in which part of the flow the sediment particle will be carried.

$P = w_s/\kappa\, u*$

Here, the Rouse number is given by P. The term in the numerator is the (downwards) sediment, the sediment settling velocity ws, which is discussed below. The upwards velocity on the grain is given as a product of the von Kármán constant, κ = 0.4, and the shear velocity, u∗.

The following table gives the approximate required Rouse numbers for transport as bed load, suspended load, and wash load.

Table 2.1 Rouse Number for a different mode of Transport

Sl. No.	Mode of Transport	Rouse Number
1	Initiation of motion	>7.5
2	Bed load	>2.5, <7.5
3	Suspended load: 50% Suspended	>1.2, <2.5
4	Suspended load: 100% Suspended	
5	Wash load	>0.8, <1.2

2.8.4 Settling Velocity

The settling velocity (also called the "fall velocity" or "terminal velocity") is a function of the particle Reynolds number. Generally, for small particles (laminar approximation), it can be calculated with Stokes' Law. For larger particles (turbulent particle Reynolds numbers), fall velocity is calculated with the turbulent drag law. Dietrich (1982) compiled a large amount of published data to which he empirically fit settling velocity curves. Ferguson and Church (2006) analytically combined the expressions for Stokes flow and a turbulent drag law into a single equation that works for all sizes of sediment, and successfully tested it against the data of Dietrich. Their equation is

$$w_s = Rg\, d^2/(C_1\, v + (0.75 C_2\, Rgd^3)^{0.5})$$

In this equation ws is the sediment settling velocity, g is acceleration due to gravity, and 'd' is mean sediment diameter. Is the kinematic viscosity of water, which is approximately 1.0 x 10^{-6} m^2/s for water at 20 °C.

2.9 Transport Rate

A schematic diagram of where the different types of sediment load are carried in the flow. Dissolved load is not sediment: it is composed of disassociated ions moving along with the flow. It may, however, constitute a significant proportion (often several persents, but occasionally greater than half) of the total amount of material being transported by the stream.

Formulas to calculate sediment transport rate exist for sediment moving in several different parts of the flow. These formulas are often segregated into bed load, suspended load, and wash load. They may sometimes also be segregated into bed material load and wash load.

2.9.1 Bed Load

Bed load moves by rolling, sliding, and hopping (or saltating) over the bed, and moves at a small fraction of the fluid flow velocity. Bed load is generally thought to constitute 5-10% of the total sediment load in a stream, making it less important in terms of mass balance. However, the bed material load (the bed load plus the portion of the suspended load which comprises material derived from the bed) is often dominated by bed load, especially in gravel-bed Rivers. This bed material load is the only part of the sediment load that actively interacts with the bed. As the bed load is an important component of that, it plays a major role in controlling the morphology of the channel.

The majority of the published relations for bed load transport are given in dry sediment weight per unit channel width. Due to the difficulty of estimating bed load transport rates, these equations are typically only suitable for the situations for which they were designed. Some Notable bed load transport formulae are discussed here.

Meyer-Peter Muller and Derivatives

The transport formula of Meyer-Peter and Müller, originally developed in 1948, was designed for well sorted fine gravel at a transport stage of about 8. The formula uses the above non-dimensional form for shear stress,

$$\tau_* = \tau/((\rho-\rho_s)gd))$$

and Hans Einstein's non-dimensional formula for sediment volumetric discharge per unit width

$$q_{s*} = q_s/(d\ ((\rho-\rho s)gd/\rho)^{0.5}) = q_s/(Re_p\ \nu)$$

Their formula reads:

$$q_{s*}=8\ (\tau^*-0.047)^{3/2}$$

Their experimentally determined value for τ_{*c} is 0.047, and is the third commonly used value for this (in addition to Parker's 0.03 and Shields' 0.06).

Because of its broad use, some revisions to the formula have taken place over the years that show that the coefficient on the left ("8" above) is a function of the transport stage:

$$Ts \approx 2 \rightarrow q_{s*} = 5.7(\tau^*-0.047)^{3/2}$$

$$Ts \approx 100 \rightarrow q_{s*} = 12.1(\tau^*-0.047)^{3/2}$$

The variations in the coefficient were later generalized as a function of dimensionless shear stress:

$$q_{s*} = \alpha_s\ (\tau_*-\tau_{c*})^n \text{ where, } n=3/2,\ \alpha_s=1.6\ \ln(\tau_*)+9.8 \approx 9.64\tau_*^{0.166}$$

Wilcock and Crowe

In 2003, Peter Wilcock and Joanna Crowe (now Joanna Curran) published a sediment transport formula that works with multiple grain sizes across the sand and gravel range. Their formula works with surface grain size distributions, as opposed to older models which use subsurface grain size distributions (and thereby implicitly infer a surface grain sorting).

Their expression is more complicated than the basic sediment transport rules (such as that of Meyer-Peter and Müller) because it takes into account multiple grain sizes: this requires consideration of reference shear stresses for each grain size, the fraction of the total sediment supply that falls into each grain size class, and a "hiding function".

The "hiding function" takes into account the fact that, while small grains are inherently more mobile than large grains, on a mixed-grain-size bed, they may be trapped in deep pockets between large grains. Likewise, a large grain on a bed of small particles will be stuck in a much smaller pocket than if it were on a bed of grains of the same size. In gravel-bed rivers, this can cause "equal mobility", in which small grains can move just as easily as large ones. As sand is added to the system, it moves away from the "equal mobility" portion of the hiding function to one in which grain size again matters.

Their model is based on the transport stage, or ratio of bed shear stress to critical shear stress for the initiation of grain motion. Because their formula works with several grain sizes simultaneously, they define the critical shear stress for each grain size class, $\tau_{ci}\ d_i$, to be equal to a "reference shear stress", τri.

They express their equations in terms of a dimensionless transport parameter, W_{i*} (with the "*" indicating non-dimensionality and the "i" indicating that it is a function of grain size):

$$W_{i*} = Rgq_{bi} / F_i\ u_*^3$$

q_{bi} is the volumetric bed load transport rate of size class i per unit channel width b. F_i is the proportion of size class i that is present on the bed.

They came up with two equations, depending on the transport stage, Ø. For Ø<1.35:

$$W_{i*} = 0.002\text{Ø}^{7.5}$$

and for Ø≥1.35:

$$W_{i*} = 14\ (1 - (0.894/\text{Ø}^{0.5}))^{4.5}$$

This equation asymptotically reaches a constant value of W_{i*} as Ø becomes large.

Wilcock and Kenworthy

In 2002, Peter Wilcock and Kenworthy T.A. , following Peter Wilcock (1998), published a sediment bed-load transport formula that works with only two sediments fractions, i.e. sand and gravel fractions. Peter Wilcock and Kenworthy T.A. in their article recognized that a mixed-sized sediment bed-load transport model using only two fractions offers practical advantages in terms of both computational and conceptual modeling by taking into account the nonlinear effects of sand presence in gravel beds on bed-load transport rate of both fractions. In fact, in the two-fraction bed load formula appears a new ingredient with respect to that of Meyer-Peter and Müller that is the proportion F_i of fraction i on the bed surface where the subscript i represents either the sand (s) or gravel (g) fraction. The proportion F_i, as a function of sand content fs, physically represents the relative influence of the mechanisms controlling sand and gravel transport, associated with the change from a clast-supported to matrix-supported gravel bed. Moreover, since fs spans between 0 and 1, phenomena that vary with fs include the relative size effects producing ''hiding'' of fine grains and ''exposure'' of coarse grains. The ''hiding'' effect takes into account the fact that, while small grains are inherently more mobile than large grains, on a mixed-grain-size bed, they may be trapped in deep pockets between large grains. Likewise, a large grain on a bed of small particles will be stuck in a much smaller pocket than if it were on a bed of grains of the same size, which the Meyer-Peter and Müller formula refers to. In gravel-bed rivers, this can cause ''equal mobility", in which small grains can move just as easily as large ones. As sand is added to the system, it moves away from the ''equal mobility'' portion of the hiding function to one in which grain size again matters.

Their model is based on the transport stage,i.e.$\emptyset$, or ratio of bed shear stress to critical shear stress for the initiation of grain motion. Because their formula works with only two fractions simultaneously, they define the critical shear stress for each of the two grain size classes, τ_{ri}, where i represent either the sand (s) or gravel (g) fraction. The critical shear stress that represents the incipient motion for each of the two fractions is consistent with established values in the limit of pure sand and gravel beds and shows a sharp change with increasing sand content over the transition from a clast- to matrix-supported bed.

They express their equations in terms of a dimensionless transport parameter, W_{i*} (with the " *" indicating non-dimensionality and the ''i'' indicating that it is a function of grain size):

$$W_{i*} = Rgq_{bi}/F_i u_*^3$$

q_{bi} is the volumetric bed load transport rate of size class i per unit channel width b . F_i is the proportion of size class i that is present on the bed.

They came up with two equations, depending on the transport stage, $\emptyset$. For $\emptyset < \emptyset'$:

$$W_{i*} = 0.002\emptyset^{7.5}$$

and for $\emptyset \geq \emptyset'$:

$$W_{i*} = A\,(1- (X/\emptyset^{0.5}))^{4.5}$$

This equation asymptotically reaches a constant value of W_{i*} as $\emptyset$ becomes large and the symbols A, $\emptyset'$, X have the following values:

A=70, $\emptyset'$=1.19, X=0.908, laboratory

A=115, $\emptyset'$=1.27, X=0.923, field

In order to apply the above formulation, it is necessary to specify the characteristic grain sizes d_S for the sand portion and d_g for the gravel portion of the surface layer, the fractions Fs and Fg of sand and gravel, respectively in the surface layer, the submerged specific gravity of the sediment R and shear velocity associated with skin friction u_*.

Kuhnle et al.

For the case in which sand fraction is transported by the current over and through an immobile gravel bed, Kuhnle et al.(2013), following the theoretical analysis done by Pellachini (2011), provides a new relationship for the bed load transport of the sand fraction when gravel particles remain at rest. It is worth mentioning that Kuhnle et al. (2013) applied the Wilcock and Kenworthy (2002) formula to their experimental data and found out that predicted bed load rates of sand fraction were about 10 times greater than measured and approached 1 as the sand elevation became near the top of the gravel layer. They, also, hypothesized that the mismatch between predicted and measured sand bed load rates is due to the fact that the bed shear stress used for the Wilcock and Kenworthy (2002) formula was larger than that available for transport within the gravel bed because of the sheltering effect of the gravel particles. To overcome this mismatch, following Pellachini (2011), they assumed that the variability of the bed shear stress available for the sand to be transported by the current would be some function of the so-called "Roughness Geometry Function" (RGF), which represents the gravel bed elevations distribution. Therefore, the sand bed load formula follows as:

$$q_{s*} = 2.29\times10^{-5} A (z_s)^{2.14} (\tau_b/\tau_{cs})^{3.49}$$

where

$$q_{s*} = q_s/[\{(s-1)gd_s\}^{0.5} \rho_s d_s]$$

the subscript s refers to the sand fraction, s represents the ratio ρ_s/ρ_w where ρ_s is the sand fraction density, $A(z_s)$ is the RGF as a function of the sand level z_s within the gravel bed, τ_b is the bed shear stress available for sand transport and τ_{cs} is the critical shear stress for incipient motion of the sand fraction, which was calculated graphically using the updated Shields-type relation of Miller et al.(1977).

2.9.2 Suspended Load

The suspended load is carried in the lower to middle parts of the flow, and moves at a large fraction of the mean flow velocity in the stream. A common characterization of suspended sediment concentration in a flow is given by the Rouse Profile. This characterization works for the situation in which sediment concentration at one particular elevation above the bed z_0 can be quantified. It is given by the expression:

$$\frac{c_s}{c_0} = [\frac{z(h-z_0)}{z_0(h-z)}]^{-\frac{P}{\alpha}}$$

Here, z is the elevation above the bed, c_s is the concentration of suspended sediment at that elevation, h is the flow depth, P is the Rouse number, and α relates the eddy viscosity for momentum K_m to the eddy diffusivity for sediment, which is approximately equal to one.

Experimental work has shown that α ranges from 0.93 to 1.10 for sands and silts.

The Rouse profile characterizes sediment concentrations because the Rouse number includes both turbulent mixing and settling under the weight of the particles. Turbulent mixing results in the net motion of particles from regions of high concentrations to low concentrations. Because particles settle downward, for all cases where the particles are not neutrally buoyant or sufficiently light that this settling velocity is negligible, there is a net negative concentration gradient as one goes upward in the flow. The Rouse Profile therefore, gives the concentration profile that provides a balance between turbulent mixing (net upwards) of sediment and the downwards settling velocity of each particle.

2.9.3 Bed Material Load

Bed material load comprises the bed load and the portion of the suspended load that is sourced from the bed. Three common bed material transport relations are the "Ackers-

White", "Engelund-Hansen", "Yang" formulae. The first is for sand to granule-size gravel, and the second and third are for sand though Yang later expanded his formula to include fine gravel. That all of these formulae cover the sand-size range and two of them are exclusively for sand is that the sediment in sand-bed rivers is commonly moved simultaneously as bed and suspended load.

Engelund-Hansen

The bed material load formula of Engelund and Hansen is the only one to not include some kind of critical value for the initiation of sediment transport. It reads:

$$q_s *= \frac{0.05}{c_f} \tau *^{2.5}$$

where $q_s *$ is the Einstein non dimensionalization for sediment volumetric discharge per unit width, c_f is a friction factor, and τ^* is the Shields stress. The Engelund-Hansen formula is one of the few sediment transport formulae in which a threshold "critical shear stress" is absent.

2.10 Agriculture and Fisheries

U Habiba, R Shaw, Y Takeuchi (2012) studied Farmer's Perception and Adaptation Practices to cope with Drought Perspectives from North-western Bangladesh. Under this study, Rajshahi and Chapai Nawabganj districts were considered with a view to finding out the farmer's problems in adapting agricultural practices to cope with the droughts. In which, only the groundwater depletion in Nachole upazilla of Chapai Nawabganj district was analyzed with respect to irrigated area.

IWM, 2015 investigated scope of irrigation along the bank of Mahananda River by storing water in the river during the dry season and assessed related environmental impact in Chapai Nawabgonj district. Mahananda River system comprises of the Mahananda River itself with its two tributaries Punarvaba and Pagla. Mahananda River is also a tributary of the Ganges. The study reveals that in dry season, the tributaries have a little contribution to the perennial flow of water to Mahananda River especially in the dry months of March-April. The Mahananda River dependent area falls within the Barind tract and Ganges floodplain. The lands of both sides of the Mahananda River are mostly cultivated by irrigation through LLP although the topography of the area is not favorable for gravity irrigation. The farmers by their own developed irrigation management system are presently running 43 irrigation schemes along the both banks of the Mahananda River. They are growing mostly Rabi season crops of which Boro crop is the dominant one. The farmers are facing a shortage of irrigation water during February, March and April because the river gradually gets dry in these months.

The area has low groundwater potential compared to other parts of the north-west region. Mahananda is the only perennial river of the area, but its flow is gradually decreasing over the last several years. In the past, farmers of the locality used to use surface water of Mahananda for irrigation. Reduced dry season flow of Mahananda has created stress on irrigation development as well as on groundwater of the area. The groundwater irrigation in the barind area faces problem during peak demand due to a decline in the groundwater table.

Existence of only limited thick potential aquifer sandwiched between thick clay layers at top and bottom in places in high barind area within the depth of 80m is a problem for cultivation for a large area (IWM, 2012).

ABM Mohsin and Emdadul Haque (2009) carried out a study titled "Diversity of Fishes of Mahananda river at Chapai Nawabganj district." They reported 56 fish species and 19 endangered fish species were found in Mahananda river among 54 IUCN declared list of endangered fish. They reported 56 species were found in Mahananda river. A list of fish species found in Mahananda river was prepared.

Islam, M.S and M.A. Hossain (1983) recorded 110 species of fishes from the river Ganges near Rajshahi. Mortuza, M.G (1982) recorded 126 fish and 13 species of fisheries items from the Barmi project area. From the abovementioned study, no comparison of species available in Mahananda was done that was available 200 years ago. The comparison will indicate a clear picture of the destruction of fish species in the Mahananda river.

At present, fish diversity of Bangladesh is facing a very critical stage. From 1960 to till now, there are massive changes occurred as declining fish production, as well as species diversity notably in open water. Therefore, it is utmost urgent to take suitable steps to protect fish fauna of Bangladeshi river. This objective will bring out the destruction, in danger and out of danger of fish species and fish like species in the river Mahananda. The study will also be able to find out the causes of that.

2.11 Water Quality and Groundwater

Albert Tuinhof, Karin Kemper (2011), studied entitled "Mitigation of Arsenic contamination in Drinking Water Supplies of Bangladesh." In this study, the severity of arsenic contamination in groundwater at Chapai Nawabgonj town was investigated thoroughly and a scheme was designed how to supply arsenic free water to the people lives in the town.

UNDP-BWDB, 1982 investigated the hydrogeological conditions of Bangladesh. During this study, countrywide general groundwater survey has been carried out. According to the report Chapai Nawabganj has limited thick sandy aquifer especially in the high Barind area and transmissibility-value ranges $500m^2$/day to $1500m^2$/day. Annual recharge varied from a minimum of 80 mm to a maximum of 190 mm. The limitation of the study is that it was based on limited data for generalized appraisal of the hydrogeological condition of the country.

Mac Donald, 1983 described brief geological description, infiltration rate, permeability range, storage range, water level fluctuations and development potential of the study area. The study was based on data analysis and water balance study. The study area consists of mainly three aquifer units namely Shibganj of 1200 sq km, High Barind Area of 3634 sq km and Little Jamuna of 980 sq km. Aquifer at Shibganj has been classified as semi-confined. Infiltration rate is 1.7 mm/day in wetland and 12 mm/day in a dry land. Permeability ranges from 30 to 60 m/day with an average of 40 m/day. Specific yield of the upper layer is 6%. At high barind area, the aquifer has been classified as semi-confined and multi-layered. Infiltration rate is 1.5 mm/day in wetland and 7.5mm/day in a dry land. Permeability ranges from 25 to 40 m/day with an average of 30 m/day. Specific yield of upper layer is approximately 4%. Semi-confined, most water derived from leakage.

IWM, 2006 studied the overall water resources of the study area for efficient planning and management of the resources for deep tubewell installation. For the assessment and future development of groundwater resources, an integrated hydrological model has been developed describing the condition in the unsaturated and saturated zone of the subsurface together with rainfall, overland flow, evapotranspiration and the condition of flow in the river. The major findings of the study are:

The sources of groundwater recharge in the study area are mainly rainfall; floodwater and return flow of irrigated water. Generally, recharge from rainfall starts in the month of May and continues to the end of October. In low Barind area, there are lots of depressions, where excess rainwater is stored during monsoon. This water is available as vertical recharge for recharging groundwater after meeting the demand of evapotranspiration after October. Thick clay layer at the top in some parts of the study area restricts the percolation of rain and floodwaters. Geological structures up to 80 m depth have been studied.

Maximum depth to groundwater table occurs at the end of April mainly due to irrigation abstraction and natural drainage. In case of average year rainfall condition, this maximum depth to groundwater table remains in the range between 2.0 m to 15.0 m in most of the study area. Some of the places in high Barind areas go below 20.0 m depth. Suction mode tubewells will not operate in these areas where, groundwater table remains below 7.0 m.

It has also been observed that during peak time, groundwater table almost regains to its original positions except for some areas of some Upazilas. This indicates that aquifers in those locations have the potential of groundwater recharge and further scope for development. However, groundwater table does not regain to its original positions in some areas of Tanore, Dhamoirhat, Godagari, Gomastapur, Patnitala, Mahadevpur, Niamatpur and Nachole Upazilas. This is mainly due to substantial use of groundwater in the monsoon period and over drainage in the vicinity of the Ganges and Mahananda river during the dry period. In these areas, recharge is less compared to the total abstractions and drainage.

The potential recharge of the present study varies from 357 mm to 725 mm. In the present study, total potential recharge in the project area is 13156 mm, while in the MPO study it is 10002 mm and in the NWMP study, it is 11855 mm. Potential recharge of IWM study is 10% higher than NWMP study and 24.1% higher than the MPO study. Potential recharge of this study is mainly higher in low Barind area compared to NWMP and MPO study. The variation of results is due to variation in approaches and parameters used. IWM considered entire physical processes that exist in the hydrological cycle using distributed modelling approach.

Useable recharge for Barind area has been estimated to a total of 9867 mm, while 7623 mm net irrigation requirement for Boro cultivation has been estimated in this area. The study confirms that in the Barind area, the total useable recharge is higher than total net irrigation requirement for Boro cultivation. However, Upazila wise comparison shows resource constraints for only Boro cultivation in Dhamoir hat, Mohadebpur and Tanore Upazilas. In addition to these three Upazilas, resource constraints are also observed in Niamatpur and Patnitala Upazilas, if supplementary irrigation from groundwater is considered. In addition to the existing tubewell, total 6533 numbers of 1-cusec capacity of DTW (80% efficiency) can be installed in different Upazilas.

Estimation of spacing between two tubewells depends on recharge conditions, command area of the tubewell, crop water demand and hydraulic properties of the aquifer. Upazila wise spacing of different capacity of tubewells have been estimated and it can be seen that the spacing of 2 cfs to 2 cfs tubewell varies from 446 m to 628 m, 2 cfs to 0.5 cfs varies from 317 m to 447 m and 0.5 cfs to 0.5 cfs varies from 203 m to 266 m in Barind area.

The study also suggested that surface water development is possible during dry period using abstraction from the Mohananda Rivers as water resources are available in the rivers. It is observed that in March, about 460 nos of LLP can be operated in the adjacent area of Atrai river up to Atrai Railway Bridge and 3880 nos of LLP can be operated in the adjacent area of Mahananda river up to Chapai Nawabganj by the construction of rubber dam.

Shahid and Hazarika, 2010 studied groundwater scarcity and drought in Rajshahi, Naogaon and Chapai Nawabganj districts. According to the study, upper aquifers in the region are unconfined or semi-confined in nature. The thickness of the exploitable aquifer ranges from 10 to 40 m. The specific yield of the aquifer in the area varies from 8 to 32% with a general decreasing trend. The maximum depth to groundwater table from a land surface varies from 7 to 30 m. Most of the shallow tube-wells which are widely used for irrigation in the area go below the suction lift capacity in the peak irrigation period. The study shows that groundwater scarcity in 42% area is an annual phenomenon in the region. Groundwater drought in this region has a direct relation with meteorological drought. If there is no severe anthropogenic intervention in the groundwater system, the cause of groundwater droughts is mainly the deficiency in precipitation. The study shows that up to the year of 1995 groundwater level follows the general relation with rainfall deficit or excess as it is the main source of groundwater replenishment in the region. Severe drought in 1994-1995 and overexploitation of groundwater for irrigation after 1995 have caused the groundwater level recedes deeper in the consecutive years. Insufficient field information to quantify the recharge and non-consideration of groundwater level based pumping management has caused over-exploitation of groundwater. Though it has been found that in some cases the aquifers replenish fully during monsoon, a large scale abstraction of groundwater has lowered the groundwater table in the dry season which has made the exploitation of groundwater costly for irrigation in the area. Water scarcity is caused by an imbalance between water supply and demand. Groundwater drought in the study area is caused both by the reduction of supply and increase of demand. Demands of groundwater have been increased due to the extension of agricultural lands and cropping intensities. Huge withdrawal of water in the international rivers in dry season and recurrent occurrence of droughts have reduced the supply of surface water as well as made the people more dependent on groundwater for irrigation. Recurrent droughts, the rapid expansion of groundwater based irrigation projects and cross-boundary anthropogenic interventions are the main causes of groundwater droughts in the northwestern districts of Bangladesh. As groundwater declination is not only due to a deficit of rainfall but also due to over-exploitation of groundwater resources, it can be concluded that groundwater droughts in the area are mainly human-induced droughts which is better to term as groundwater scarcity. Development of surface water resources for irrigation is essential to reduce growing pressure on groundwater table.

