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Channel Planform Dynamics of the Ganga-Padma System, India

by

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ABSTRACT

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The Landsat programme, which started in 1972, initiated an era of space-based Earth observation relevant to the study of large river systems through the provision of spatially continuous, synoptic and temporally repetitive multi-spectral data. Free access to the Landsat archive from mid-2008 has enabled the scientific community to reconstruct the Earth's changing surface and, in particular, to reconstruct the planform dynamics of the world's largest rivers. The present research reconstructs the planform dynamics in the lower reaches of one of the Asian mega-rivers, the River Ganga-Padma (Ganges), from 1972-2010 using the Landsat archive. The research based on sequential river planform maps generated from the time series revealed a periodic pattern of evolution of the river system over the study period which began by means of meandering at four locations. The meander bends increased in sinuosity until chute cut-offs were triggered, returning the river to a state similar to that at the beginning of the sequence. This periodic pattern is constrained by natural and artificial hard points, and by the Farakka Barrage, meaning that the observed cyclic pulsing is likely to continue into the future.

The characteristics and dynamics of meandering rivers have been the subject of extensive research, though the mechanisms involved are still not completely understood. Presently, availability of archival satellite sensor data at regular and frequent intervals for almost four decades presents a great potential for increasing our understanding of the natural processes of meander growth. Though early research indicates that meander growth can be explained by instability of alternate bars in a straight channel, but research based on field data and simulation models have shown that instability of river meanders is an inherent property and the meanders reach a critical value of sinuosity when cut-offs occur and then the complex system undergoes an self-adjusting process. The meander dynamics of the lower reaches of the Ganga-Padma system has been studied in the context of threshold response of a complex system. A conceptual model was developed based on spatial information from the sensor data and quantitative information on river metrics to explain the behaviour of the river system including evidence for self-organising criticality and the attempts of the river to reach dynamic equilibrium. The meandering channel pattern with a tendency of braiding of the river Ganga-Padma were explained based on existing empirical models as well as models based on mobility number and channel stabilization criterion. The threshold for chute cut-off was explored and subsequently the conditions for soft avulsion / branching were studied which showed that the condition for chute cut-off in the Ganga-Padma system is not due to bankfull flow velocity and the super elevation of flow at the centreline of channel but may be due to lack of vegetation stabilization on the Ganga-Padma floodplain.

The effect of tectonics and meandering in the moderately paced avulsion of the Ganga-Bhagirathi system to the present Ganga-Padma system was modelled in the present research. It was found that gradient advantage and bend upstream of bifurcation does not result in modelled avulsion as observed in small and medium rivers and large rivers in tectonically inactive regions. A tectonic uplift results in a modelled avulsion period consistent with historical observations. It was found that backwater effect and high sediment mobility keep both bifurcated channels active to attain an anabranching pattern. The backwater effect was found to play an important role for sustaining the anabranch planform of many of the largest rivers of the world.

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DECLARATION OF AUTHORSHIP

I, Niladri Gupta

declare that the thesis entitled

Channel Planform Dynamics of the Ganga-Padma System, India

and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

this work was done wholly or mainly while in candidature for a research degree at this University;
where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
where I have consulted the published work of others, this is always clearly attributed;
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I have acknowledged all main sources of help;
where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
parts of this work have been published as:
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Signed: …………………………………………..

Date:…………………………………………….

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Definitions and abbreviations

GBM	Ganga – Brahmaputra – Meghna basin
IGB	Indo-Gangetic Brahmaputra Plain
IRS	Indian Remote Sensing Satellite
LGP	Lower Ganga Plain
LISS	Linear Imaging Self Scanner
MGP	Middle Ganga Plain
MSL	Mean sea level
MSS	Multi Spectral Scanner
SOC	Self-organising criticality
SOI	Survey of India
TM	Thematic Mapper
UGP	Upper Ganga Plain
USGS	United States Geological Survey

To Titli

"The frequent alterations in the course of the Ganges, and of the rivers which flow through Bengal, have been a subject of wonder to the generality of Europeans residing in these provinces; although to the natives, who have long witnessed such changes, the most remarkable encroachments of the rivers, and deviations of the streams, are productive of little surprise.