Groundwater hydrographs and rainfall time-series reveal that ever-increasing groundwater extraction for irrigation in the dry season and recurrent droughts are the causes of groundwater level drop in the region (left bank of Mahananda River- especially in high barind areas such as Tanore) (Shahid and Hazarika, 2010).

The operation of a few thousands of deep tubewells (DTWs) for irrigation during dry periods creates problems for the operation of shallow tubewells, hand tubewells and dug wells (Akram et al., 2012). It is anticipated that if surface water availability could be increased, surface water irrigation area could be increased.

Surface water and groundwater are not isolated components of the hydrologic cycle. Instead, all surface water bodies are often hydraulically connected to groundwater and the interaction between them affects both their quantity and quality (Spanoudaki et al., 2010). The application of surface water for irrigation in the area is expected to minimize the stress on groundwater. The utilization of surface water for irrigation to the area from the Mohananda River will also augment groundwater recharge in the area.

3 DATA AND METHODS

3.1 Morphological Data

Satellite images of 1989, 1995, 2001 and 2015 have been collected from CEGIS, Dhaka. These data have been analyzed to know the extent of river bank shifting. Also, Google Earth images are being analyzed to come in focus of the sinuosity and meander parameters of the river Mahananda.

3.2 Hydrological and Geo-hydrological Data

Historical discharge, water level, rainfall, and groundwater level data have been collected from BWDB. These data have been analyzed through by spreadsheet analysis.

3.2.1 Discharge

There is only one discharge measurement station (SW 211.5) at Chapai Nawabgnaj on Mohananda River where BWDB measures discharge on a regular basis which is the only source of historicallly measured discharge in Mohananda. The discharge data was collected for the years 1981 to 2017.

3.2.2 Water Level

In the study area, BWDB is the only source of historical water level data. Station Chapai Nawabganj is located on Mohananda river and Rohanpur is located on Punarbhova river. Water level data have been collected from both of these stations. Another station Hardinge Bridge is located on Ganges-Padma river has also been collected. List of water level stations is given in the table below.

Table 3.1 Water level Stations

Sl No.	Data type	River name	Station ID	Station name	Data source
1	Non tidal water level	Ganges-Padma	SW90	Hardinge Bridge	BWDB
2	Non tidal water level	Mahananda	SW211.5	Chapai Nawabganj	BWDB
3	Non tidal water level	Punarbhaba	SW238	Rohanpur	BWDB

3.2.3 Rainfall

BWDB maintains 6 rainfall stations in and around the study area. Rainfall data for the period of 1980-2015 of the 6 stations have been collected from BWDB. List of these stations is given in the table below.

Table 3.2 Rainfall Stations

Sl No.	Data type	Station name	Station ID	Data source
1	Rainfall	Bholahat	CL158	BWDB
2	Rainfall	Godagari	CL172	BWDB
3	Rainfall	Nachole	CL190	BWDB
4	Rainfall	Chapai-Nawabganj	CL195	BWDB
5	Rainfall	Rohanpur	CL208	BWDB
6	Rainfall	Shibganj (Rajshahi)	CL215	BWDB

3.2.4 Groundwater Level

There are a number of BWDB groundwater monitoring wells located in the study area out of which 12 nos. is listed in Table 3.3. Groundwater level data of these wells for the period of 2001 to 2015 have been collected and processed for trend analysis.

Table 3.3 Ground Water Level Stations

Sl No.	Data type	Station name	Well ID	Data source
1	Groundwater level	Nawabganj	GT7066013	BWDB
2	Groundwater level	Nawabganj	GT7066014	BWDB
3	Groundwater level	Nawabganj	GT7066016	BWDB
4	Groundwater level	Nawabganj	GT7066018	BWDB
5	Groundwater level	Godagari	GT7066018	BWDB
6	Groundwater level	Godagari	GT7066019	BWDB
7	Groundwater level	Godagari	GT7066022	BWDB
8	Groundwater level	Godagari	GT7066028	BWDB
9	Groundwater level	Paba	GT8172035	BWDB
10	Groundwater level	Paba	GT8172036	BWDB
11	Groundwater level	Paba	GT8172038	BWDB
12	Groundwater level	Paba	GT8172040	BWDB

3.3 Historical Cross-section Data

In the study area, BWDB is the only source of historical cross-section data. There are 12 cross-section stations along the total reach of Mahananda river. Cross section data of 2001 to 2015 have been collected, processed and analyzed for understanding the river geometry. List of these stations is given in the table below.

Table 3.4 Historical River cross-sections ID

Sl No.	Data type	Cross section ID	Data source
1	River cross section	RMMA1	BWDB
2	River cross section	RMMA2	BWDB
3	River cross section	RMMA3	BWDB
4	River cross section	RMMA4	BWDB
5	River cross section	RMMA5	BWDB
6	River cross section	RMMA6	BWDB
7	River cross section	RMMA7	BWDB

8	River cross section	RMMA8	BWDB
9	River cross section	RMMA9	BWDB
10	River cross section	RMMA10	BWDB
11	River cross section	RMMA11	BWDB
12	River cross section	RMMA12	BWDB

3.4 Real Survey Data

3.4.1 River Cross-section

Cross-section survey of about 75 km of Mahananda river has done by Globe Survey Company, Dhaka. The data of total 153 cross-sections have been analyzed to know the present channel geometry.

3.4.2 River Bed and Bank Material

223 of the river bed and bank material samples were collected during cross-section survey of about 75 km reach of Mahananda river. These samples have been tested in the Sediment Laboratory of RRI, Faridpur. The soil particle information of Mahananda River is shown in the table below.

Table 3.5 Soil particles Information of Mahananda River

Particle size D_{50} (mm)	Position from where samples collected	Barui Para to Gomastapur (Reach-1)	Gomastapur to Diabetic Hospital (Reach-2)	Diabetic Hospital to Sultanganj (Reach-3)
Range	Total Reach	0.02996-0.19354	0.00995-0.26847	0.00595-0.31538
Average D_{50}	LB	0.04132	0.074163	
	RB	0.03019	0.053697	
	Centre/River bed	0.313377	0.075661	

3.4.3 Environmental Data

The environmental study was carried out based on In-situ Investigation. In-situ water quality parameters which were measured in situ conditions are as follows:

- Dissolve oxygen (DO)
- pH
- Total Dissolve Solid (TDS)
- Electrical conductivity (EC)

Arsenic and Manganese test was conducted in the month of June, 2017 for both river and groundwater. For arsenic testing, Hach 2822800 Arsenic Ez Dual Range Test Strips and EZ Arsenic Reagent Set was used. And for manganese test, HACH DR 2800 Spectrophotometer with required reagent was used.

Dissolve oxygen (DO), pH, Total Dissolve Solid (TDS), Electrical conductivity (EC), were measured in situ conditions in month of February, 2017 for river water. To assess the value of water quality parameters HACH HQ30d Digital Single input Multi-parameter Meter was used.

In-situ water quality parameters were compared with several standard levels set by different organizations like World Health Organization (WHO), Department of Environment (DoE), Food and Agricultural Organization (FAO) and Canadian Council of Ministers of the Environment (CCME). These standard values were fixed up for drinking, irrigation and aquatic life purposes. The following table represents the value of standard water quality parameters set by different organizations:

Table 3.6 Guideline value for heavy metals set by different organizations for Drinking water, Irrigation water and Aquatic life Purposes

Parameter	Drinking water		FAO (1994) Irrigation water
	WHO (2011)	DoE (ECR,1997)	
Arsenic	0.01 mg/l	0.05 mg/l	0.10 mg/l
Manganese	0.10 mg/l	0.10 mg/l	0.01 mg/l

Table 3.7 The standard water quality value set by different organizations for different purposes

Parameter	For Drinking water		For Irrigation water FAO (1994)	For Aquatic Life CCME (2007)
	WHO (2011)	DoE (ECR, 1997)		
Dissolve Oxygen (DO)	-	6 mg/l, *5mg/l or above	-	6.0–9.5 mg/l
pH	6.5–8.5	6.5–8.5	8.5	6.5–9.0
Total Dissolve Solid (TDS)	-	1000 mg/l	2000 mg/l	-
Electrical Conductivity (EC)	-	-	3000 μs/cm	-

*5mg/l or above = For Aquaculture and Irrigation

* EC=2250 μS/cm for Irrigation DoE (ECR, 1997

3.4.4 Socio-economic Data

Questionnaire surveys have been done from 230 respondents in the river bank area. In this study, simple random sampling method was used. The study was done on the basis of data collection through questionnaire survey, observation and discussion with limited participation of the people of the study area. Sample of respondents was selected from the river bank community randomly both male and female and they were interviewed through a structured questionnaire. A structured Questionnaire has prepared including causes of pollution, availability of fish, health hazards, use of river water and crop production etc.

3.5 Methods of Analysing Data

This study has been carried out by a team consisting of RRI officials/ scientists. Each of the team members has been given with specific responsibility for the smooth accomplishment of study works within the scheduled time. The Coordinator has been responsible for organizing the team members, holding meetings regularly and review the progress. He has decided about any adjustment in the future course of actions in consultation with other team members. On the other hand, the chief investigator has been responsible for technical aspects of the study including taking appropriate steps for collecting all necessary data and processing and analysis of the collected data. The chief investigator has been responsible for report writing, reviewing and editing the report to ensure technical quality and he has also guided the other team members.

This investigation has done based on the data collected from different sources and necessary questionnaire survey from the fields. Planform analysis has been carried out with available time series satellite imageries using appropriate tools. The cross-sectional geometry of the river and its evolution with time has been determined by analyzing the present and historical cross-sections. Historical discharge and water level data have been analyzed to identify the trend of change of hydrology of river and catchment. Probable discharges and water levels have been determined by flood frequency analysis using appropriate methods. Planform parameters have been determined from high resolution (5m) time series satellite images and interrelationships among planform parameters have been established in space and time. Stakeholder consultations were limited to Upazila government officials concerned, local Union Parishad chairmen and members and village people. The methods of stakeholder consultation were meeting and individual interview. Moreover, a questionnaire survey was carried out in 2017 to establish the present socio-economic and environmental status of the study area.

4 RESULTS AND DISCUSSIONS

This chapter describes the results of hydrological and morphological analysis, Planform and river geometry, sediment load (sediment transport capacity) of Mahananda river, environmental and socio-economic analysis. This chapter also describes the relationship among different hydro-morphological parameters of Mahananda river.

4.1 Hydrological Analysis

4.1.1 Discharge

There is one discharge measurement station (SW211.5) at Chapai Nawabgnaj on Mahananda river where BWDB measures discharge on a regular basis which is the only source of historically measured discharge in Mahananda. The collected discharge data was analyzed in a different way. Decade wary monthly average discharge plots show the decreasing tendency of peak values, which is shown in Figure 4.1.

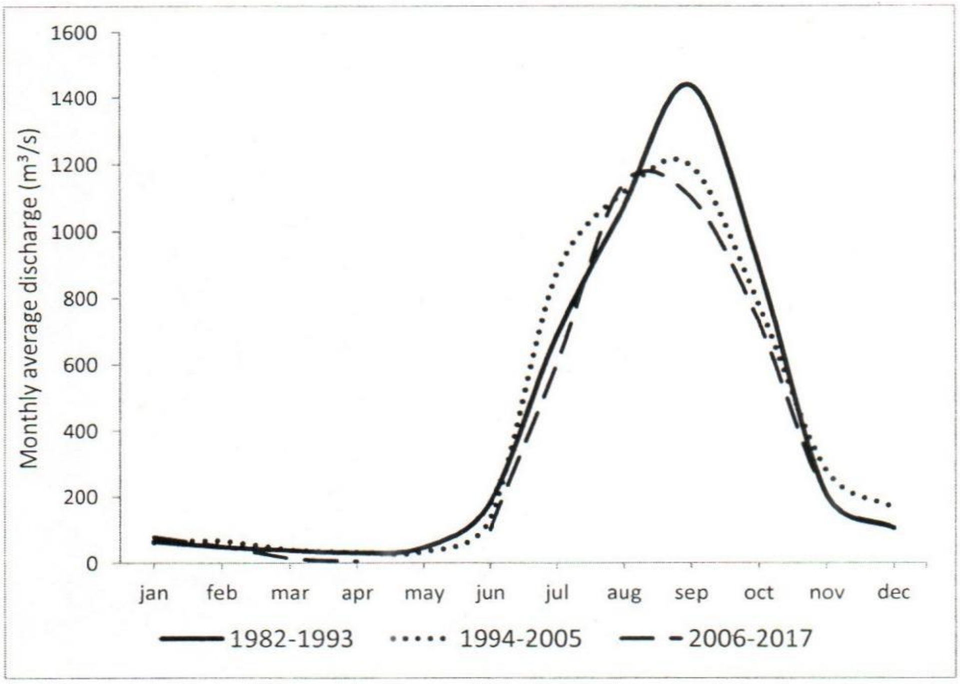

Figure 4.1: Decade wise monthly average discharge Mahananda River

The trend of historical discharge shows the maximum values gradually decreases and minimum values gradually increases but insignificant, which are shown in Figure 4.1 and Figure 4.2.

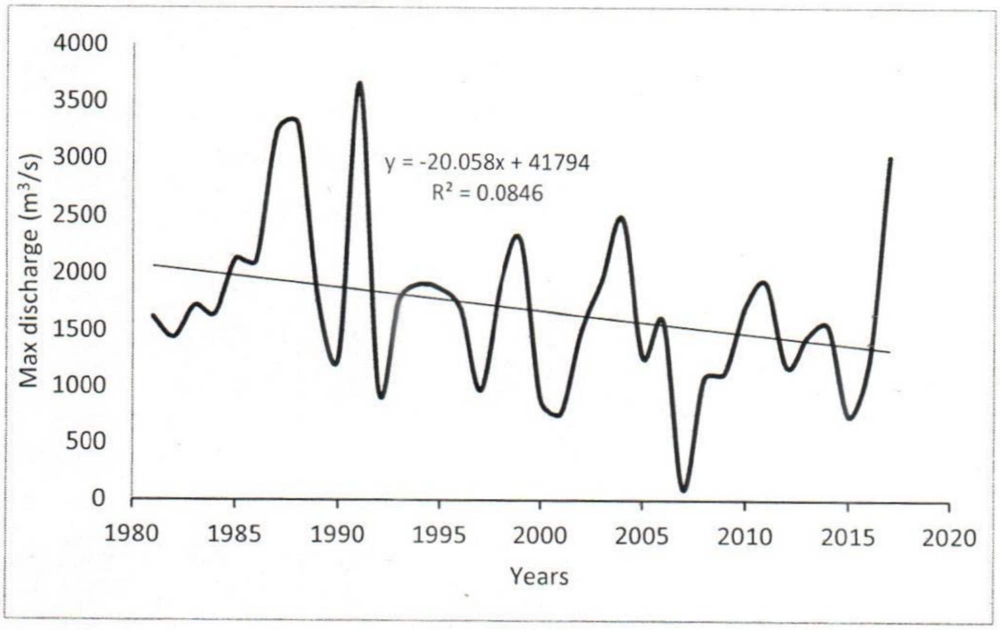

Figure 4.2: Trend of historical discharge (Maximum)

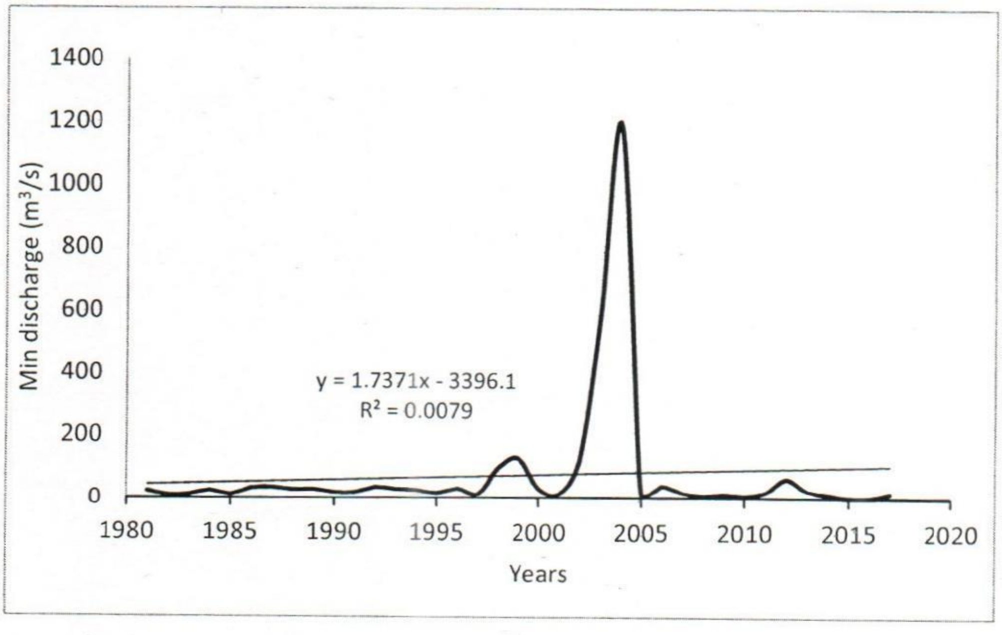

Figure 4.3: Trend of historical discharge (Minimum)

Frequency analysis has done to know the long term flow situation of the river by EVI and GEV method. shows the Maximum and Minimum discharge in the different return period.

Table 4.1 Frequency analysis (discharge) of Mahananda river

Return period (years)	Maximum discharge (m^3/s)	
	EVI	GEV
10	2734	2732
15	2993	2974
25	3315	3267
50	3746	3650
100	4173	4018

It is seen from frequency analysis that the discharge in both cases increases. But the minimum flow is not more than the minimum flow required for flora and fauna.

4.1.2 Surface Water Level

In the study area, BWDB is the only source of historical water level data. Station Chapai Nawabganj is located on Mahananda river, Rohanpur is located on Punarbhova river and Hardinge bridge is located on Ganges river. Water level data has been collected from such of these stations. Plots of water level at Chapai Nawabganj station show that over the last decade there is a decreasing trend of water levels in the Mahananda which are shown in Figure 4.4 and Figure 4.5.

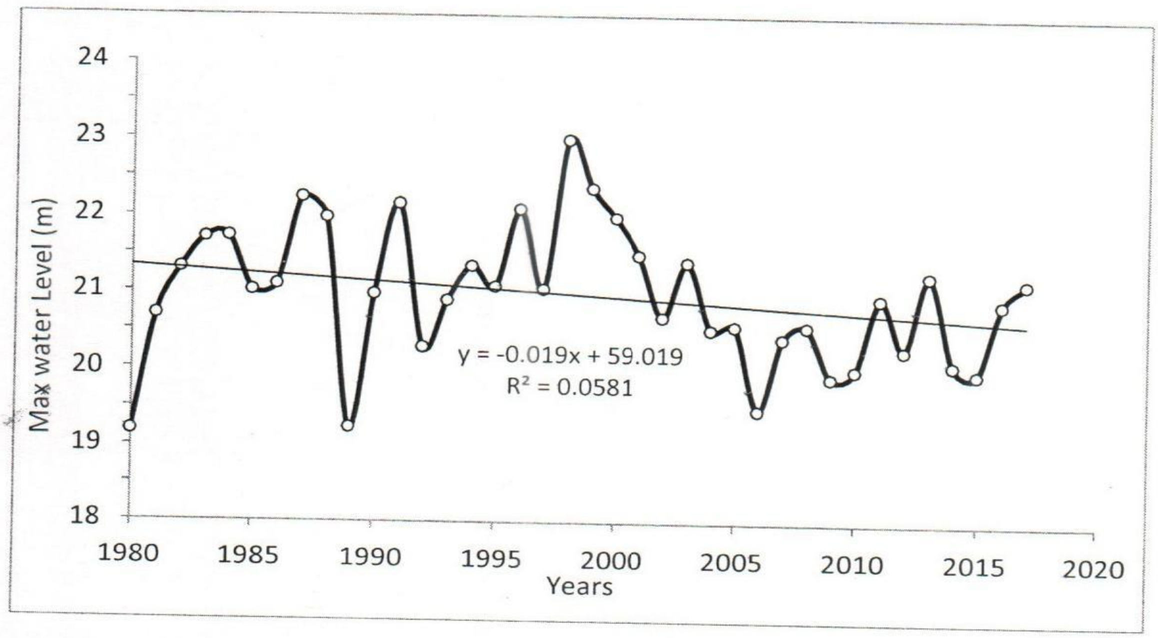

Figure 4.4: Trend of historical water level (maximum) of Mahananda

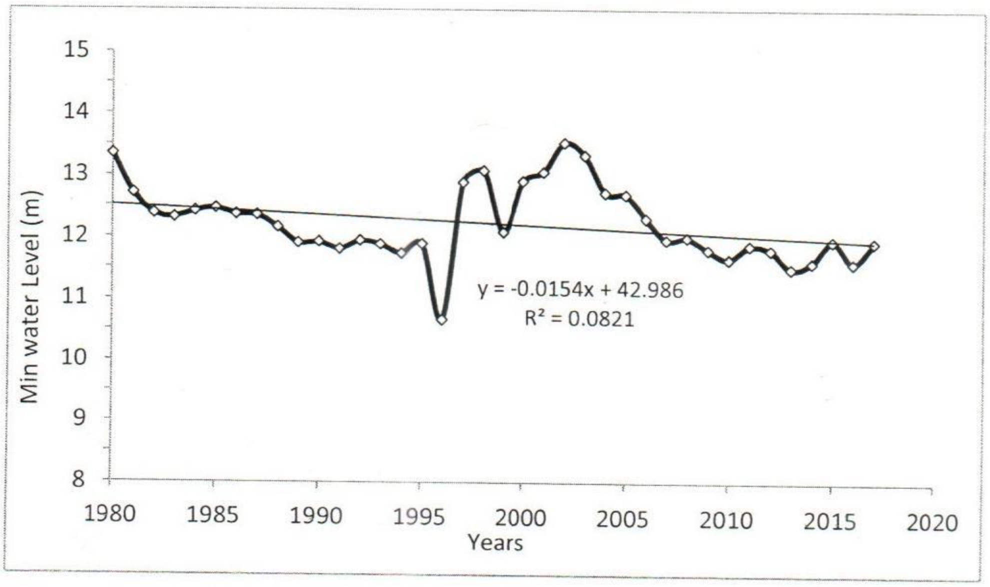

Figure 4.5: Trend of historical water level (minimum) of Mahananda

Plots of mean monthly water level of Mahananda river show that the water level peak is decreasing and is shown in Figure 4.6.

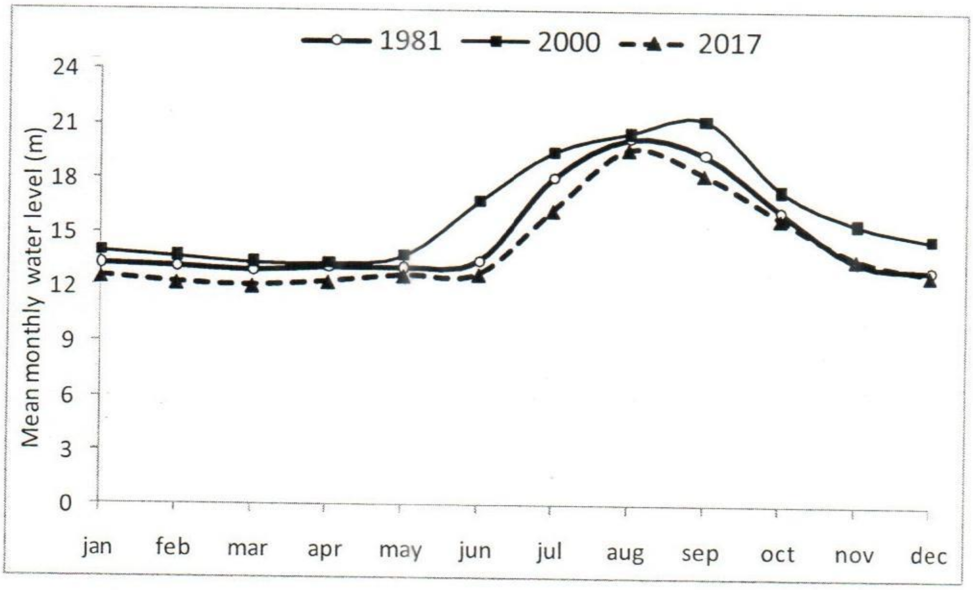

Figure 4.6: Mean monthly water level of Mahananda

Plots of water level of Hardinge bridge stations show that over the last decade there is a decreasing trend of water levels in the Ganges and which are shown in Figure 4.7 and Figure 4.8.

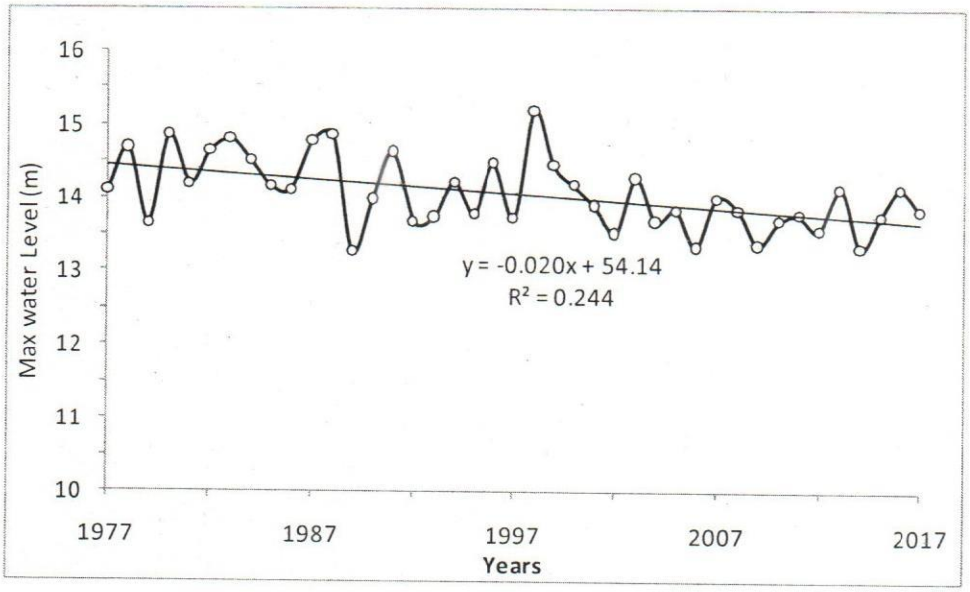

Figure 4.7: Trend of historical water level (maximum) of Ganges

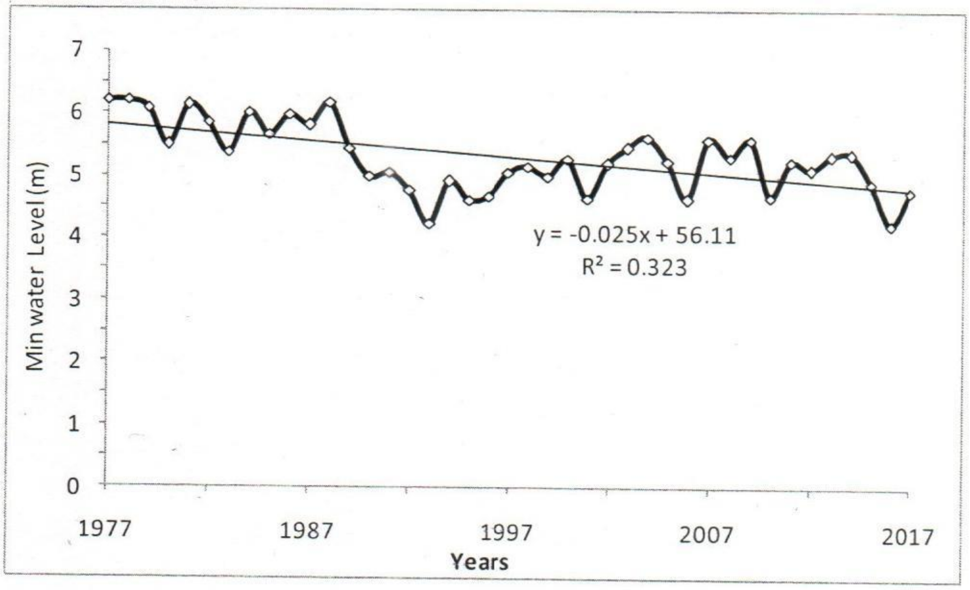

Figure 4.8: Trend of historical water level (minimum) of Ganges

Plots of mean monthly water level of the Ganges river show that the water level peak is decreasing and is shown in Figure 4.9.

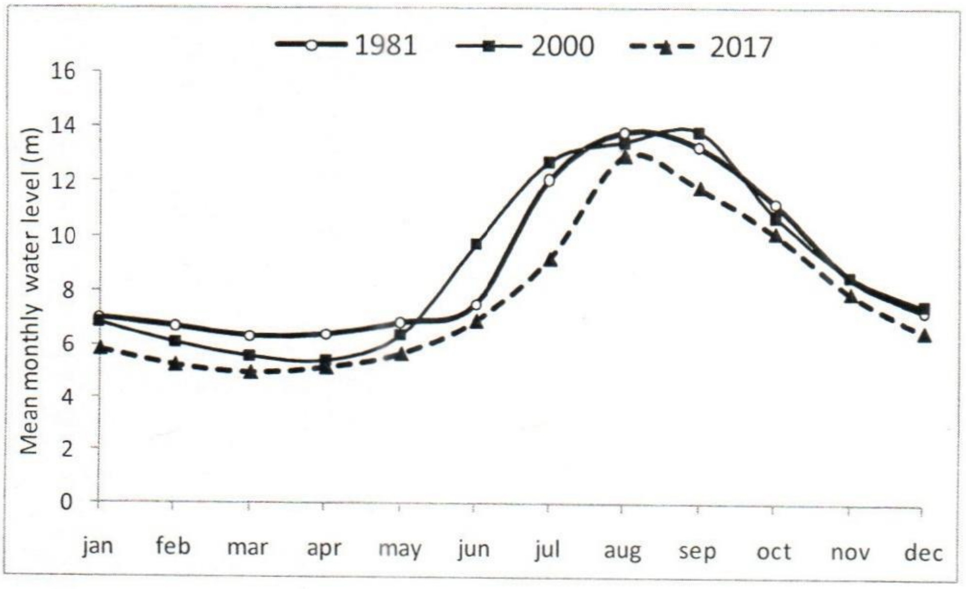

Figure 4.9: Mean monthly water level of Ganges

Plots of water level of Rohanpur station shows that over the last decade there is a decreasing trend of water levels in Punarbhova river and which are shown in Figure 4.10 and Figure 4.11.

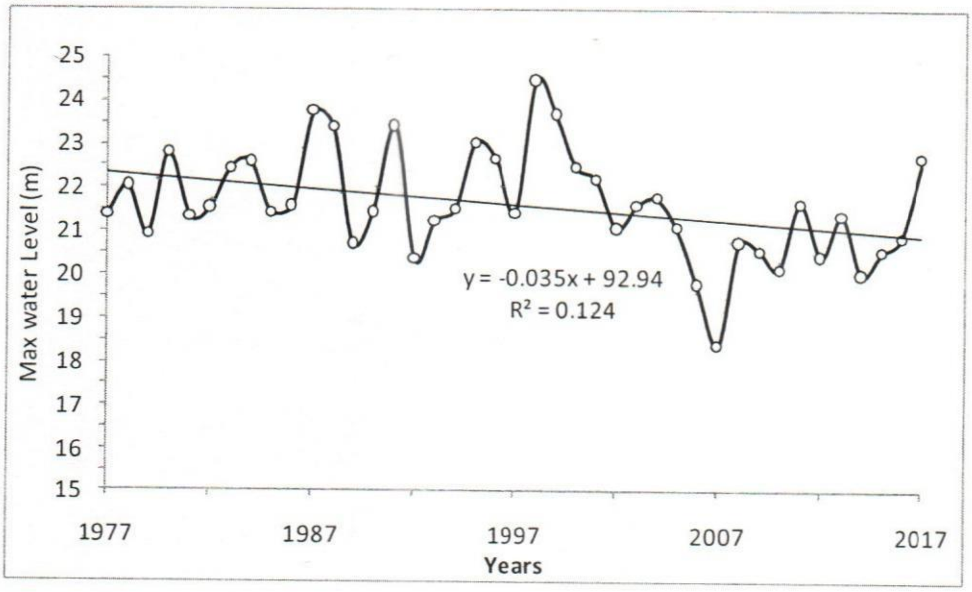

Figure 4.10: Trend of historical water level (maximum) of Punarbhaba

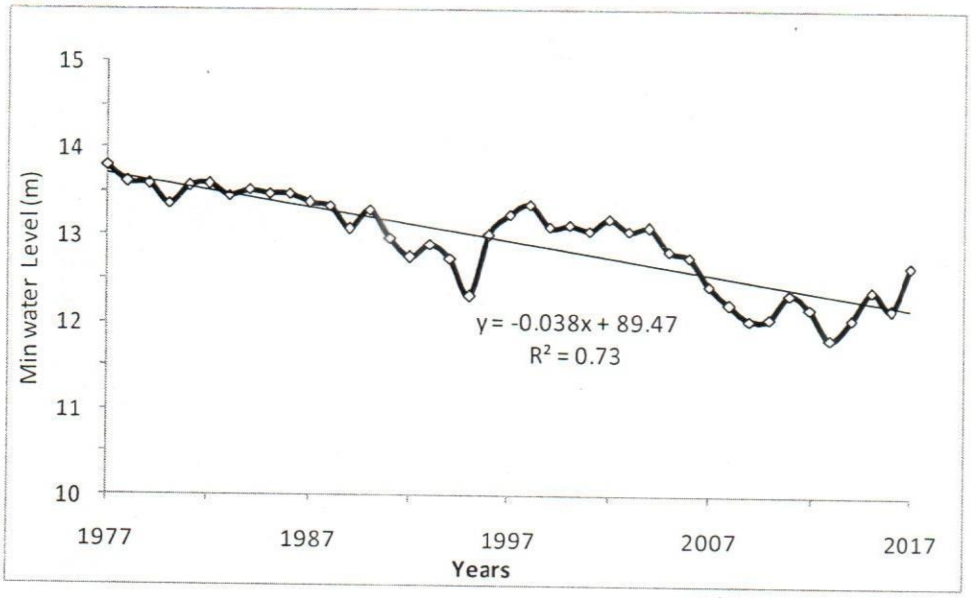

Figure 4.11: Trend of historical water level (Minimum) of Punarbhaba

Plot of mean monthly water level of Punarbhova river shows that the water level peak is decreasing which is shown in Figure 4.12.

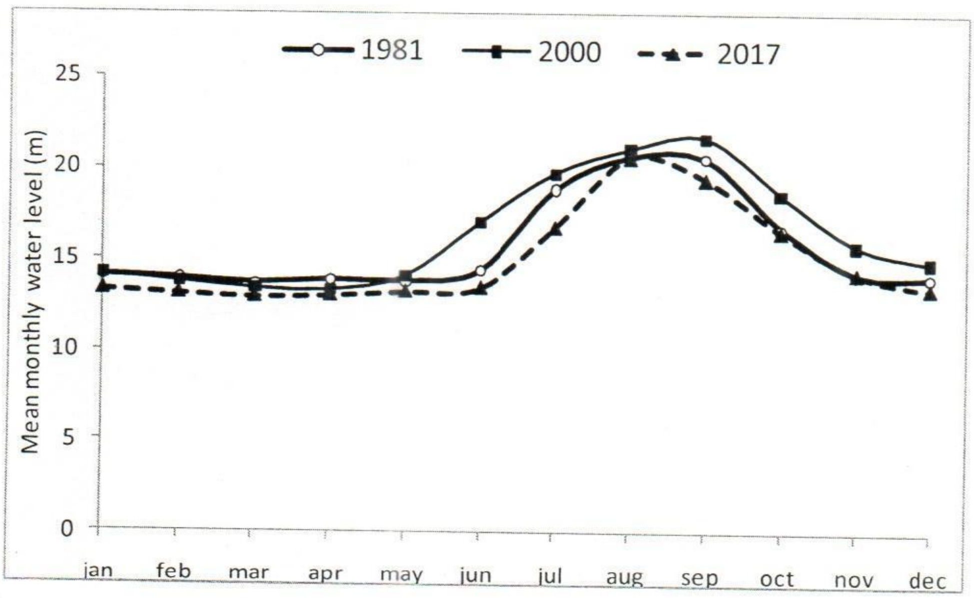

Figure 4.12: Mean monthly water level of Punarbhaba

Frequency analysis has also done to know the long term water level situation of three rivers by EVI and GEV method. Table 4.2, 0.3 and 0.4 shows the Maximum and Minimum water level in different return period for Mahananda, Ganges and Punarbhaba river respectively.

Table 4.2 Frequency analysis (water level) of the Mahananda river

Return period (years)	Maximum water level(m)	
	EVI	GEV
10	22.55	22.49
15	22.95	22.74
25	23.45	23.02
50	24.11	23.33
100	24.77	23.58

Table 4.3 Frequency analysis (water level) of the Ganges river

Return period (years)	Maximum water level(m)	
	EVI	GEV
10	14.97	14.96
15	15.20	15.13
25	15.48	15.34
50	15.86	15.59
100	16.24	15.82

Table 4.4 Frequency analysis (water level) of the Punarbhaba river

Return period (years)	Maximum water level(m)	
	EVI	GEV
10	23.61	23.57
15	24.11	23.94
25	24.74	24.35
50	25.57	24.85
100	26.40	25.28

4.1.3 Rainfall

BWDB maintains 6 rainfall stations in and around the study area. Rainfall data for the period of 1980-2015 of the 6 stations have been collected from BWDB. List of these stations are given in Table 3.2. In general, most of the stations contain long time series data. However, there are certain gaps in the data record, which has been duly filled in using data from adjacent stations after carrying out necessary quality checking. Quality checking of rainfall includes visual observation of plots of rainfall, estimation of yearly mean values, and comparison of monthly values. After the necessary consistency and quality checking, Rainfall data has been used in this analysis. It has been observed from the mean monthly rainfall of all the stations that, in the study area rainfall excess is for the period of May to October and rainfall deficit is for the period of November to April. A comparison of yearly sum of rainfall of Nawabganj, Godagari, Bholahat and Nachole stations is given in Figure 0.13. Observing following graph for this area it is concluded that the change of rainfall is insignificant i.e. rainfall has no major impact on river flow especially on dry season.

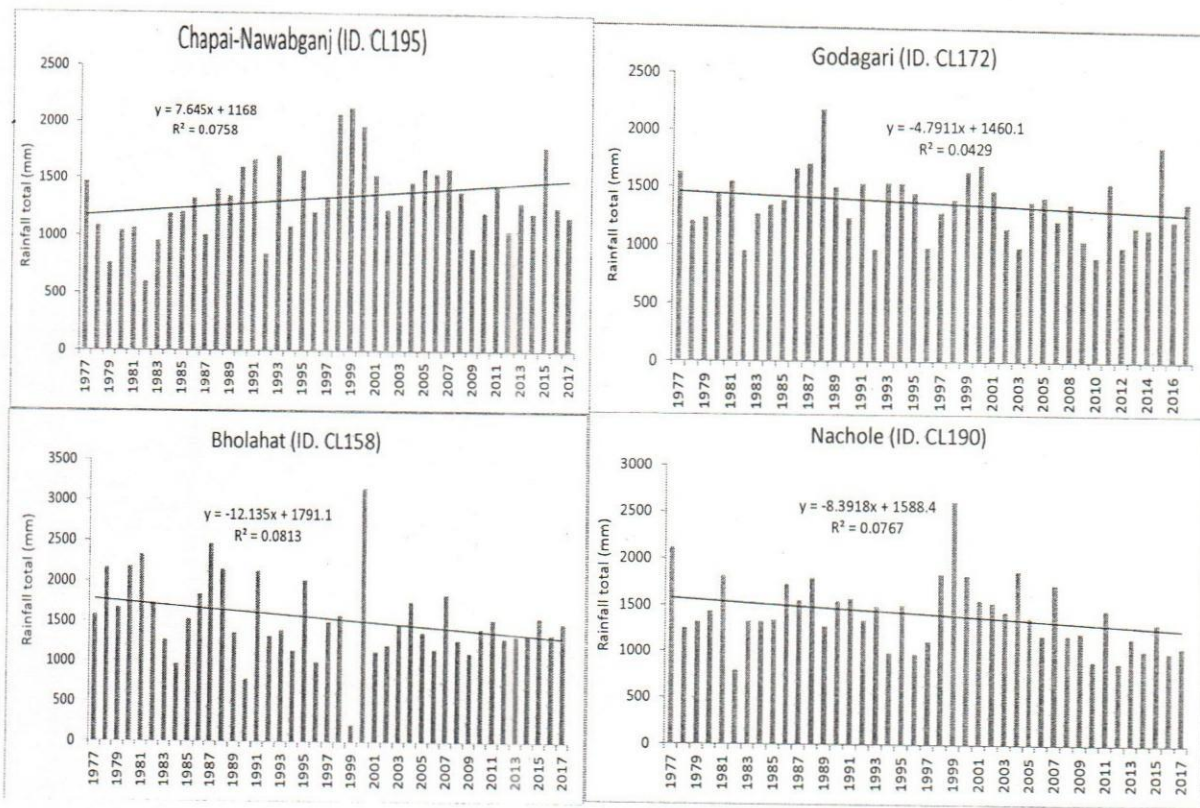

Figure 4.13: Yearly total rainfall of different stations

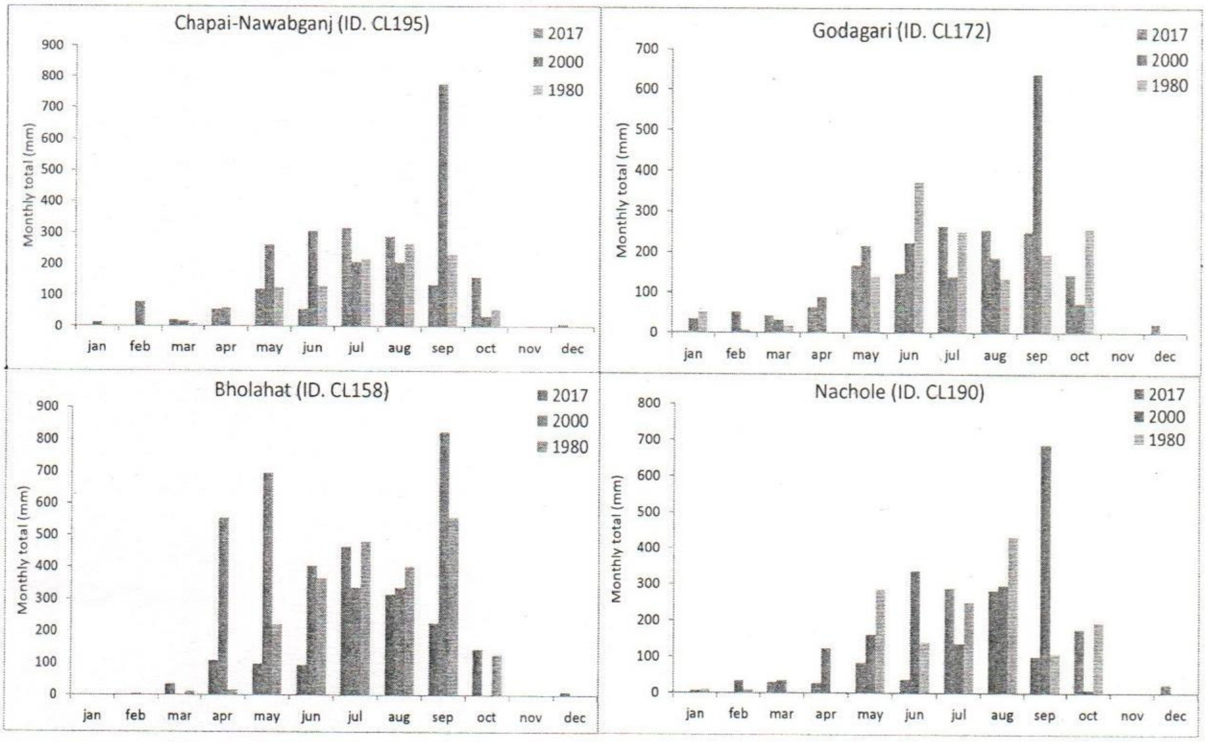

Figure 4.14: Comparison of monthly total rainfall for the years 1980, 2000, 2017 at different stations

4.1.4 Groundwater Level

There are a number of BWDB groundwater monitoring wells located in the study area out of which 12 is selected for analysis and is given in Table 3.3. Groundwater level data of BWDB wells for the period of 1985 to 2015 have been collected. After necessary quality checking, analyses have been carried out for evaluating seasonal variation and trend of groundwater of the study area. Analysis reveals that groundwater table for Nawabgonj sadar ranges from 11.0 m to 22.0 m below ground surface. The fluctuation of groundwater levels is shown in Figure 4.15 and Figure 4.16.

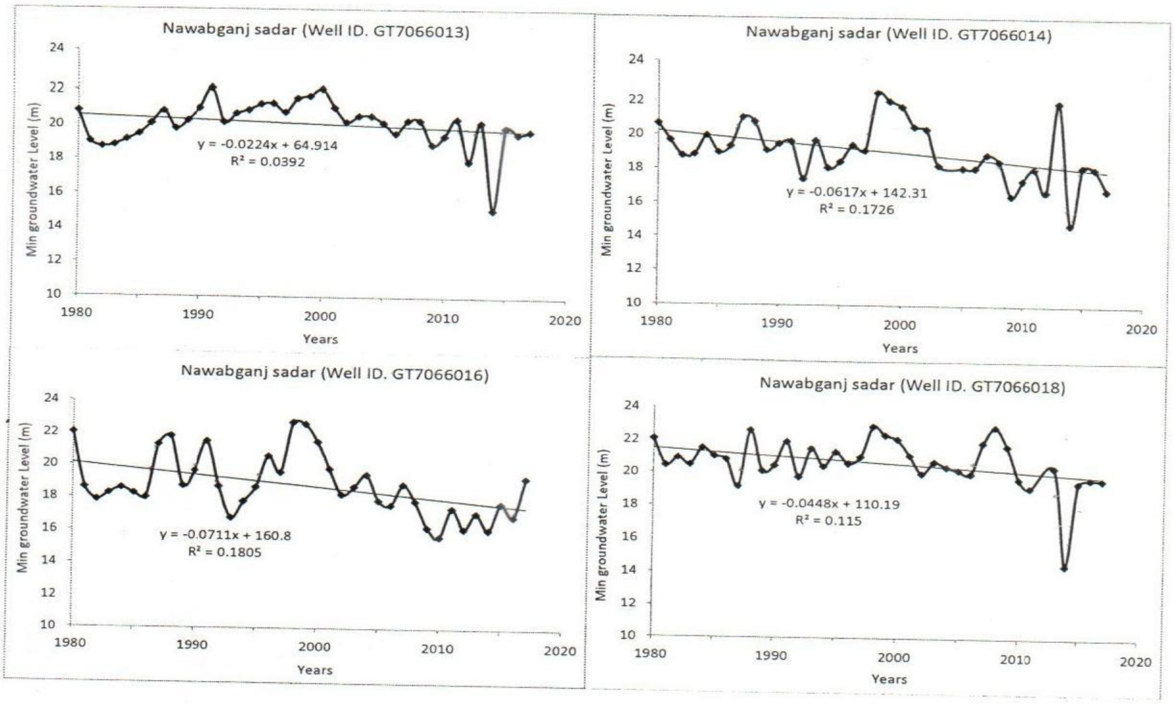

Figure 4.15: Trend of minimum groundwater level at Nawabgonj sadar

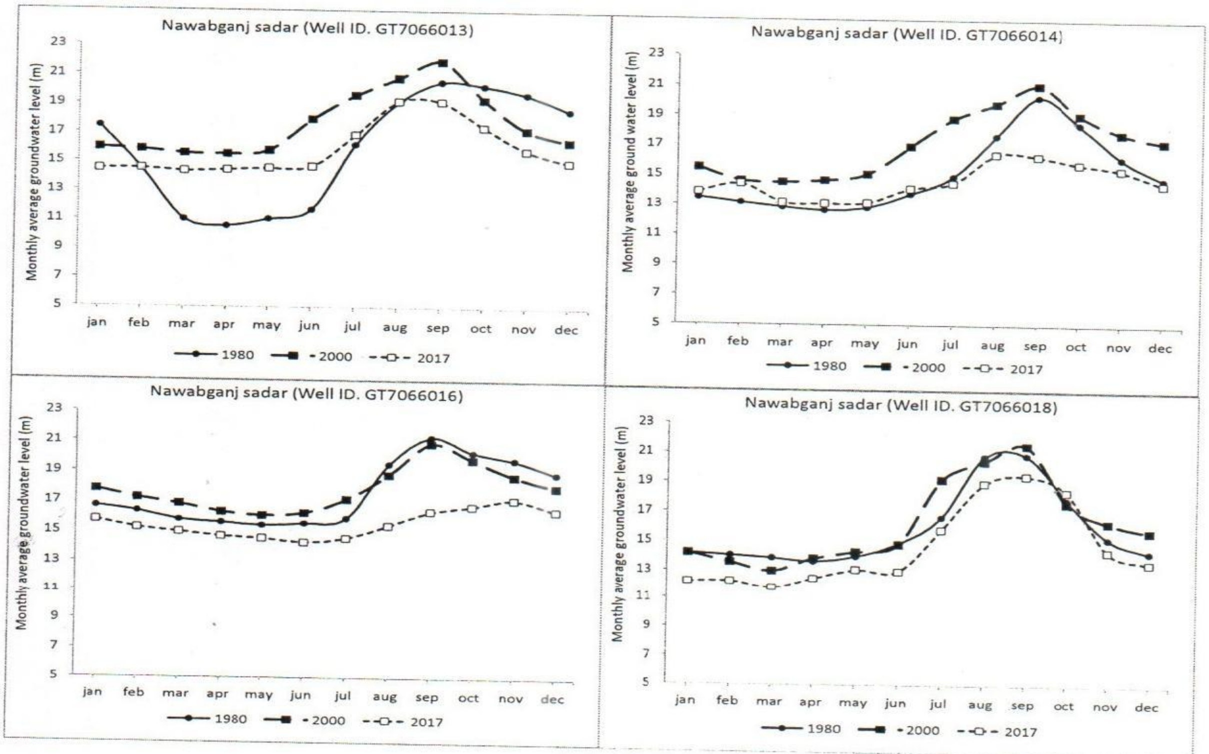

Figure 4.16: Monthly average groundwater level at Nawabgonj sadar (1980, 2000, 2017)

Analysis reveals that the groundwater table for Godagari ranges from 5.0 m to 25.0 m below ground surface. The fluctuation of groundwater levels at Godagari wells is shown in Figure 4.17 and Figure 4.18.