It is chiefly during the periodical floods, or while the waters are draining off, that the greatest mischief is done; and if it be considered, that at the distance of two hundred miles from the sea, there is a difference of more than twenty five feet in the perpendicular height of the water, at this season, while at the outlets of the rivers (excepting the effect of the tides) they preserve nearly the same level at all seasons, some idea may be formed of the increased velocity with which the water will run of, and of the havoc which it will make on the banks. Accordingly, it is not unusual to find, when the rainy season is over, large portions of the bank sunk into the channel; even whole fields and trees, which, with the growth of a century, had acquired strength to resist the most violent storms, have been undermined and hurled into the stream."

Excerpts from the paper "*On the course of the Ganges through Bengal by Major R. H. Colebrooke published in the Transactions of the Asiatic Society in 1801"*

1 Raging Rivers: Always on the Move

A river basin is a distinct hydrological unit and has its own 'geo-bio-cultural' interactions (Chakrabarti, 1998). Any change in water-sediment regime within a river basin, triggered by either natural or anthropogenic causes has a lagged effect on the downstream activities of the river in terms of morphology as well as lateral bankline stability. This, in turn, affects the integrity of the riparian agriculture and can threaten the infrastructure, economy and social cohesion of riparian communities. Fluvial systems adjust their floodplains and channels to a combination of controls and a strong correlation exists between channel patterns of rivers and the sedimentological characteristics of the floodplain (Nanson and Croke, 1992; Bridge, 2003). Fluvial systems respond to changes in regional physiography, hydrology, and sediment load by changing their hydraulic geometry and channel pattern (Nanson and Knighton, 1996). Although basic knowledge of fluvial geomorphology comes from the study of small and medium rivers (Lambert and Walling, 1987;Leeks *et al.*, 1988;Hooke, 1995; Winterbottom, 2000; Kleinhans *et al.*, 2009), theoretical models (Ikeda *et al.*, 1981; Eaton *et al.,* 2004; Parker and Andrews, 1986; Mosselman, 1995; Stølum, 1996, Kleinhans *et al.*, 2008, 2011) and laboratory flume studies (Friedkin, 1945; Smith *et al.*, 1998; Kleinhans *et al.*, 2010), it is recognised that large rivers are unique fluvial systems, in terms of controls, processes and from a management point of view (Potter, 1978; Junk *et al.*,1989; Makaske, 2001; Latrubesse *et al.,* 2005; Gupta, 2008; Latrubesse, 2008).

1.1 Tropical Rivers

The tropical regions of the world contain the world's largest rivers. The rivers of tropical regions generally have large catchment areas, very high discharge and due to the complexity of the climate systems in the tropics can be divided into various regimes based on rainfall distribution, water available from glaciers feeding the river systems and some combination of the two (Latrubesse *et al.*, 2005). Moreover, due to their large size and extent, knowledge of such large river systems is still limited. Various studies have been carried out on large tropical rivers investigating their geomorphology (Coleman, 1969; Baker, 1978; Thorne *et al.*, 1993; Sinha, 1996; Goswamy, 1998; Latrubesse and Stevaux, 2002), sedimentological processes (Smith, 1986; Santos and Stevaux, 2000; Warne *et al.*, 2002), flood (Sinha and Jain, 1998; Latrubesse *et al.*, 2002) and tectonic / fluvial processes (Iriondo and Suguio, 1981; Ouchi, 1985; Latrubesse and Rancy, 2000; Schumm *et al.*, 2000). Alluvial rivers are generally divided into three main categories based on their planform (Schumm, 1977); straight, meandering and braided (Leopold and Wolman, 1957; Schumm and Khan, 1972; Lewin and Brewer, 2001). Rivers also exhibit a variety of the above mentioned channel forms and, particularly in large basins, can show transitional characteristics. Tropical rivers are found to drain regions which are often highly populated. For example the Yangtze basin, has one of the largest populations in the world while on the other hand the Ganges-Brahmaputra basin is the most densely populated (Haque and Hossain, 1988; Wasson, 2003; Immerzeel *et al.*, 2010), with a chaotic urban growth and a high demand for water. Amongst the various tropical rivers of the world, the Asian rivers are prone to flood due to high discharge during the monsoon season. The Asian rivers support a huge population and the rivers are an important source of water for irrigation, domestic and industrial consumption. However, the flooding characteristics of these rivers and ensuing bank erosion are responsible for loss of fertile agricultural land, life and property. Anthropogenic interference by construction of dams and barrages often affects the river systems leading to aggradation and degradation in certain reaches and changes in the natural ecosystem of the rivers due to changes in the supply of sediments and nutrients (Vorosmarty *et al.*, 2003; Latrubesse *et al.*, 2005).