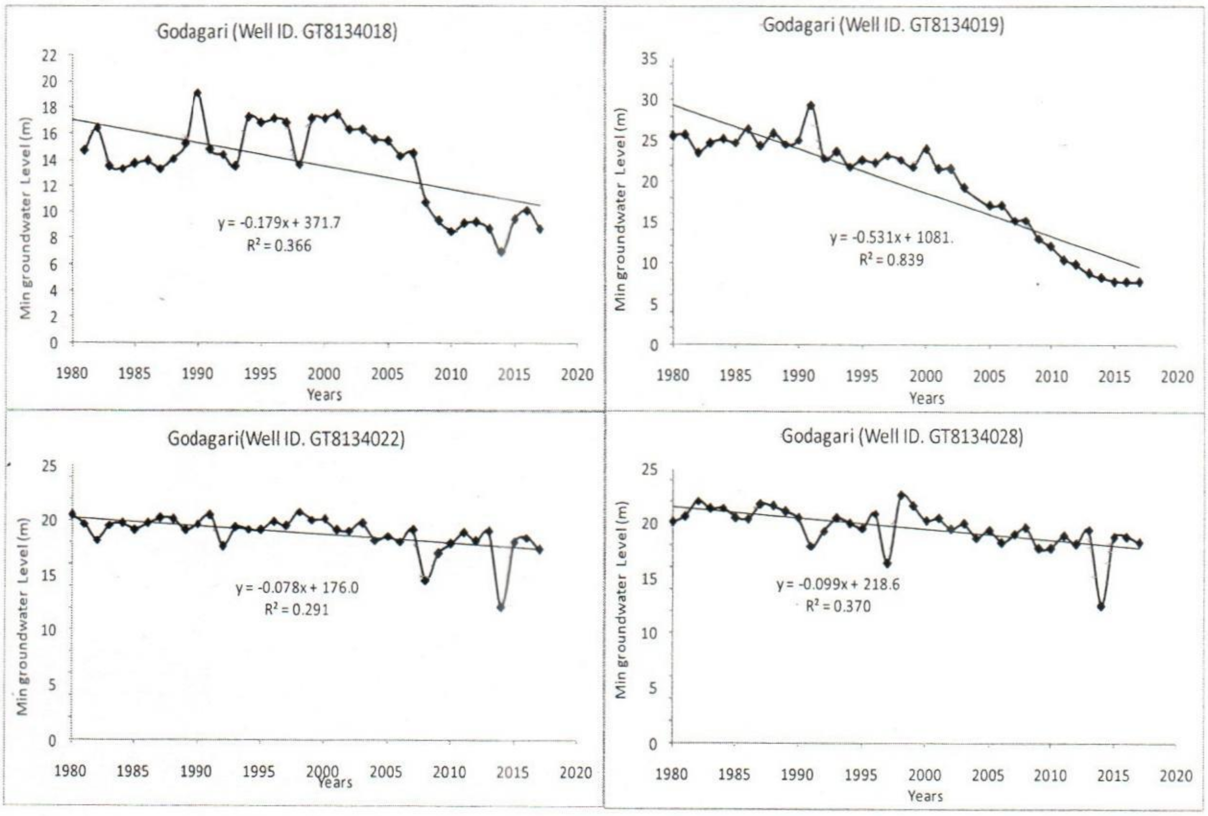

Figure 4.17: Trend of minimum groundwater level at Godagari

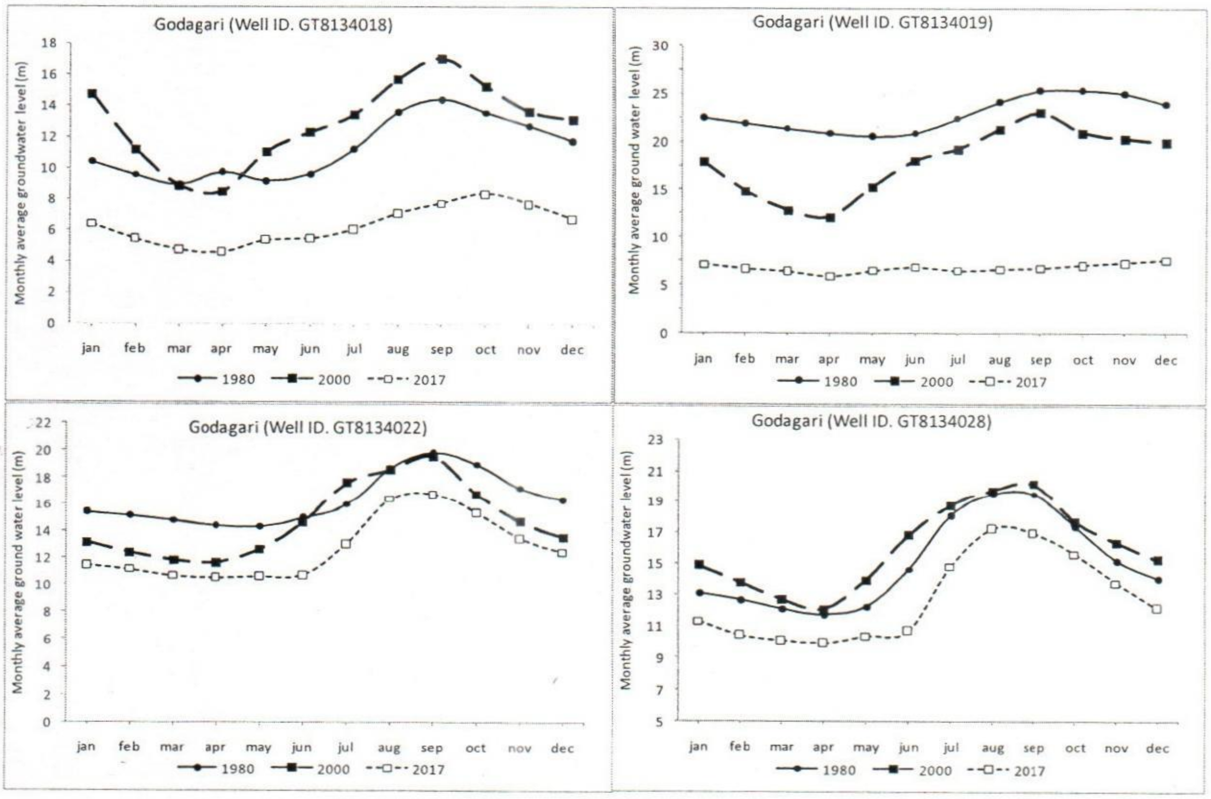

Figure 4.18: Monthly average groundwater level at Godagari (1980, 2000, 2017)

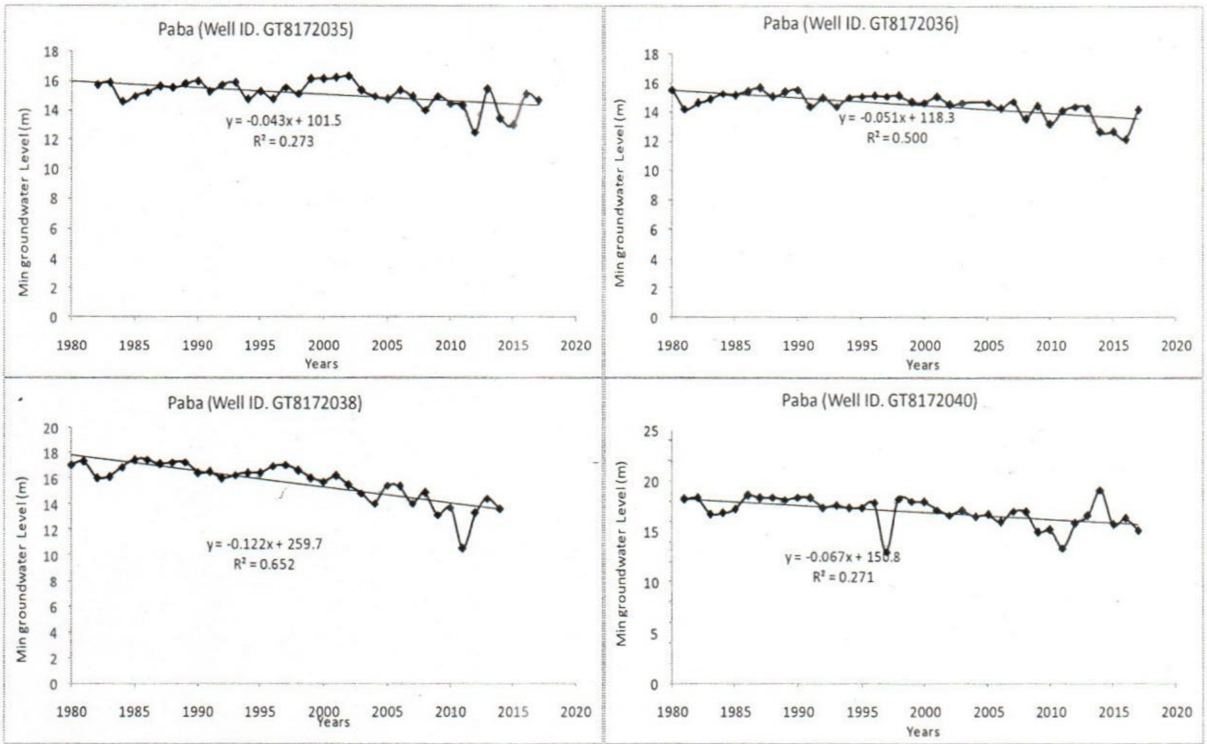

Figure 4.19: Trend of minimum groundwater level at Paba

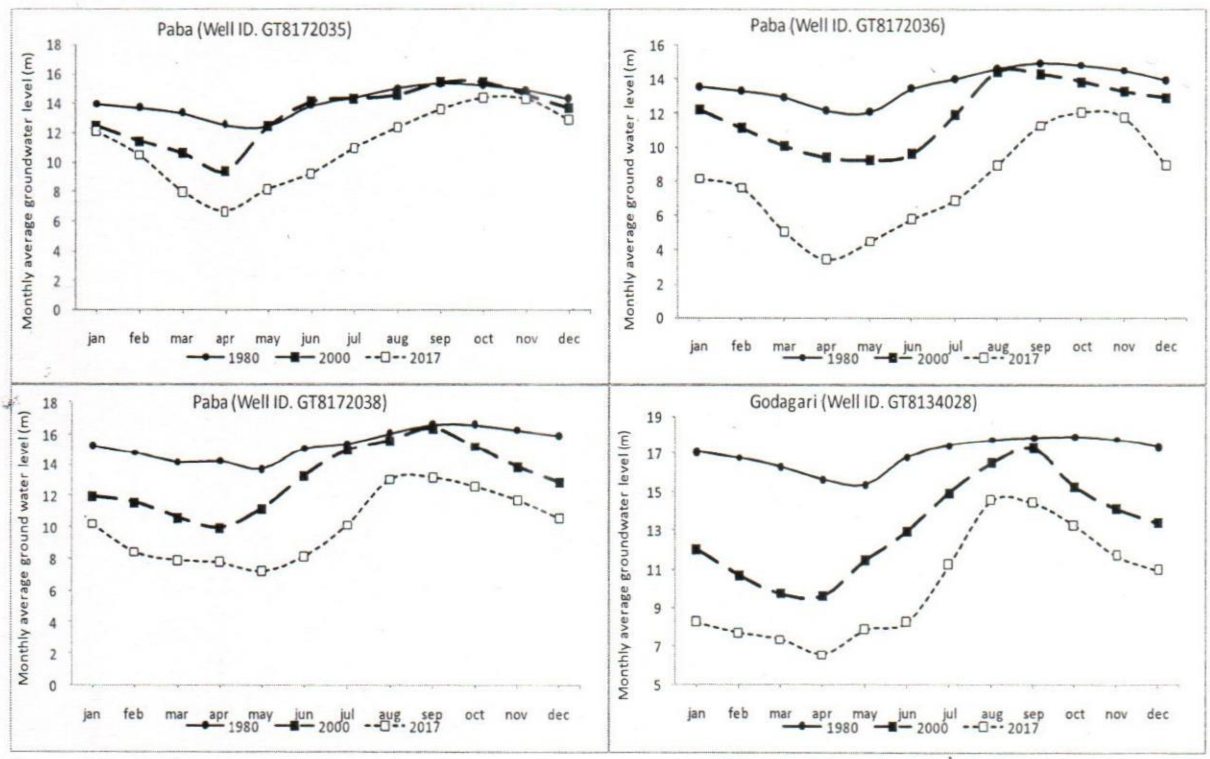

Figure 4.20: Monthly average groundwater level at Paba (1980, 2000, 2017)

Analysis reveals that the groundwater table for Paba ranges from 4.0 m to 17.0 m below ground surface. The fluctuation of groundwater levels at Godagari wells is shown in Figure 4.19 and Figure 4.20.

4.2 Morphological Analysis

4.2.1 River Bank Shifting

Channel migration is believed to be dependent on the variation in discharge from season to season. High variation is usually associated with a significant shift in the deepest channel while low variation is associated with the comparatively stable channel. There may be some exceptions to this general observation. Lateral movement of thalweg at different locations in an alluvial river from year to year is measured quantitatively. The river channel migration at different locations (bends) is shown in table 4.5.

Table 4.5 River Channel migration at different bends.

Cross Section/bend position	Period	Bank	Erosion/Migration (m)
Mirer Kholan Boat Ghat	89-95	L/B	140
	89-95	R/B	42
	95-01	L/B	573
	95-01	R/B	666
	01-18	L/B	561
	01-18	R/B	431

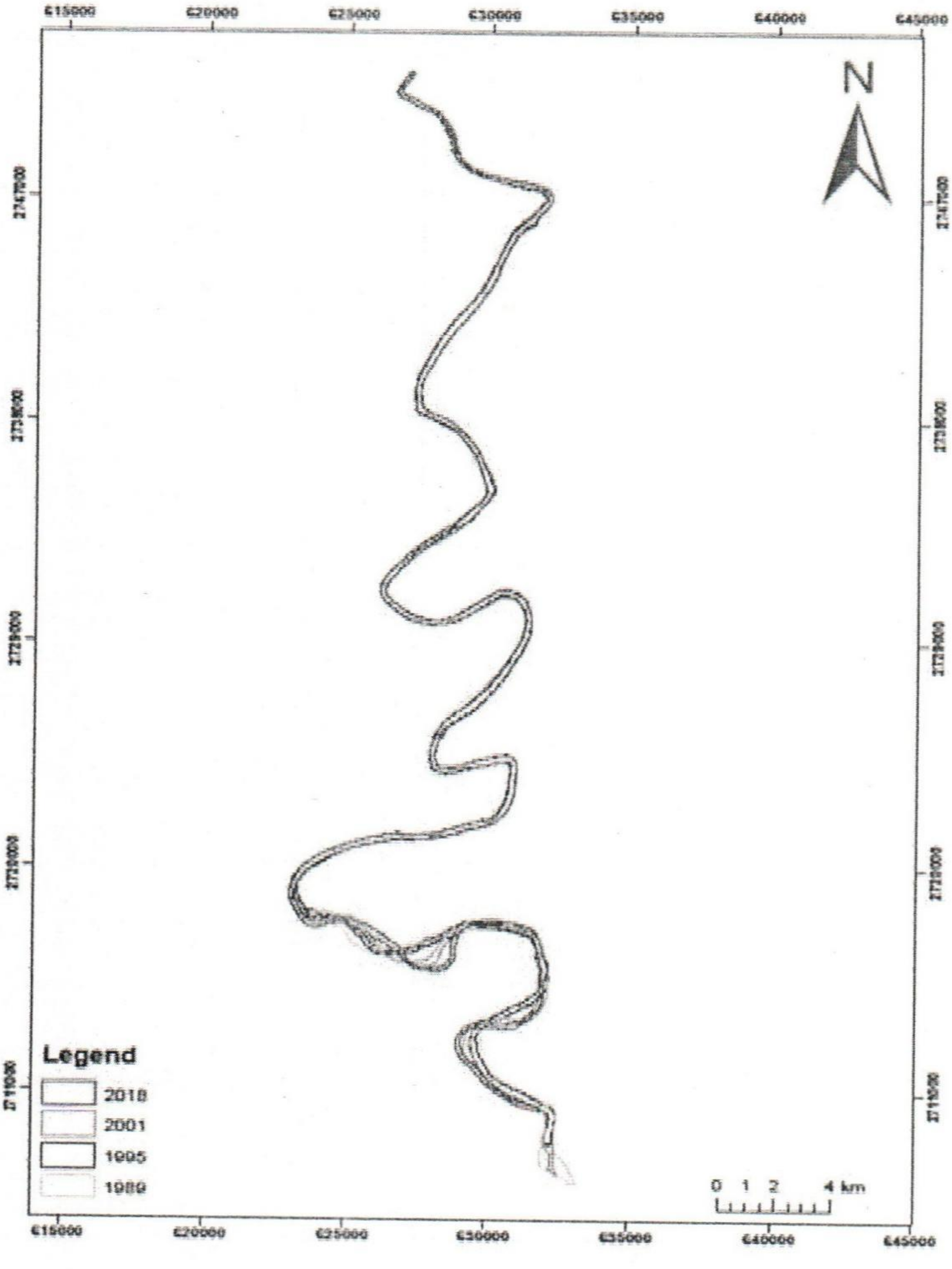

Figure 4.21 Shifting of Mahananda during 1989, 1995, 2001 and 2018.

4.2.2 Sediment Load

All of the water that reaches a stream and its tributaries carries sediment eroded from the entire area drained by it. The total amount of erosional debris exported from such a drainage basin is its sediment yield. Mass of sediment passing through a stream cross-section in a specified period of time, expressed in millions of tons (mt), is the amount of sediment carried by running water. The sediment that is being moved by a stream, i.e. the sediment delivered to and transported by a stream is its sediment load. This can be classified into three types, depending on sediment size and the competence of the river as bed load, suspended load and dissolved load. These three types of sediment constitute the total sediment load of the stream and, of course, the sediment yield of the drainage basin.

4.2.2.1 Estimation of Sediment Load

The sediment load or total sediment transport can be measured in different ways. In this study, Englund and Hensen formula has been used. Table 4.6 shows the river bed and bank material size of the Mahananda river which is used in this calculation.

	Baruipara to Gomastapur (reach-1)			Gomastapur to Diabetic Hospital (reach-2)			Diabetic Hospital to Sultanganj (reach-3)		
	LB	RB	Center	LB	RB	Center	LB	RB	Center
Average. D_{50}	0.038455	0.03848	0.057709	0.074163	0.053697	0.075661	0.04132	0.030195	0.313377

Table 4.6: River bed and bank material size of Mahananda river.

The Englund and Hensen formula can be used as,

The total sediment load in m^2/s, $St = 0.05\frac{C^2}{g}\theta^{\frac{5}{2}}\sqrt{(s-1)gd_{50}^3}$

Where C = Chezy Co-efficient ($m^{0.5}/s$) and found from $C = 20h^{0.5}$

$\theta = \frac{hi}{\Delta d50}$

h= Average depth in meter

i=Slope of the channel/ water surface

d_{50}= Median diameter of the particle in meter

$(s-1) = \Delta = 1.65$

$g= 9.81\ m/s^2$

Using this formula total sediment load estimated in three cross-sections for Mohananda river is shown in Table 4.7 below;

Table 4.7: Sediment transport (ton/day) at three reaches.

Reach1 (U/S)	Reach2 (Middle)	Reach3 (D/S)
14740.00	3820.91	884.064

It is observed from Table 4.7 that the Sediment transport (ton/day) rate is low in the down valley. It indicates that the river bed in the downstream is silted up. As a result river water depth is decreasing gradually.

4.3 The Planform of Mahananda River

4.3.1 Sinuosity

In studies of rivers, the sinuosity index is similar but not identical to the general form. The difference from the general form happens because the downvalley path is not perfectly straight. The sinuosity index can be explained, then, as the deviations from a path defined by the direction of the maximum downslope. For this reason, bedrock streams that flow directly downslope have a sinuosity index of 1, and meandering streams have a sinuosity index that is greater than 1.

It is also possible to distinguish the case where the stream flowing on the line could not physically travel the distance between the ends: in some hydraulic studies, this leads to assign a sinuosity value of 1 for a torrent flowing over rocky bedrock along with a horizontal rectilinear projection, even if the slope angle varies.

For rivers, the conventional classes of sinuosity, SI, are:

- SI <1.05: almost straight
- $1.05 \leq$ SI <1.25: winding
- $1.25 \leq$ SI <1.50: twisty
- $1.50 \leq$ SI: meandering

In this study the average SI values has found less than 2. Total and reach wise sinuosity values in different years are shown in table 4.8 below:

Table 4.8: Sinuosity Index (SI) of Mohananda River

Year	Sinuosity Index			
	Total study reach	River reach-1	River reach-2	River reach-3
1989	1.74	1.38	1.64	2.09
1995	1.77	1.39	1.66	2.20
2001	1.82	1.39	1.66	2.34
2018	1.85	1.40	1.66	2.54

It is observed from above table the river reach-1 (upstream valley) is twisty, reach-2 (middle valley) is meandering and reach-3 (down valley) is highly meandering, where the Mahananda river meets the Ganges river.

4.3.2 Meander Parameter of the Channel

Meander formation is a result of natural factors and processes. The waveform configuration of a stream is constantly changing. Fluid flows around a bend in a vortex. Once a channel begins to follow a sinusoidal path, the amplitude and concavity of the loops increase dramatically due to the effect of helical flow sweeping dense eroded material towards the inside of the bend, and leaving the outside of the bend unprotected and therefore vulnerable to accelerated erosion, forming a positive feedback loop. In the words of Elizabeth A. Wood, this process of making meanders seems to be a self-intensifying process, in which greater curvature results in more erosion of the bank, which results in greater curvature.

The cross-current along the floor of the channel is part of the secondary flow and sweeps dense eroded material towards the inside of the bend. The cross-current then rises to the surface near the inside and flows towards the outside, forming the helical flow. The greater the curvature of the bend, and the faster the flow, the stronger is the cross-current and the sweeping. Due to the conservation of angular momentum, the speed on the inside of the bend is faster than on the outside. Since the flow velocity is diminished, so is the centrifugal pressure. However, the pressure of the super-elevated column prevails, developing an unbalanced gradient that moves water back across the bottom from the outside to the inside. The flow is supplied by a counter-flow across the surface from the inside to the outside. This entire situation is very similar to the Tea leaf paradox. This secondary flow carries sediment from the outside of the bend to the inside making the river more meandering. In this study, the total study reach has been divided into three reach and meander parameters for each reach have been determined separately in order to draw interrelationships between meander parameters which is discussed later on.

4.3.3 Channel Geometry

River cross section data has been collected from BWDB for Mahananda River. The spacing of cross sections is found to be on average 2500-3000m. The cross sections collected from Mahananda's outfall at Sultanganj to near northern border (about 2 km west of Nasir Bazar in Bhangabaria union under Gomastapur Upazila), located at about 7 km upstream of Mukarrampur- about 78 km river reach. These historical cross-section data have been analyzed to understand the trend of geometric change of the river Mahananda. Cross-section survey of about 75 km of Mahananda river has done by Globe Survey Company, Dhaka. The data of total 153 cross-section have been analyzed to know the present channel geometry. Figure 4.21 shows the variation of cross-sectional area, Figure 4.22 shows the variation of width, Figure 4.23 shows the variation of depth, Figure 4.24 shows the variation of mean bed level and Figure 4.25 shows the variation of width-depth ratio along Mahananda river reach.

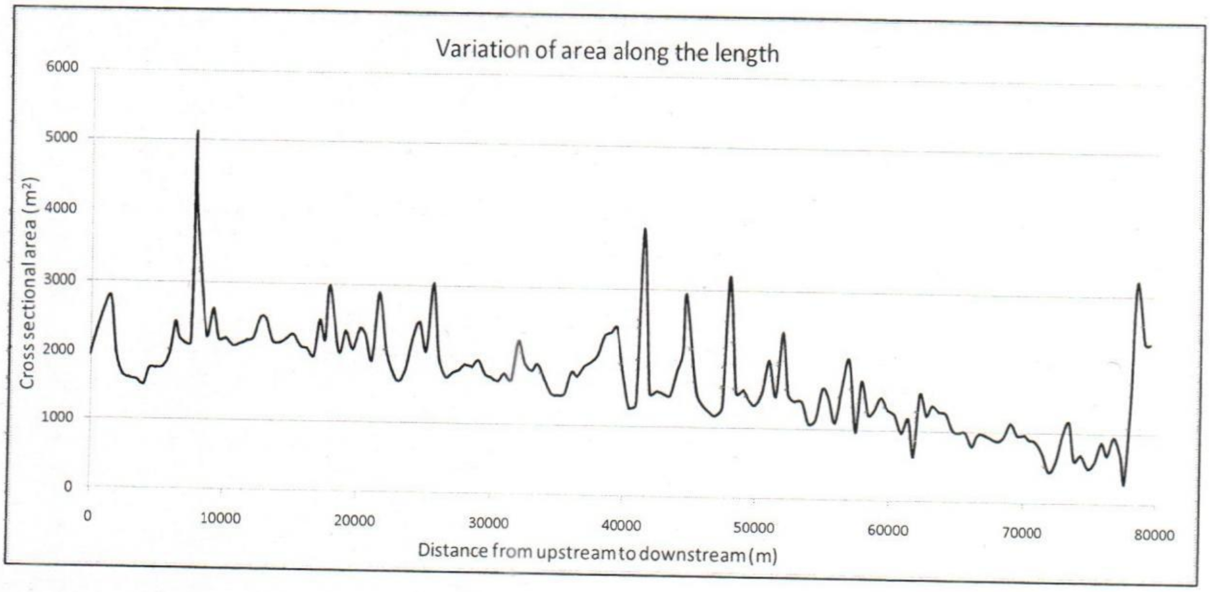

Figure 4.22: Variation of cross-sectional area along the Mahananda river reach

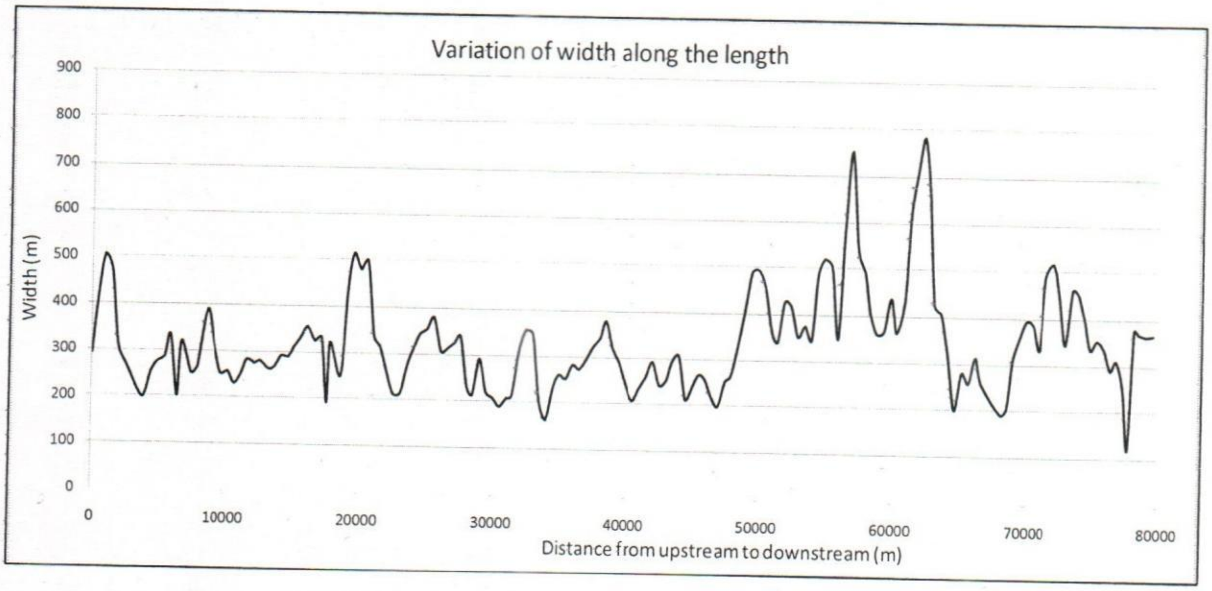

Figure 4.23: Variation of width along the Mahananda river reach

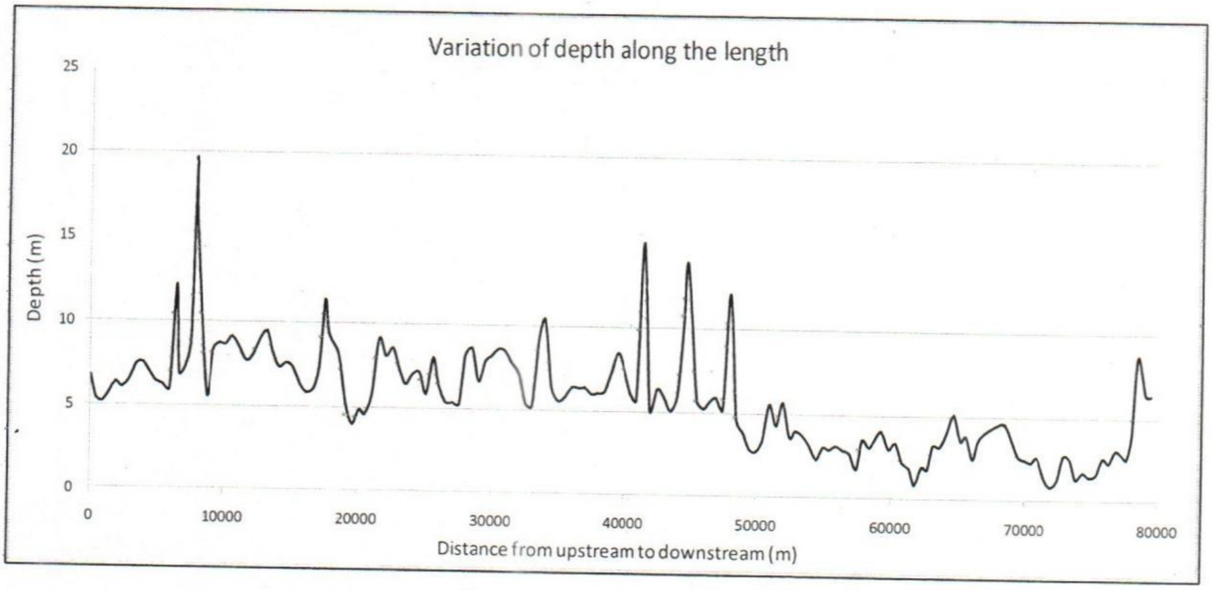

Figure 4.24: Variation of depth along the Mahananda river reach

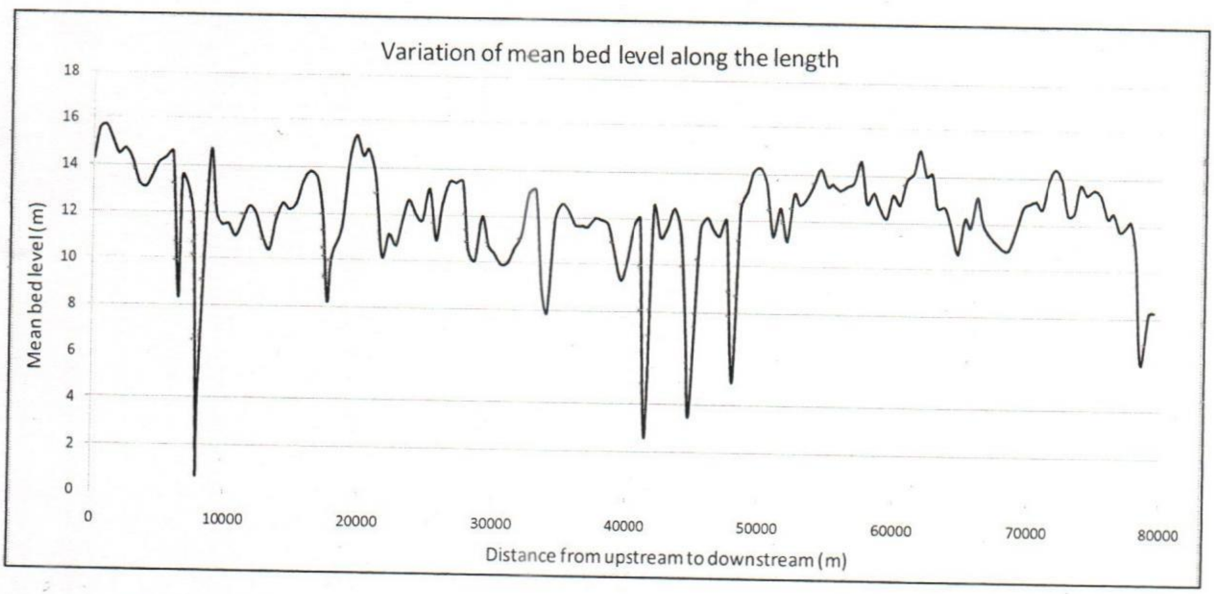

Figure 4.25: Variation of mean bed level along the Mahananda river reach

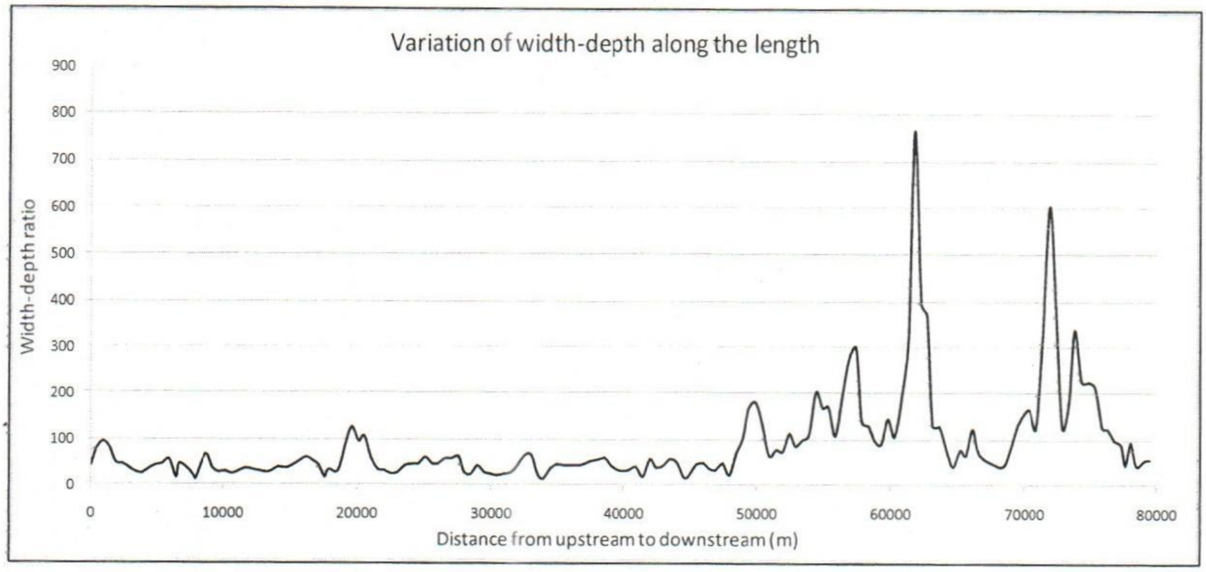

Figure 4.26: Variation of width-depth ratio along the Mahananda river reach

4.4 In Situ Water Quality Data Analysis and Interpretation of Results

4.4.1 Arsenic (As)

Arsenic is a naturally occurring semi-metallic element with an atomic weight of 74.9. Pure arsenic exists in three allotropic forms: yellow (alpha), black (beta), and gray (gamma) (HSDB 2009). It is highly toxic in its inorganic form. Many inorganic arsenic compounds are found in the environment, frequently occurring as the sulfide form in complex minerals containing copper, lead, iron, nickel, cobalt, and other metals. Arsenic compounds occur in trivalent and pentavalent forms; common trivalent forms are arsenic trioxide and sodium arsenite, and common pentavalent forms are arsenic pentoxide and the various arsenates. In water, elemental arsenic is insoluble but inorganic arsenic is soluble. People are exposed to elevated levels of inorganic arsenic through drinking contaminated water, using contaminated water in food preparation and irrigation of food crops, industrial processes, eating contaminated food and smoking tobacco.

Long-term exposure to inorganic arsenic, mainly through drinking-water and food, can lead to chronic arsenic poisoning. Skin lesions and skin cancer are the most characteristic effects. The greatest threat to public health from arsenic originates from contaminated groundwater.

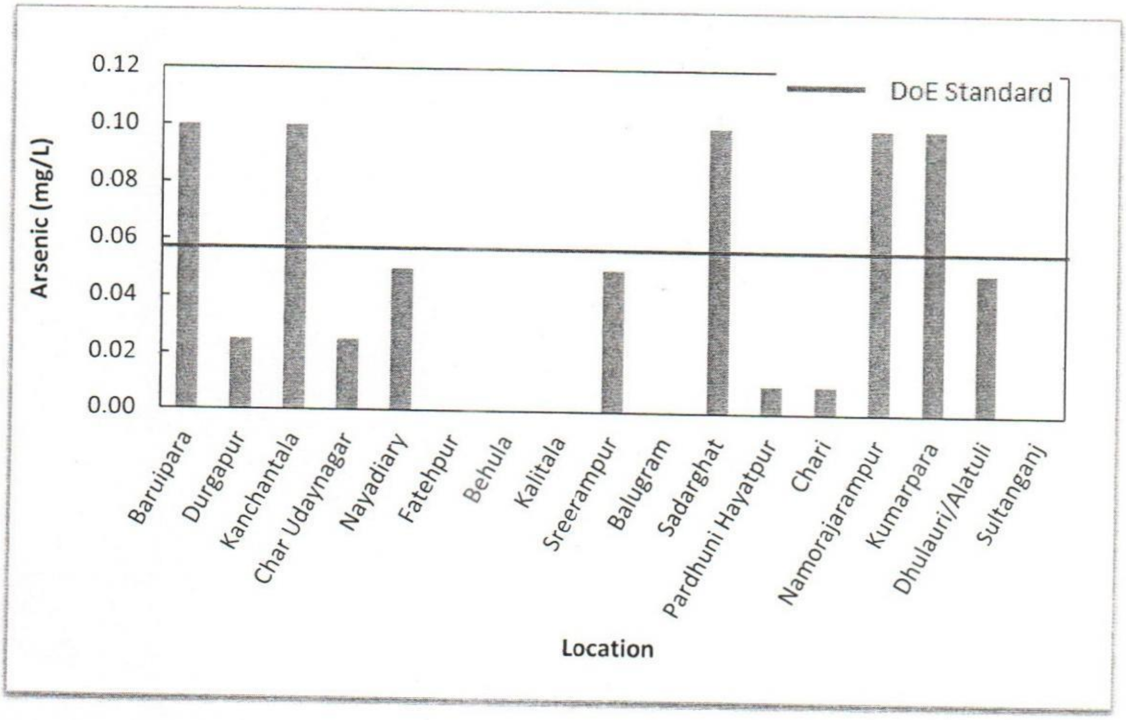

Figure 4.27: Arsenic concentrations in groundwater in the study area

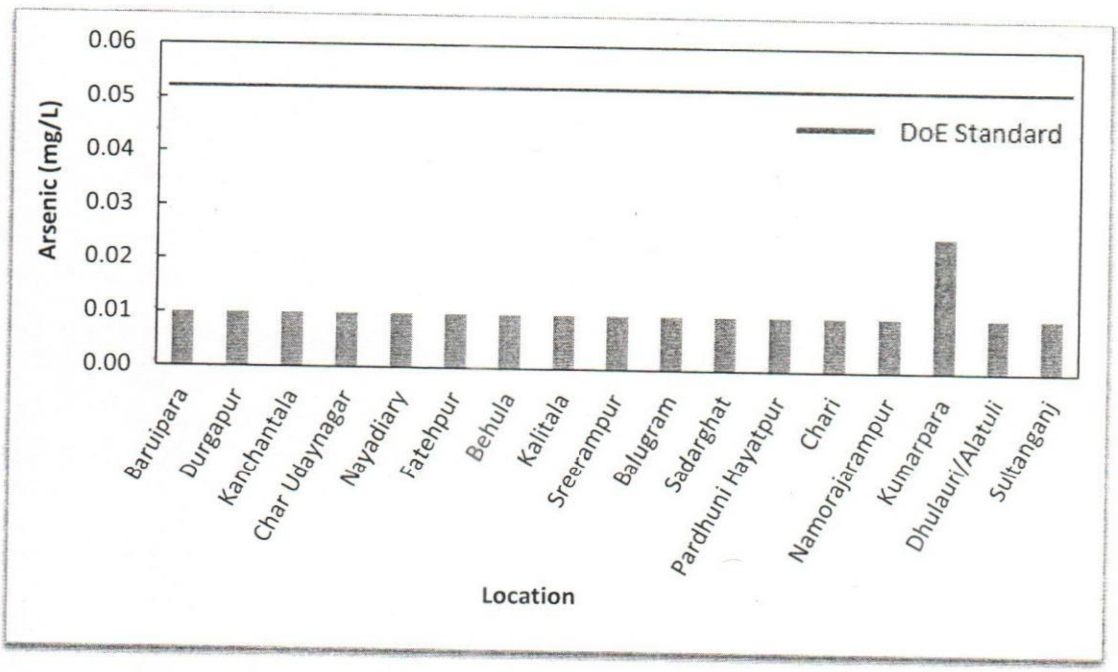

Figure 4.28: Arsenic concentrations in river in a the study area

Test of arsenic concentration determination in groundwater was carried out in seventeen places at different locations in the study area. From the measured value of arsenic concentration, it was observed that groundwater in the study area crosses the safe limit of arsenic concentration set by DoE in five locations namely Baruipara, Kanchantala, Sadarghat, Namorajarampur and Kumarpara. In other places, arsenic concentration determination of groundwater was observed within the safe limit of DoE standard.

On the contrary arsenic concentrations in the river water were found within the safe limit of DoE standard in the aforesaid locations. Figure 4.26 shows the Arsenic concentration in groundwater and figure 4.27 shows Arsenic concentration in river water in the study area.

4.4.2 Manganese (Mn)

Manganese is a pinkish-gray, chemically active element with atomic mass 54.938. It is a hard metal and is very brittle. It is hard to melt but easily oxidized. Manganese is reactive when pure, and as a powder, it will burn in oxygen, it reacts with water (it rusts like iron) and dissolves in dilute acids. Mn is an essential component in the biological system but its excessive concentration in drinking water is harmful to human beings since it overdose is associated with nervous system toxicity that produces a Parkinsonism like a syndrome.

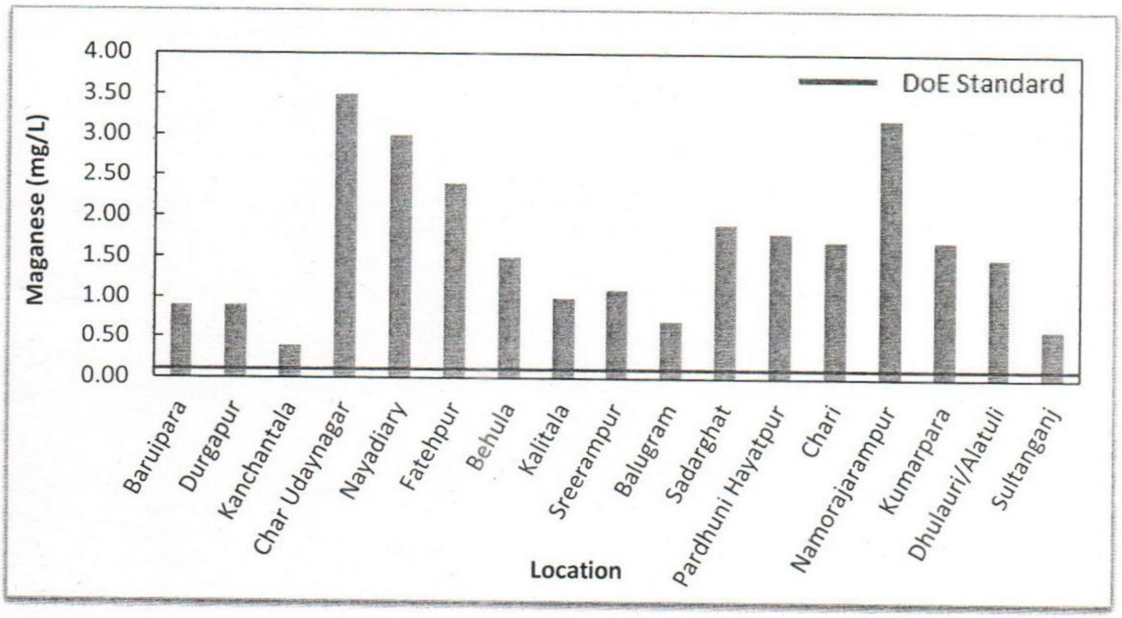

Figure 4.29: Manganese concentrations in groundwater in the study area

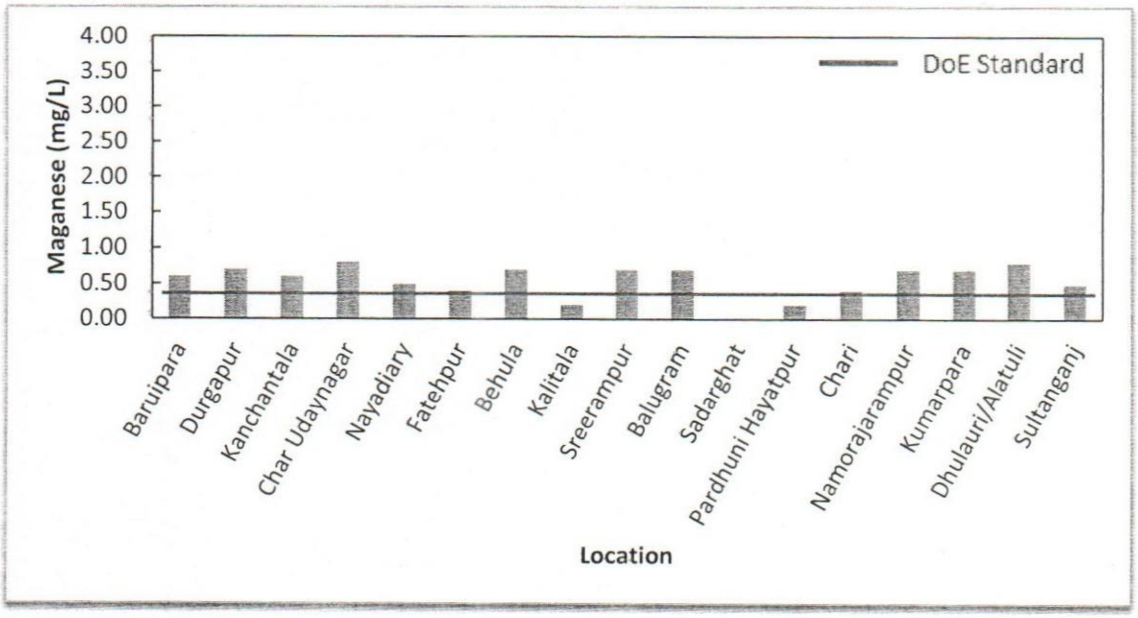

Figure 4.30: Manganese concentrations in river water in the study area

The values of manganese concentrations in groundwater were found to be many times higher than the acceptable limit of DoE standard at all the locations in the study area. For also river water manganese concentrations surpassed the acceptable limit of DoE standard at all locations but not higher than that of groundwater. Figure 4.28 shows the Manganese concentration in groundwater and figure 4.29 shows Manganese concentration in river water in the study area.