1.2 Himalayan Rivers

The Himalayan Rivers in India reveal certain special characteristics because they undergo large seasonal fluctuations in flow and sediment load. The rivers are adjusted to an array of discharges and exhibit morphologies related to high-magnitude floods. The flow pattern of the Himalayan rivers is somewhat governed by snow melt from the Himalayas although the rivers also exhibit high discharge variability due to flood peaks during the summer monsoon and low discharge in the remaining months. Rivers in the Ganga-Brahmaputra plain exhibit a 40-50 times greater discharge (Figure 1-1) during the monsoon months (June – September) compared to the non-monsoon months (Sinha and Friend, 1994; Sinha and Jain, 1998). The highly dynamic environment with extreme variability of discharge and sediment load results in a dynamic morphology. Due to the hydro-climatic and morpho-tectonic setup many Himalayan rivers display unusual and uncommon characteristics (Kale, 2002). One of the striking characteristics is that the rivers originating from the Himalayan orogenic belt are highly sediment laden and contribute 20% of the global sediment input into the oceans (Milliman and Meade, 1983). For example, the Ganga and Brahmaputra basins transport about 900 – 1200 million tons of sediments annually (Latrubesse *et al.*, 2005).

Amongst the major Himalayan river system, the Ganga is one of the largest in the world. The river has its origin at the Gangotri glacier in the north-western Himalayas and traverses a distance of 2525 km to the sea. The river derives its fluvial sediment from the northern part of the Indian subcontinent and drops it in the Ganga-Brahmaputra delta as well as in the Bengal submarine fan (Singh *et al.,* 2007). Along with the Brahmaputra and the Meghna, the Ganga River is responsible for the creation of one of the largest deltas and deep sea fans with one of the thickest sedimentary sequences in the world (Singh *et al.,* 2007).

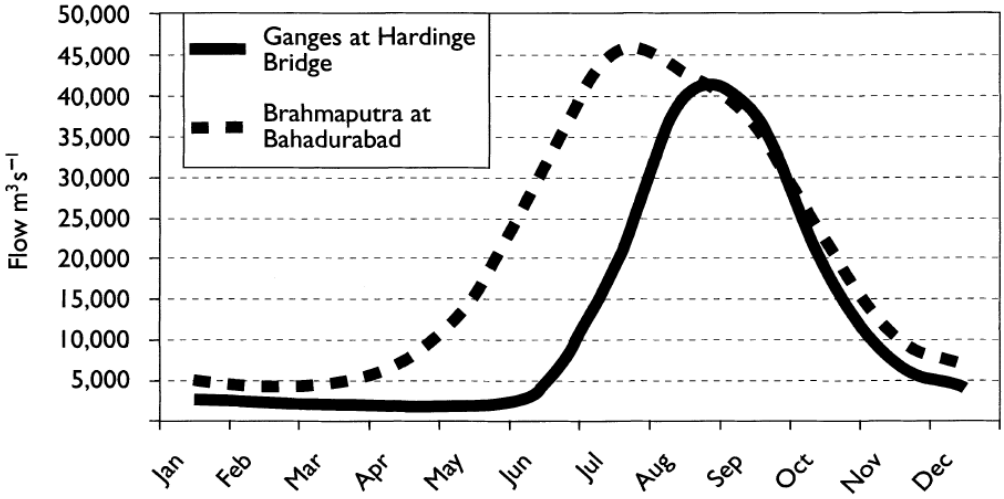

Figure 1-1[1]Annual average hydrograph of Ganga and Brahmaputra (Source: Brichieri-Colombi and Bradnock, 2003)

The Indo – Gangetic – Brahmaputra (IGB) plains (Figure 1-2) are known to engineers and earth scientists for a long time for their dynamic character. Due to a general lack of cohesive bank materials and the presence of erodible bank materials, the rivers in the IGB plain respond to large changes in discharge and sediment load by shifting their courses and / or by dramatically changing their morphology and bedforms. Evidence of this can be found by the presence of abundant ox-bow lakes, meander scars and abandoned channels throughout the IGB plains (Kale, 2002).