4.4.3 pH

pH is a measure of how acidic or basic water is. The range goes from 0 - 14, with 7 being neutral. pHs of less than 7 indicate acidity, whereas a pH of greater than 7 indicates a base. pH is really a measure of the relative amount of free hydrogen and hydroxyl ions in the water. Water that has more free hydrogen ions is acidic, whereas water that has more free hydroxyl ions is basic. Since pH can be affected by chemicals in the water, pH is an important indicator of water that is changing chemically.

The pH of water determines the solubility (the amount that can be dissolved in the water) and biological availability (the amount that can be utilized by aquatic life) of chemical constituents such as nutrients (phosphorus, nitrogen, and carbon) and heavy metals (lead, copper, cadmium, etc.). For example, in addition to affecting how much and what form of phosphorus is most abundant in the water, pH also determines whether aquatic life can use it. In the case of heavy metals, the degree to which they are soluble determines their toxicity. Metals tend to be more toxic at lower pH because they are more soluble.

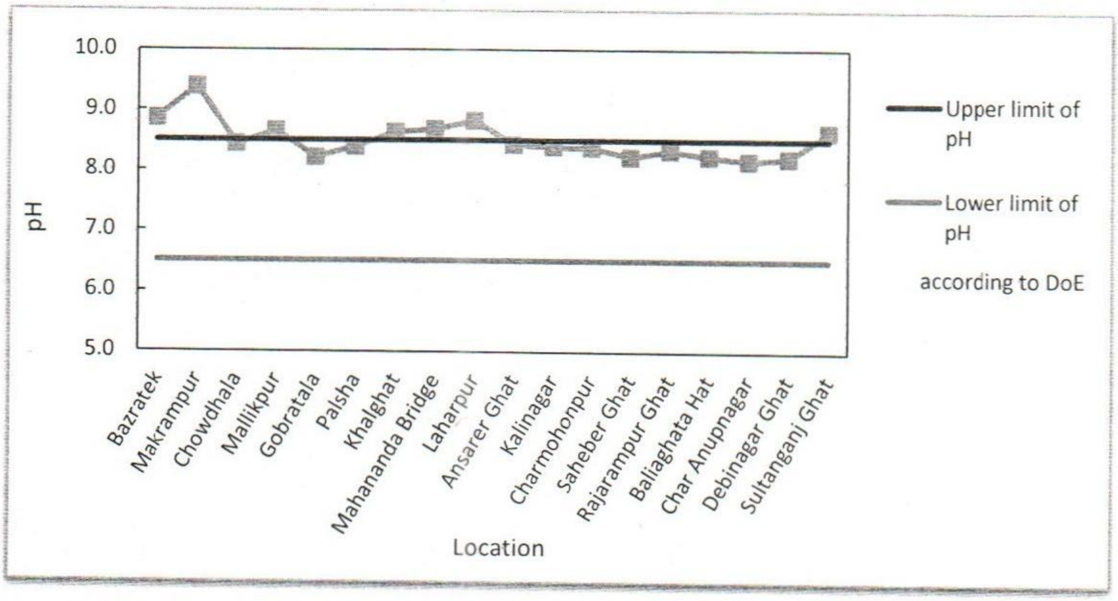

Figure 4.31: pH values in river water in the study area

At all the locations in the study area, it was observed that all the values of pH were in near beneath or near above of the permissible limit of DoE except Makrampur. Figure 4.30 shows the pH values in river water in the study area.

4.4.4 Dissolve Oxygen

Both aquatic plants and animals depend on dissolved oxygen (DO) for survival. Like people, fish and other aquatic organisms need oxygen to live. As air or water moves past an animal's breathing apparatus (gills or lungs), oxygen is transferred to their blood. It is more difficult to transfer oxygen from water to blood than it is to transfer oxygen from the air to blood. Therefore, it is critical that an adequate amount of oxygen is maintained in the water for this transfer to take place efficiently and sustain aquatic life. In addition to being required by aquatic organisms for respiration, oxygen is necessary to help decompose organic matter in the water and bottom sediments. It is also necessary for other biological and chemical processes. Dissolved oxygen depletion could plummet respiration, cause the death of fish, depress feeding or affect embryonic development and hatching success due to oxygen shortage.

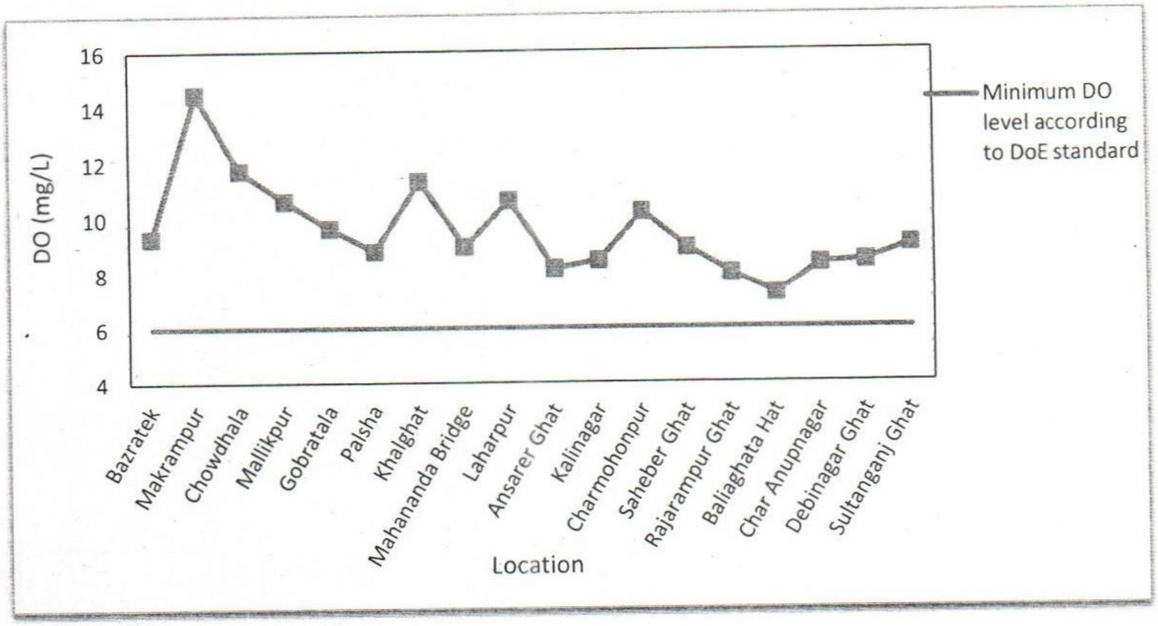

Figure 4.32: DO concentration in river water in the study area

Dissolved oxygen concentration the most important water quality parameter was found much higher than the minimum required level of DO concentration. Figure 4.31 shows DO concentration in river water in the study area.

4.4.5 Total Dissolved Solid

Water is a good solvent and picks up impurities easily. Pure water is tasteless, colorless, and odorless and is often called the universal solvent. Dissolved solids are referred to any minerals, salts, metals, cations or anions dissolved in water. Total dissolved solids (TDS) comprise inorganic salts (principally calcium, magnesium, potassium, sodium, bicarbonates, chlorides, and sulfates) and some small amounts of organic matter that are dissolved in water. TDS in drinking-water originate from natural sources, sewage, urban run-off, industrial wastewater, and chemicals used in the water treatment process, and the nature of the piping or hardware used to convey the water, i.e., the plumbing. In general, the total dissolved solids concentration is the sum of the cations (positively charged) and anions (negatively charged) ions in the water. Therefore, the total dissolved solids test provides a qualitative measure of the amount of dissolved ions but does not tell us nature or ion relationships. In addition, the test does not provide us insight into the specific water quality issues, such as Elevated Hardness, Salty Taste, or Corrosiveness. Therefore, the total dissolved solids test is used as an indicator test to determine the general quality of the water. The sources of total dissolved solids can include all of the dissolved cations and anions, but the following table can be used as a generalization of the relationship of TDS to water quality problems.

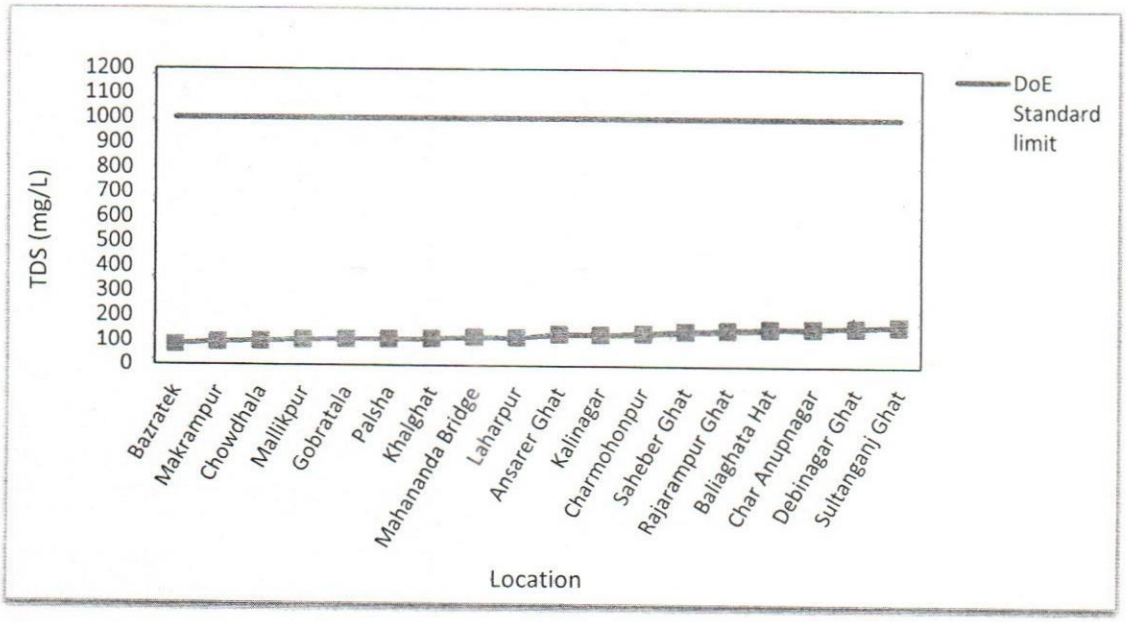

Figure 4.33: Total dissolved solids in the river water

Total dissolved solids in Mahanada river water were much lower than the permissible limit of DoE (Figure 4.32).

4.5 Socio-economic Point of View

Questionnaire surveys have been done from 230 respondents in the river bank area. In this study, simple random sampling method was used. The study was done on the basis of data collection through questionnaire survey, observation and discussion with limited participation of the people of the study area. Sample of respondents was selected from the river bank community randomly both male and female and they were interviewed through a structured questionnaire. A structured Questionnaire has prepared including causes of pollution, availability of fish, health hazards, use of river water and crop production etc. Public opinion is expressed in Figure 4.33 to Figure 4.36.

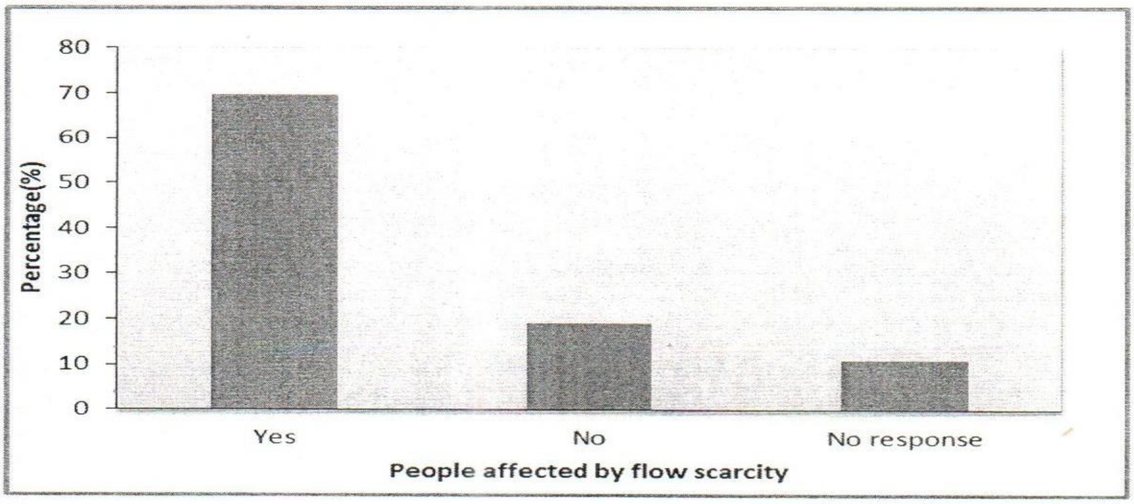

Figure 4.34: Effect of flow scarcity on human life

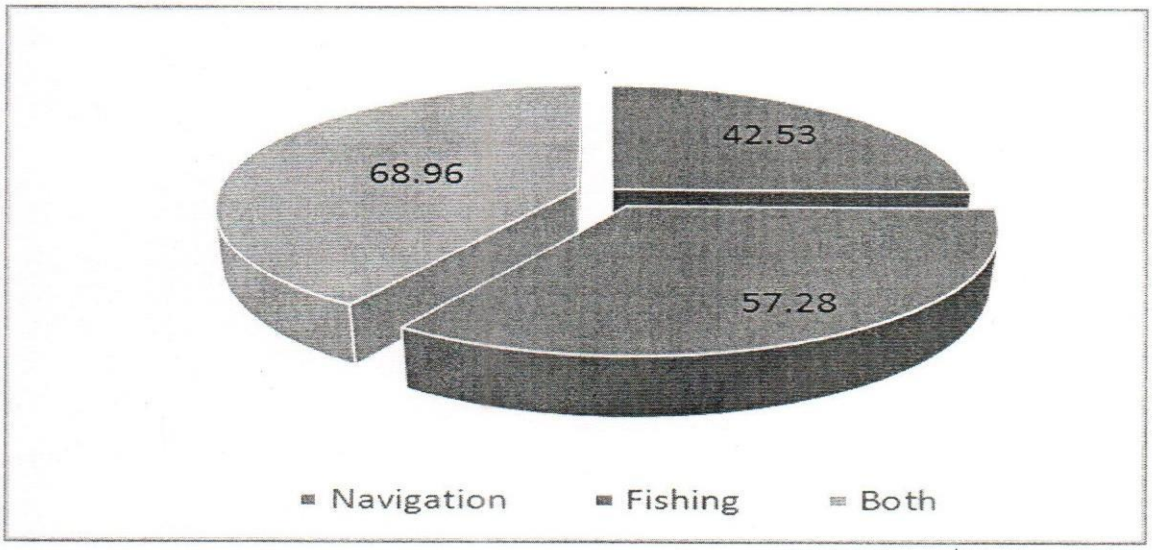

Figure 4.35: Affected Sector due to flow scarcity

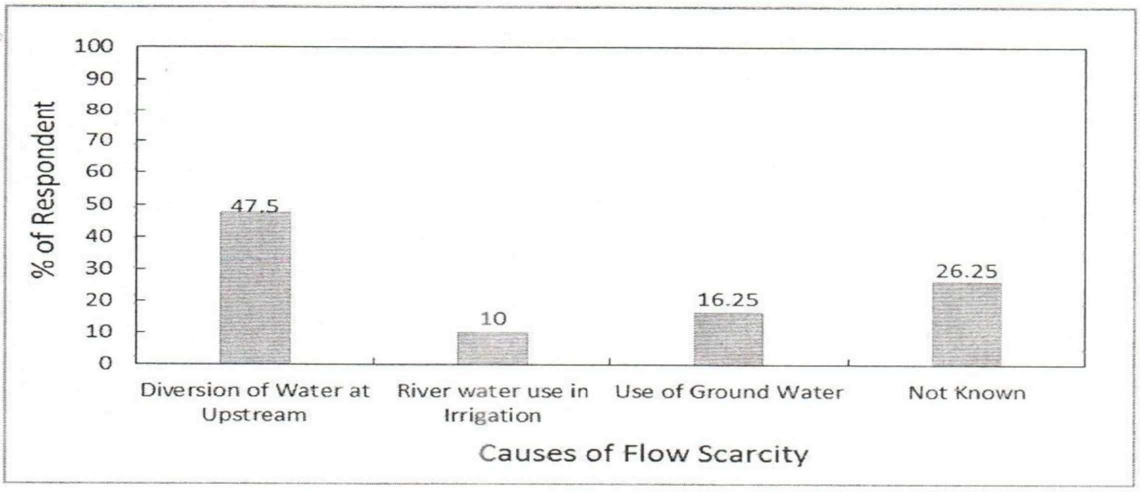

Figure 4.36: Causes of flow scarcity in public insight

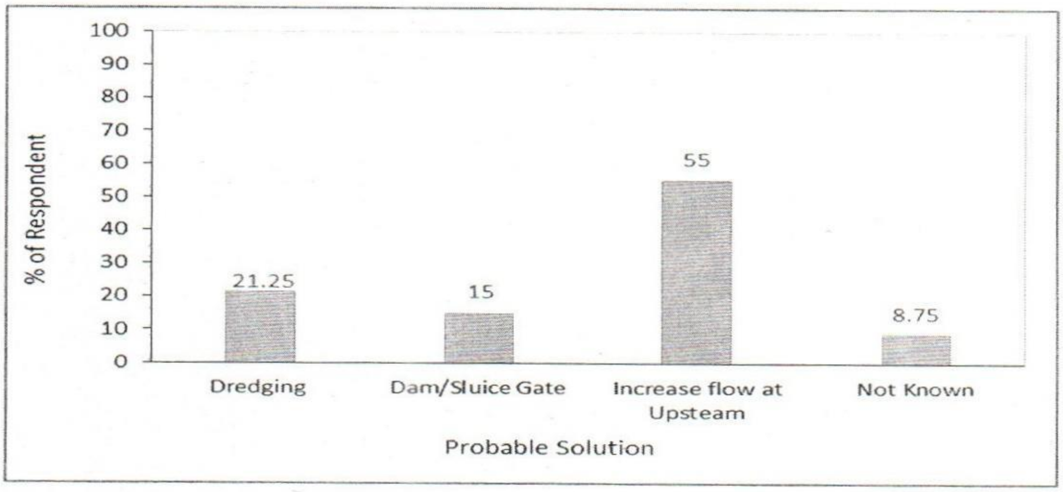

Figure 4.37: Flow scarcity solution in public insight

4.6 Discussion on Relationship among Different Parameters

In this study reach, cross-sections are laid out normal to the direction of flow at an interval of about 500 m distance is measured along the center line of the main channel. Since the river channel is the result of flowing water, magnitude and frequency of run-off events are major factors in determining the character of the river channel. It is therefore, possible to show qualitative relationships between river flow on one hand and different aspects of channel morphology like channel dimensions, shape, gradient etc. on the other. For a short term evaluation of changes in river parameters, an attempt has been taken for understanding and find out the interrelationship among the variables stated above and described hereafter.

4.6.1 Inter-relationships among Meander Parameters

Meander parameters of the river Mahananda have been measured from the spot images for the year 1983, 1984, 1992 and 1993. The images are prepared at a scale of 1: 1,00, 000. Since the upper course of the river is more or less stable despite being sinuous, the active lower course has been selected for developing relationships. All active bends of this reach have been taken into account for analysis.

The measurements of meander wavelength (M_L) and channel width (W) provide following average relationships for different years:

Year	Linear Relation
1989	$M_L = 29.58W$
1995	$M_L = 31.13W$
2001	$M_L = 31.82W$
2018	$M_L = 30.71W$

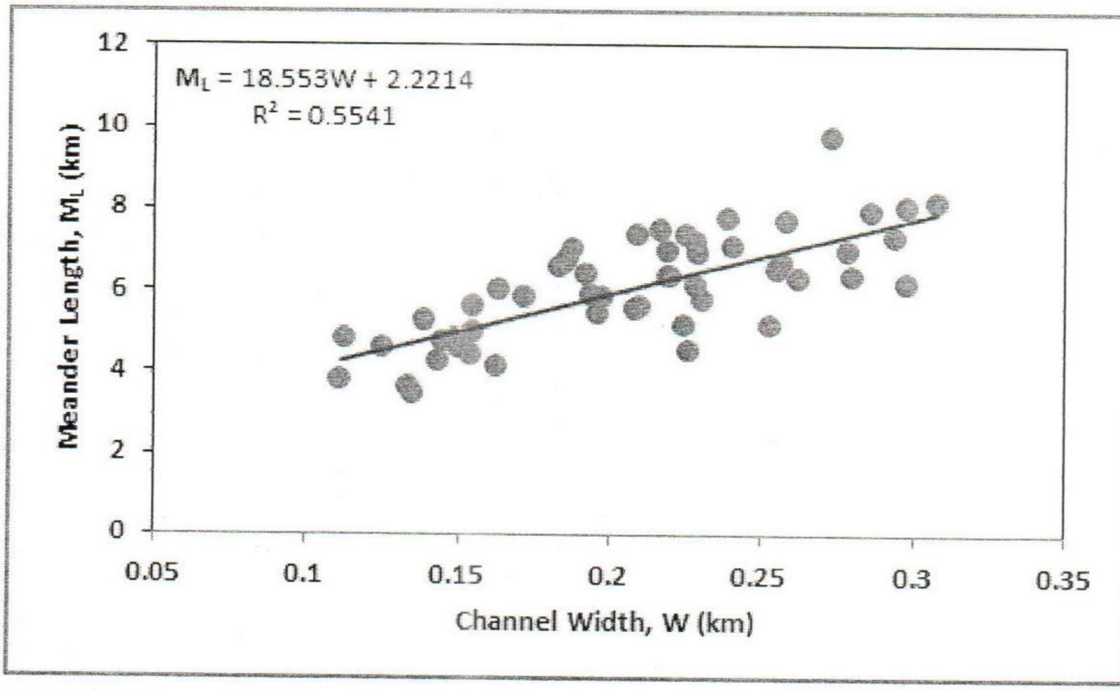

Figure 4.38 Linear Relationship between Meander Length (M_L) and channel width (W) for the period 1989 to 2018

The general relationship for whole period is as follows

ML = 5.1707 M 8-0.1365 where both Mi and MB are in Km.