1.3 Planform dynamics of the River Ganges

The Ganga basin is considered a sub-part of the IGB plains and, in geological terms, is an important consequence of the Himalayan foreland. The River Ganga is characterised by changes in its course over its recorded history, particularly in its seaward reaches before entering the Bay of Bengal. The river is prone to bank erosion (Appendix 8.1) leading to changes in its planform during high discharge. The lateral migration of the river results in displacement of population and loss of fertile agricultural land as it is one of the most densely populated regions of the world. Though loss of fertile agricultural land from one part of the river ultimately leads to build up of new fertile land further downstream but the problem lies in the fact that the Ganga-Padma system is a trans-boundary river between India and Bangladesh with

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one bank of the river being part of India and the other bank being part of Bangladesh below the Farakka barrage. Thus land lost in India is actually gained in Bangladesh and vice versa leading to permanent loss of land for the owner giving rise to a more complex socio-political issue. Similar complex socio-political situation exists above the barrage where the river banks are shared between the Indian states of Bihar and West Bengal leading to a similar situation where land lost in West Bengal is actually gained in Bihar. The socio-political issue will not be explored in the present research and will focus mainly on the morphological aspects of the cause and effect of the change. Changes in planform of the river have been recorded from as early as pre-800 AD as mentioned in historical literature (Colebrooke, 1803; Hayden and Pascoe, 1910).

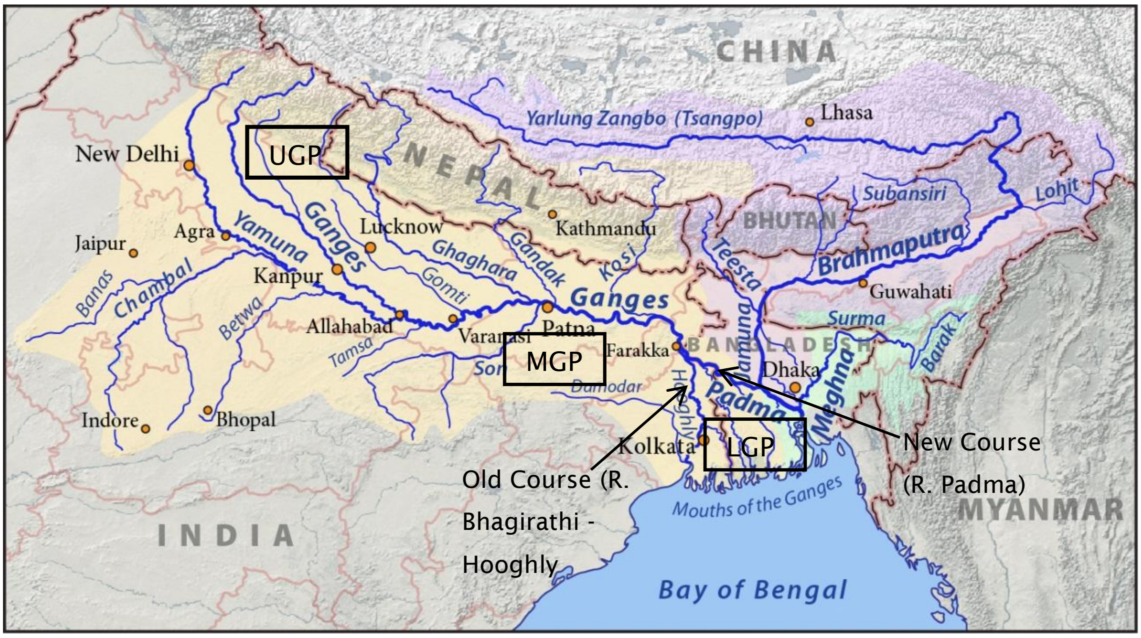

Figure 1-2 Ganga – Brahmaputra - Meghna River Basin (Source: Natural earth. Free vector and raster data @naturalearthdata.com); UGP: Upper Ganga Plain, MGP: Middle Ganga Plain, LGP: Lower Ganga Plain.