Relationships between meander belt (MB) and channel width (W) have been developed for different years and shown hereunder:

Year	Linear Relation
1989	$M_B = 19.45W$
1995	$M_B = 18.36W$
2001	$M_B = 17.51W$
2018	$M_B = 19.44W$

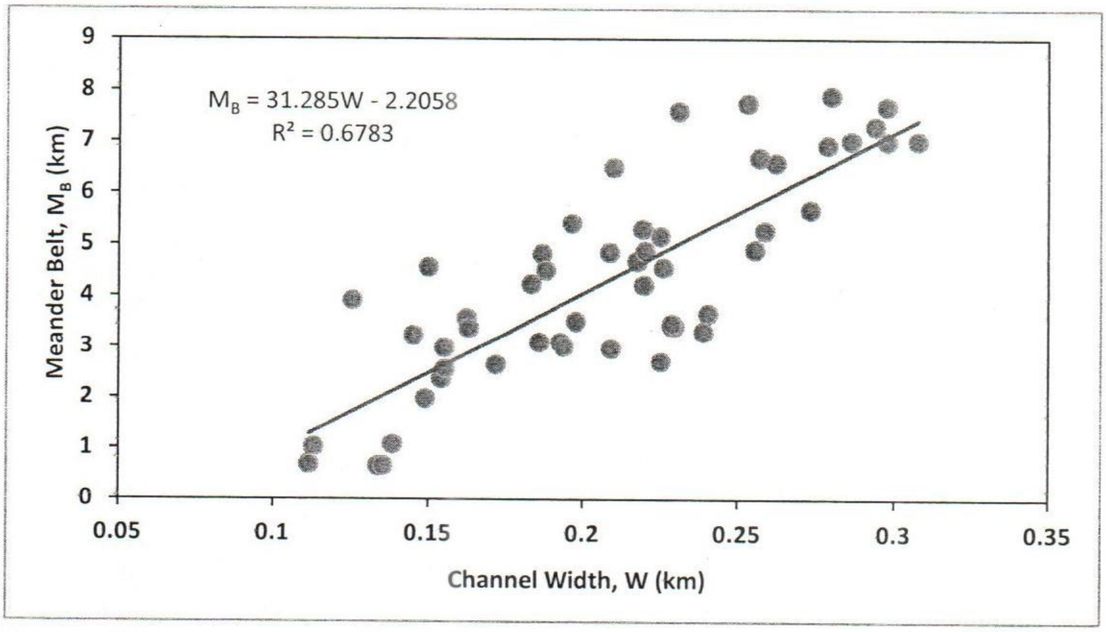

Figure 4.39 Linear Relationship between Meander Belt (MB) and channel width (W) for the period 1989 to 2018

The relationship between the meander belt (MB) and meander length (ML) for different years as found from the study has been shown below:

ML	=	1.42 MB	in	1989
ML	=	1.70 MB	In	1995
ML	=	1.82 MB	In	2001
ML	=	1.55 MB	In	2018

The above relationships show that from 1989 up to 2001 the ratio between meander length (ML) and meander belt (MB) gradually increased i.e. meander ratio decreased.

4.6.2 Inter-relationships among Geometric Parameters

4.6.2.1 Temporal Variation in the Area-Elevation Relationship

The temporal variation in the Area-Elevation relationship has been shown by plotting and superimposing the area versus elevation graph for three years. This is done for three x-sections covering the total stretch of the river. These three x-sections are: RMMA1, RMMA3 and RMMA10. As to first two x-sections it is done for the years 1984, 1987 and 1994 whereas for the third one it is done for the years 1984, 1987 and 1994. The temporal variation in the Area-Elevation relationship as observed at RMMA1 appears in the Figure 4.40.

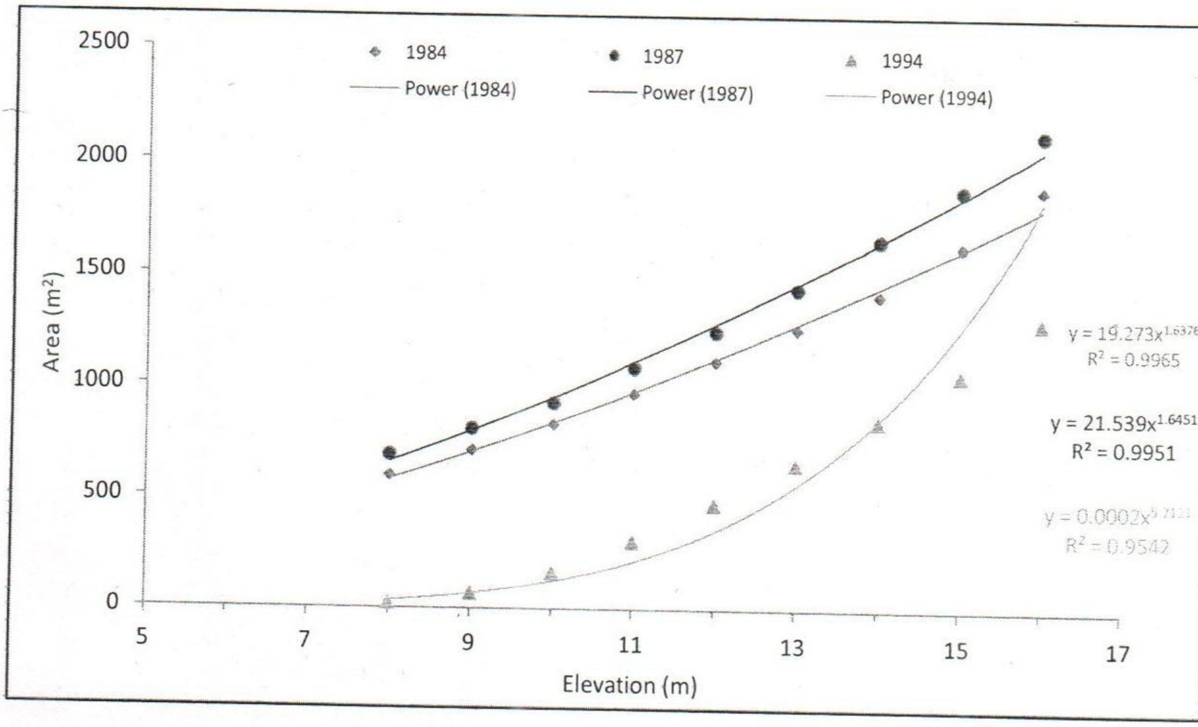

Figure 4.40: Area (A) versus elevation (EL) relationship at RMMA-1 (1984, 1987, 1994)

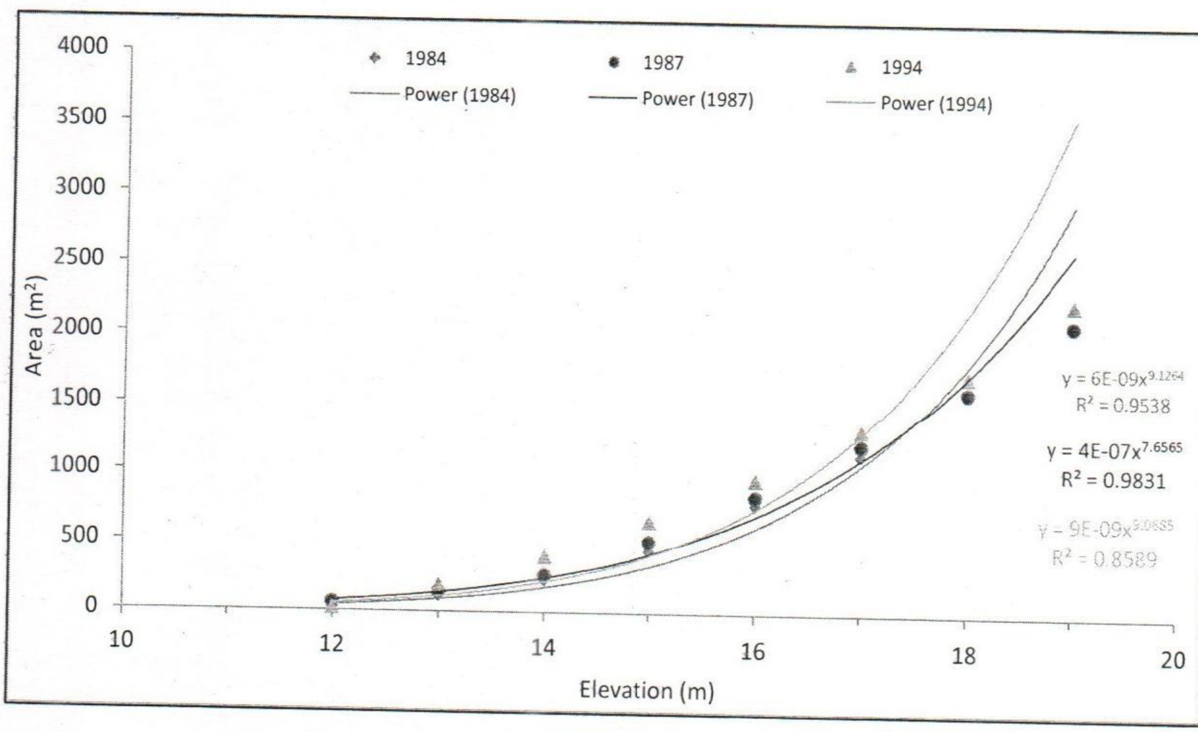

Figure 4.41: Area (A) versus elevation (EL) relationship at RMMA-3 (1984, 1987, 1994)

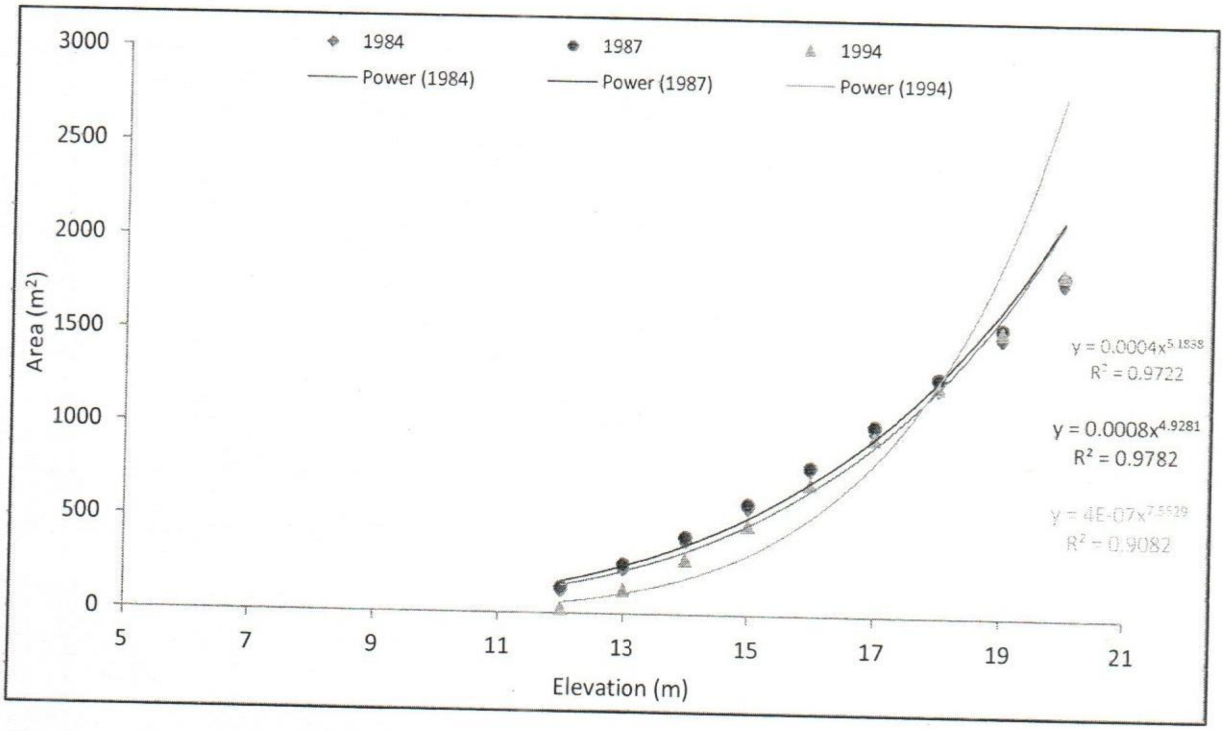

Figure 4.42: Area (A) versus elevation (EL) relationship at RMMA-10 (1984, 1987, 1994)

The figure shows that in 1984 situation a higher elevation is required to have the same x-sectional area compared to the situation in 1987. In 1994 situation a further higher elevation can result in the same x-sectional area. It only means that the lowest bed level of the river is going up with time i.e. aggradation is a dominant process in the river. As to the situation at RMMA3 it can be seen from the Figure 4.41 that substantial bed level rise occurred in 1987 compared to the situation in 1984. It is also indicative of the fact that the river also widened considerably during the period from 1984 to 1994. The little change between 1987 and 1994 situation resulted from a little bit widening of the river at that section rather than any further rise in the bed level. It means the river was more or less stable at that section in terms of bed level change. The temporal variation in the Area-Elevation relationship at RMMA10 for the years 1984, 1987 and 1994 has been shown in the Figure 4.42. It is noticeable from the graph that here also a relatively higher elevation was required for a given X-sectional area. However, unlike the situation in the previous two cases where it is caused mainly due to the narrowing of the river rather than rise in the bed level. The temporal variation in the Area-Elevation relationship for three x-sections at three different locations thus reveals the fact that the river underwent aggradation in the upper and middle course and narrowing in the lower course.

4.6.2.2 Temporal variation in the width and depth

The three trend lines for three different years the river assumes, different depths for a given width in its attempt to adjust itself to a quasi-equilibrium state. In this case, it is caused by bed leve variation, bank erosion and bank build up. In 1984 situation the rate of increase in the width is faster than the increase in the depth.

However, in both 1987 and 1994 situation, the rate of increase in the depth is much faster than the increase in the depth initially but it gradually decreases as both depth and width increase. The graph also reveals the prevailing aggradation process .

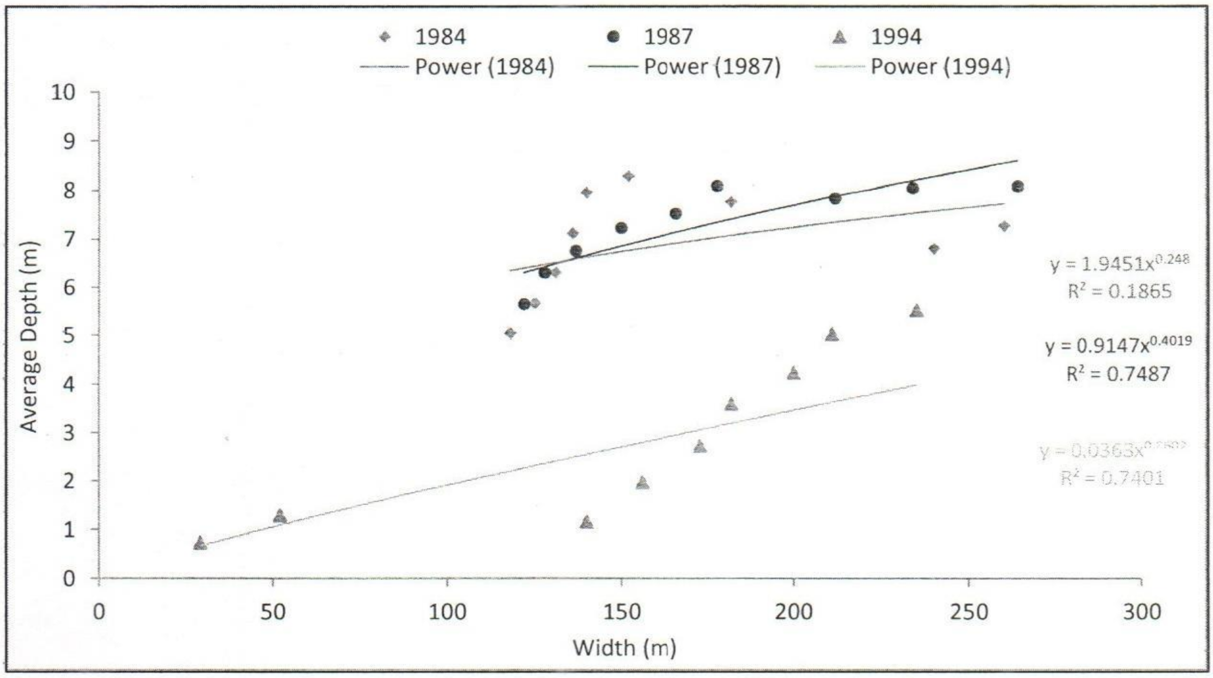

Figure 4.43: Average depth versus width relationship at RMMA-1 (1984, 1987, 1994)

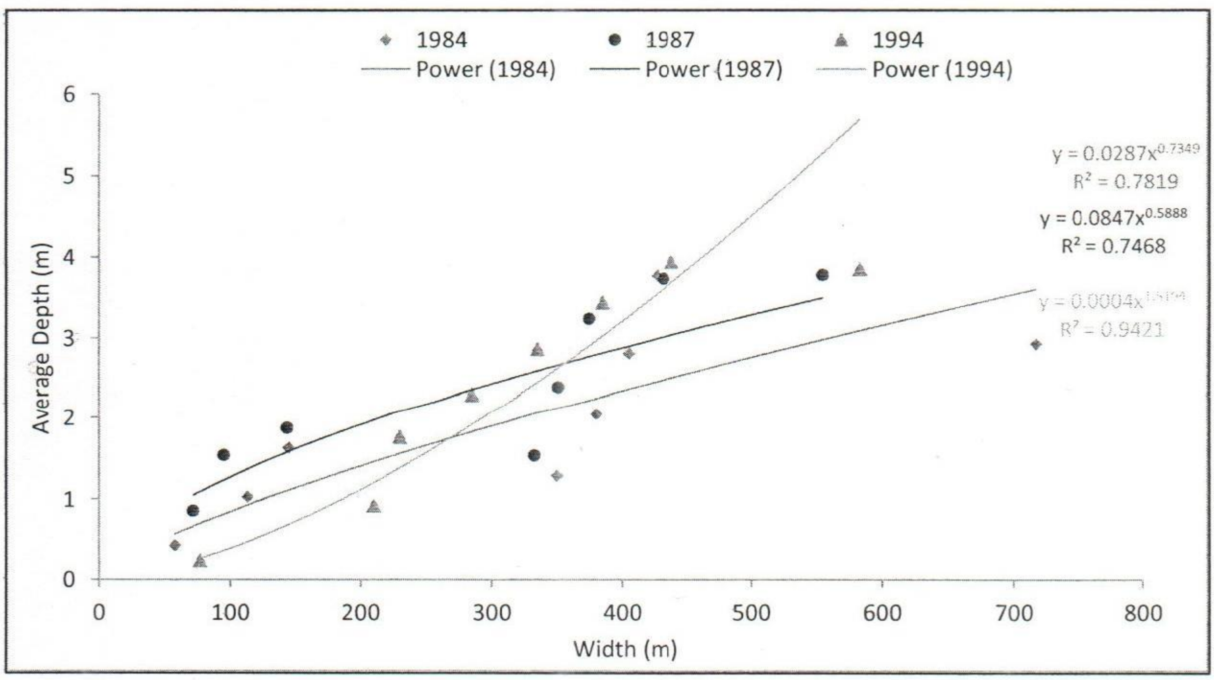

Figure 4.44: Average depth versus width relationship at RMMA-3 (1984, 1987, 1994)

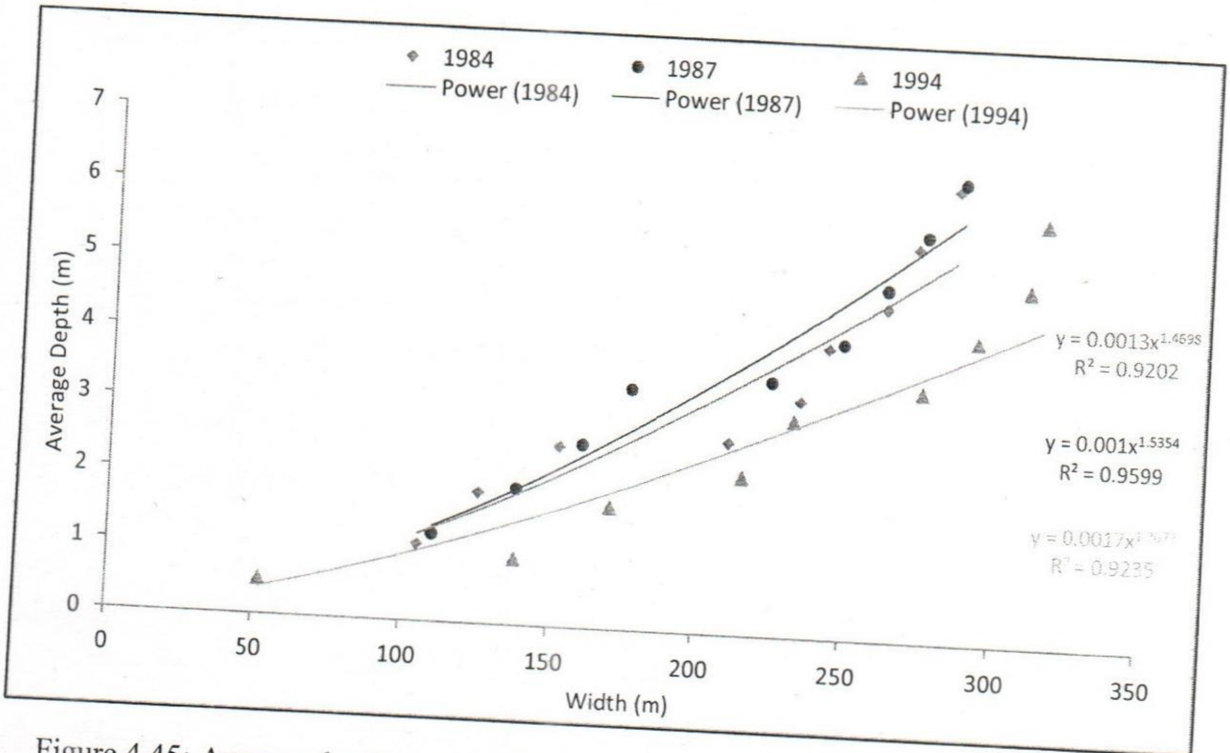

Figure 4.45: Average depth versus width relationship at RMMA-10 (1984, 1987, 1994)

The temporal variation in the Width-Depth relationship at RMMA1 appears in Figure 4.43. Here also it is very much clear that the river assumed different depths for a given width in different years and necessarily the curves indicate that the river was undergoing siltation during the considered time period. It can be concluded from the trend lines that in 1984 and 2001 situations the rate of increase in width was faster than the rate of increase in the depth. However ,in 1996situation reverse trend is noticeable. The gradual decrease in the depth with time for a given width indicates that aggradation and bank erosion were active at this location .

It can be seen from Figure 4.44 that at RMMA3 in all the three different years the depth was increased faster than the width. The slope of the curves indicates that this rate of increase was the highest in 1997 and the lowest in 1994. The narrowing of the river at this location is also visible from the curves.

4.6.2.3 Temporal variation in Mean Bed Level

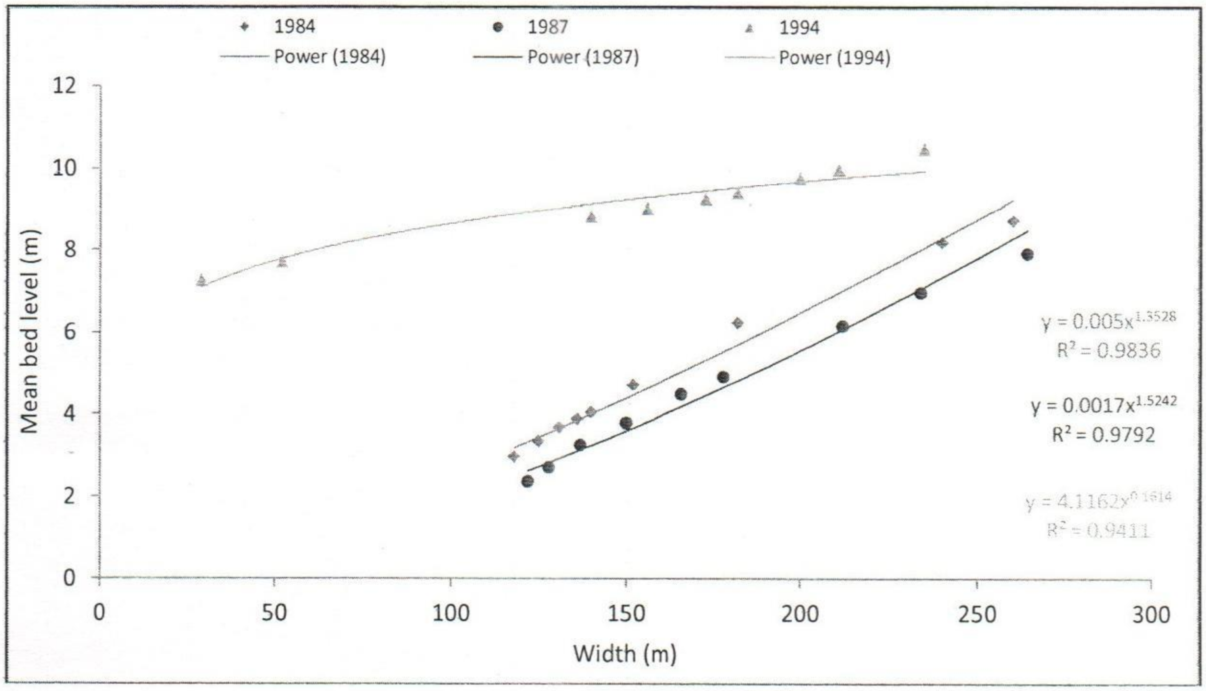

Figure 4.46: Mean bed level versus width relationship at RMMA-1 (1984, 1987, 1994)

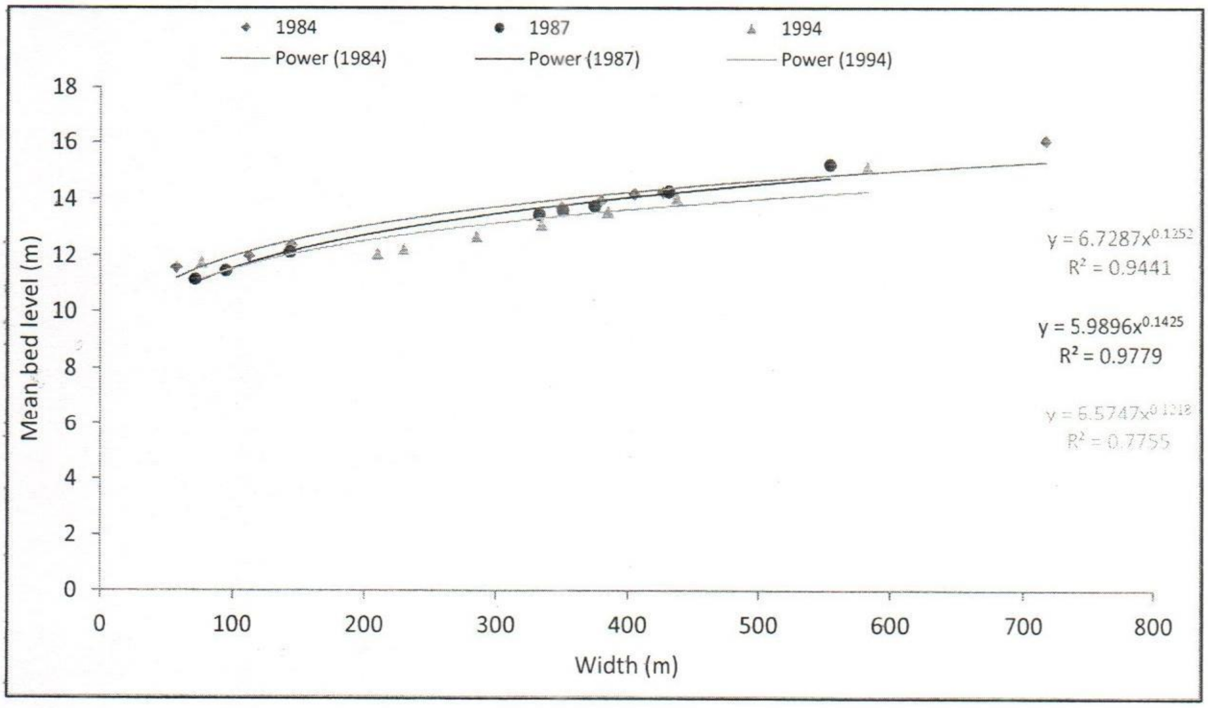

Figure 4.47: Mean bed level versus width relationship at RMMA-3 (1984, 1987, 1994)

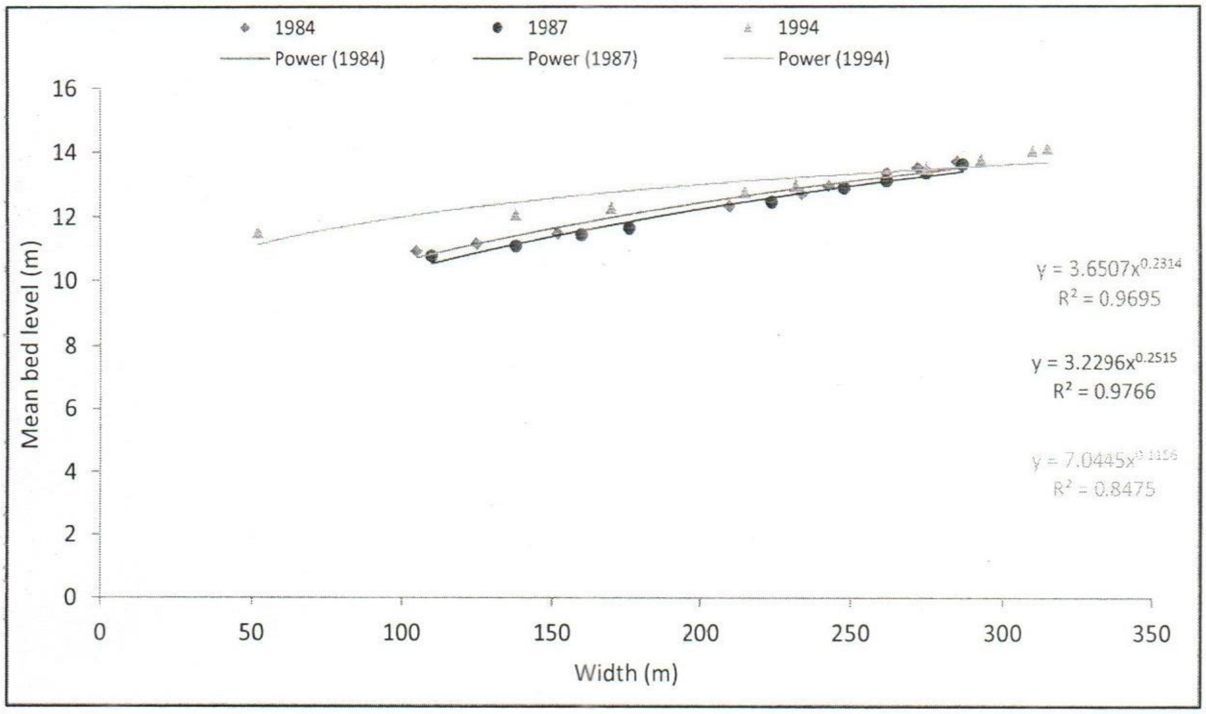

Figure 4.48: Mean bed level versus width relationship at RMMA-10 (1984, 1987, 1994)

At GRBGM8 this variation is shown between 1984 and 1987 (Figure 7.10). It is clear from the figure that for a given width the mean bed level went up in 1994 as compared to 1984 situation. It also indicates that bank erosion took place at that mean bed level.

5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Based on field observation, public consultation, data analysis and study outcomes the following conclusions have been drawn;

1. The Mahananda is a natural non-prismatic non-perennial mobile boundary meandering river.
2. Diversion of water at the upstream in the lean period is one of the major causes of flow scarcity in Mahananda.
3. It is observed from discharge hydrograph that discharge is gradually decreasing, sometimes even no flow condition occurs in lean period.
4. Minimum discharge of 9.82 m^3/s, 13.62 m^3/s, 5.55 m^3/s, and 0 m^3/s has been found for the years 1982, 1997, 2008 and 2016 respectively.
5. Minimum water level of river water shows a decreasing trend at Nawabjang sadar, Godagari and Paba over the period from 1980 to 2017.
6. Monthly average groundwater level of 1980, 2000 and 2017 shows a clear indication of lowering of groundwater level at all stations (Nawabjang sadar, Godagari and Paba).
7. A decreasing trend of minimum groundwater level is observed at Nawabjang sadar, Godagari and Paba.
8. Cropping pattern in the study area has been changed a lot and cropping intensity has been increased with mechanized agriculture. Thus extraction of groundwater is increased.
9. It is noticed that rainfall has minimum or no significant effect for the scarcity of flow in Mahananda.
10. From the geometric analysis along the river reach (upstream to downstream), it is noticed that the cross sectional area has gradually decreased, the width has suddenly increased at the downstream, the depth has gradually decreased and the width depth ratio has suddenly increased at the downstream.
11. From the calculations of sinuosity it is observed that the upstream valley is twisty, the middle valley is meandering and the downstream valley is highly meandering.
12. The migration of bends of Mahananda river in the lower reach has been counted 7 to 111 m/year.
13. Meander wavelength and meander belt are strongly correlated with the average channel width. It is also observed that the ratio of average meander wavelength to average mender belt is increased from 1989 to 2001 but the ratio has slightly decreased in the recent time.
14. Man-made intervention, i.e. about 10 km embankment has been found both in right and left bank in the Mahananda river.

15. The amount of Manganese found both in groundwater and river water is much higher than the DoE standard. Specially, it is dangerous threat for the groundwater users.
16. River water is comparatively safe from Arsenic but groundwater is highly contaminated with Arsenic.
17. It is found that Total Dissolved Solid (TDS) is much lower in the water than the permissible limit of DoE.
18. pH value is very good both in groundwater and river water.
19. From the questionnaire survey it is found that 70% people think that they are affected by flow scarcity and most vulnerable sectors are navigation and fishing from their point of view.
20. People think diversion of water is the main cause of flow scarcity in the Mahananda and availability of water at the upstream is the solution to the problem.

5.2 Recommendations

(i) Close interaction with the upper riparian country in order to have just share of dry season flow may be considered.

(ii) Steps may be taken for ensuring environmental flow in the Mahananda river.

(iii) A plan may be devised for storing rest of monsoon flow for use in the dry season.

(iv) Potential for constructing a barrage within the Bangladesh territory or constructing of weirs across the river at a number of locations may be considered.

(v) Construction of rubber dam could be a feasible solution to the dry season flow scarcity problem.

(vi) Feasibility of different interventions for augmenting dry season flow may be studied to decide about appropriate and sustainable solutions to the problem.

REFERENCES

ABM Mohsin and Emdadul Haque 2009. Diversity of Fishes of Mahananda River at Chapai Nawabganj district, Journal of Biological Science, Vol. 4, Page 828-831.

Ackers, P.; White, W.R. (1973). "Sediment Transport: New Approach and Analysis". Journal of the Hydraulics Division. ASCE. 99 (11): 2041–2060.

Akram, F., Rasul, M.G., Khan, M.M.K., and Amir, M.S.I.I., (2012): 'A Comparative View of Groundwater Flow Simulation Using Two Modelling Software - MODFLOW and MIKE SHE', in PA Brandner& BW Pearce (eds.) Proceedings of the Eighteenth Australasian Fluid Mechanics Conference, 3-7 December, Launceston, Tasmania, Australasian Fluid Mechanics Society, Hobart, Tasmania, Australia.

Ackers, P.; White, W.R. (1973). "Sediment Transport: New Approach and Analysis". Journal of the Hydraulics Division. ASCE. 99 (11): 2041–2060.

Ali, M.Y., 1982. Keynote address of Inland open water fisheries resources research. Proceeding of the National Seminar on Fisheries Research, (NSFR'82), BARC, pp: 18-24.

Albert Tuinhof, Karin Kemper, 2011. Mitigation of Arsenic contamination in Drinking Water Supplies of Bangladesh-the case of Chapai Nawabganj. Published by Ground Water Management Advisory Team (GW-MATE), World Bank, U.S.A.

Ariffin, J.; A.A. Ghani; N.A. Zakaira; A.H. Yahya (14–16 October 2002). "Evaluation of equations on total bed material load" (PDF). International Conference on Urban Hydrology for the 21st Century. Kuala Lumpur

Bhuiyan, A.L., 1964. Fishes of Dacca. 1st Edn., Asiatic Society of Pakistan, Dacca, pp: 148.

Cheng, Nian-Sheng (2002). "Exponential Formula for Bedload Transport". Journal of Hydraulic Engineering. 128 (10): 942. doi:10.1061/(ASCE)0733-9429(2002)128:10(942)

DoF, 2005. Fish Fortnight Souvenir: Department of Fisheries (DoF), Ministry of Fisheries and Livestock, Dhaka, Bangladesh, PP: 152.

Dietrich, W. E. (1982). "Settling Velocity of Natural Particles" (PDF). Water Resources Research. 18 (6): 1615–1626. Bibcode: 1982WRR.. 18.1615D. doi:10.1029/ WR018i006 p01615.

Fernandez-Luque, R; van Beek, R (1976). "Erosion and transport of bedload sediment". Jour. Hyd. Research. 14 (2).

Francis Hamilton (1822): An Account of the fishes found in the River Ganges and its branches. Printed for Archibald Constable and Company, Edinburgh; And Hurst, Robinson, and Co. 90, Chrapside, London.

Google Earth, Satellite Image 2016 of Mahananda River

Haque, A.K.M., 1982. Keynote address on Inland culture fisheries in Bangladesh: Need for a co-ordinated action programme. Proceedings of the National Seminar of Fisheries Research, (NSFR'82), BARC, pp: 7-17.

Haque, M. Inamul, 2008. Water Resources, Management in Bangladesh, published by CharuFerdousiNaima, Anushilan, Chuadanga & Dhaka.

Harris, Courtney K. (March 18, 2003). "Lecture 9: Suspended Sediment Transport II" . Sediment transport processes in coastal environments. Virginia Institute of Marine Science. Archived from the original on 28 May 2010. Retrieved 23 December2009.

Hickin, E.J. (1,974):The Development of Meanders in Natural River Channels, American journal of science, 274, pp. 414-42.

Hickin, E.F&Nanson, G.C. (1975) : The Character of Channel Migration on the Beatton river, North-east British Columbia, Canada, Bull. of the Geo. Society, of America, 86, April, PP.487-94.

Hook, J.M. (1987): Discussion on "Lateral Migration Rates of River Bends, by Hickin, E.J.andNanson, .G:C.,'1984, Nov.-Vol. 110, No. 11, J: of HydEngg., ASCE, Vol. 113, No.7, July, pp 915-918.

Hagerty, D.J. (1991) :Piping/Sapping Erosion. 1 :Basic Considerations, ASCE Journal of Hydraulic Engineering, Vol. 117, NO.8.

Hossain, M:M. (1989) : Geomorphic Characteristics of the Ganges upto Brahmaputra Confluence, Final Report, R02/89, IFCDR, BUET

IWM (2015) : Feasibility Study for Irrigation using Mathematical Modelling along the Bank of Mohananda River including EIA in ChapaiNawabganj District. Final Report.

IWM (2012) : Groundwater Resource Study and DSS Development of Rajshahi, Naogaon, ChapaiNawabganj, Pabna and Natore Districts and also remaining Districts

IWM (2015) : Feasibility Study for Irrigation using Mathematical Modelling along the Bank of Mohananda River including EIA in ChapaiNawabganj District. Final Report.

Islam, M.S. and M.A. Hossain, 1983. An account of the fisheries of the Padma near Rajshahi. Raj. Fish Bull., 1: 1-3.

IWM (2006) : Groundwater Model Study for Deep Tubewell Installation Project in Barind Area. Final Report.

Inglis, C.C (1949) :The Behaviour and Control of Rivers and Canals, Pt. 1, CWPINRS, Res. pub. No. 13, Poona

Islam, M. M., P. Kanungoe.and S. M. Anwaruzzaman(1999) :Characteristics of Bank Migration in Alluvium: A Review, RRI Technical Journal, Vo1.06, No.01, November 1999. pp 86-97.

Inglis, C.C. (1947) Meanders and Their Bearing on River Training, Proc of the Inst. of Civil Engrs. London, Maritime & Water Engg div.

Klaassen, G. J. and GredMasselink(1992) : Planform Changes of a Braided River with Fine Sand as Bed and Bank Material, 5 th International Symposium on River Sedimentation, April1992, Karlsruhe, F R of Germany.

Kuhnle, R. A.; Wren, D. G.; Langendoen, E. J.; Rigby, J. R. (2013). "Sand Transport over an Immobile Gravel Substrate". Journal of Hydraulic Engineering. 139 (2). doi:10.1061/(ASCE)HY.1943-7900.0000615

Lane, E.W. (1955). The importance of fluvial morphology in hydraulic engineering. Proc. ASCE, 81(745):1-17.

Lane, E.W. (1957). A study of the shape of channels formed by natural stream flowing in erodible material, M.R.D. Sediment Series No.9, U.S. Army Engineer Division, Missouri River, Corps Engineers, Omaha, NE.

Leopold, L.B., and Maddock, Jr., T. (1953). The hydraulic 9comclry or stream channels and some physiographic implications, U.S: Geol. Surv. Prof. r\q)(~r 242, Washington, DC, 57 p.

Leopold, L.B., and Wolman, M.G. (1957). Rivo: CllW1IHJi piill (braided, meandering and straight). U.S. Geol. Surv. Pr I. I J;lp r ; I I, Washington, DC.

Dury, GH (1955). Bed width and Wave length in Meandering Valleys, Nature, 176-31.

Dury, G.H. (1965): Theoretical Implication of Under fit Streams- General Theory of Meandering Valleys, USGS Prof. Paper 452-G.

Meyer-Peter, E; Müller, R. (1948). Formulas for bed-load transport. Proceedings of the 2nd Meeting of the International Association for Hydraulic Structures Research. pp. 39–64.

Mortuza, M.G., 1982. Fish and fisheries of the river Barnai: Flood plain fisheries (FCD) project. M.Sc. Thesis, Department of Zoology Rajshahi University.

Miller, M.C.; McCave, I.N.; Komar, P.D. (1977). "Threshold of sediment motion under unidirectional currents". Sedimentology. 24 (4): 507–527. Bibcode:1977Sedim..24..507M. doi:10.1111/j.1365-3091.1977.tb00136.x.

Nikora, V; Goring, D; McEwan, I; Griffiths, G (2001). "Spatially averaged open-channel flow over rough bed". J. Hydraul. Eng. 127(2). doi:10.1061/ (ASCE)0733-9429 (2001)127:2(123)

Osman, A.M. and CR Thorne (1988) : Riverbank Stability Analysis. 1 :Theory, ASCE Journal of Hydraulic Engineering, Vol. 114, No.2.

Parker, G.; Klingeman, P. C.; McLean, D. G. (1982). "Bedload and Size Distribution in Paved Gravel-Bed Streams". Journal of the Hydraulics Division. ASCE. 108 (4): 544–571.

Pellachini, Corrado (2011). Modelling fine sediment transport over an immobile gravel bed. Trento.

Thorne, C.R. and Osman, A.M. (1988). Riverbank stability analysis II: Applications," Jl. of Hydraulic Engineering, ASCE, 114(2):151-172.

Rahman, A.K.A., 2005. Freshwater Fishes of Bangladesh. Zoological Society of Bangladesh, Dhaka, Bangladesh.

Rahman, M.A., Uddin, M.A.H., Harun - or – Rashid, M., and Shamsunnahar, M. (2011): Geographical posiion and aquatic resources of the river Mahananda. J. Agrofor. Environ. 5 (2): 109-112, 2011, ISSN 1995 -6983.

Shafic, M. and M.M.A. Quddus, 2001. Bangladesher Matshaw Sampad (Bangla). Kabir Publications, Dhaka, Bangladesh, pp: 485.

Sharad K. Jain; Pushpendra K. Agarwal; Vijay P. Singh. (2010) : Hydrology and Water Resources of India. P-360. Google books. Retrieved 2010-05-14.

Shahid, S. and Hazarika, M.K. (2010): Groundwater Drought in the Northwestern Districts of Bangladesh. Water Resources Management, August 2010, Volume 24, Issue 10, pp 1989–2006

Sarkar SK, Bhattacharya A, Bhattacharya B. (2003) : The river Ganga of northern India: an appraisal of its geomorphic and ecological changes. Water Sci Technol. 2003;48(7):121-8.

Swapan Kumar Maity and RamkrishnaMaiti, Sediment Load: Concentration and Transport, Sedimentation in the Rupnarayan River, 10.1007/978-3-319-62304-7_5, (61-78), (2017).

Sarah Praskievicz, A coupled hierarchical modeling approach to simulating the geomorphic response of river systems to anthropogenic climate change, Earth Surface Processes and Landforms, 40, 12, (1616-1630), (2015).

Schumm, S.A. (Ed.) (1972) River Morphology. Benchmark papers in geology. Dowden, Hutchinson & Ross Inc. Stroudsburg, Penn. USA, 429 pp.

Schumm, S.A. (1963) Sinuosity of alluvial rivers in the Great Planes. Bull. Geol. Soc. Am.,.}4, pp: 1089-1100

Talwar, P.K. and A.G. Jhingran, 1991. Inland Fishes of India and Adjacent Countries. Vol. 1-2, Oxford and IBH Publishing Co. Pvt. Ltd., New Delhi, Calcutta, India, Pages: 1158.

U Habiba, R Shaw and Y Takeuchi, 2012. Farmer's Perception and Adaptation Practices to cope with Drought: Perspectives from North-Western Bangladesh, published in the International Journal of Disaster Risk Management.

UNDP (United Nation Development Programme) (1982) Ground-water survey: the hydrogeological conditions of Bangladesh.Technical Report DP/UN/BGD-74-009/1, UNDP, New York MacDonald (1982) : Northwest Bangladesh Groundwater modelling Study, Sir M MacDonald & Partners England, Final Report.

Walker, T.R., Grant, J. (2009) Quantifying erosion rates and stability of bottom sediments at mussel aquaculture sites in Prince Edward Island, Canada. Journal of Marine Systems. 75: 46-55. doi:10.1016/j.jmarsys.2008.07.009

Wiberg, Patricia L.; Dungan Smith, J. (1989). "Model for Calculating Bed Load transport of Sediment". Journal of Hydraulic Engineering. 115: 101. doi:10.1061/(ASCE)0733-9429(1989)115:1(101)

Wilcock, Peter R.; Crowe, Joanna C. (2003). "Surface-based Transport Model for Mixed-Size Sediment". Journal of Hydraulic Engineering, 129 (2): 120. doi: 10.1061/ (ASCE)0733-9429(2003)129:2(120)

Wilcock, P. R. (1998). "Two-fraction model of initial sediment motion in gravel-bed rivers". Science (280): 410-412. Bibcode: 1998Sci..280-410W. doi:10.1126/ science. 280.5362.410

Wilcock, Peter R.; Kenworthy, T. (2002). "A two-fraction model for the transport of sand/gravel mixtures". Water Resour. Res. 38 (10): 1194. Bibcode:2002WRR....38. 1194W. doi:10.1029/ 2001WR000684

Wilson, K. C. (1966). "Bed-load transport at high shear stress". J. Hydraul. Div. ASCE. 92 (6): 49–59.