A comparative study of the historical maps of Jao Barros (1550), Gastaldi (1561), Van den Broucke (1660) and James Rennell (1764-76) carried out by O'Malley (1914) and Roy (1952) and analysis of historical accounts of the region indicate a three stage change in the course of the river from west to east until about 1600 AD. During 1700 AD the river again changed its course to the present configuration leaving the former flood plain deposits and spill channels / older meander scrolls as remnants (Chakrabarti, 1998; Sengupta, 1969; Roy, 1952). Studies also indicate that the geological character and neotectonism of this region may also be responsible for changes in the river course over time. Major seismic activity in the past has brought about drastic shifts in the courses of the tributaries of the river Ganga (Bhattacharya, 1959). For example, a major former Ganga tributary (river Teesta) has changed its course (Figure 1-3) and is presently a tributary of the river Brahmaputra due to major seismic activity in the mid-1800s (Bhattacharya, 1959, Chowdhury and Kamal, 1996). Besides the shift of course of the tributaries of the Ganga the river itself has shifted its older course from the Bhagirathi-Hooghly system to the present Ganga-Padma system (Parua, 2009). (Refer Figure 1.2).

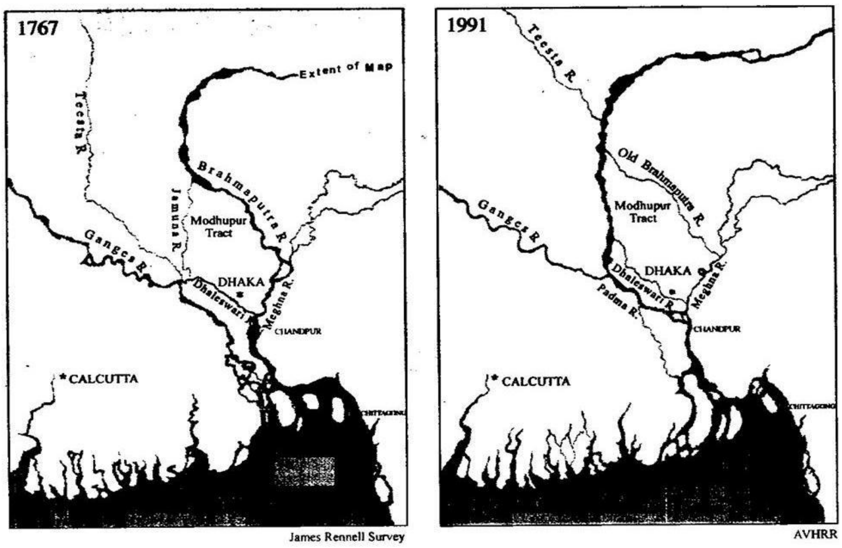

Figure 1-3 Change in course of the River Teesta and River Brahmaputra in IGB Plain due to tectonic effect.

1.3.1 Bank erosion: An effect of the planform change

The River Ganga changes its planform and its course by the process of meander migration or by means of new distributaries. The old courses of the River Ganga are presently distributed as abandoned channels. The resulting bank erosion in the River Ganga due to planform change has been recorded in the river over historical time scales (Colebrooke, 1803; Hayden and Pascoe, 1910) and is continuing till the present time. A process response system for the phenomenon can be conceptualized as seen in Figure 1-4. A combination of (+) ve and (-) ve feedback leads to erosion of the bank and subsequent planform change of the river.

Indian media reports depict a grave situation for the entire region. Huge losses of land and property are reported regularly in the media and questions are raised about a barrage located across the river at Farakka which was commissioned in 1975. The loss of agricultural land is estimated about 3 km^2 to 3.5 km^2 annually upstream of the Farakka barrage (Chattopadhyay, 2003). The total loss of land upstream of Farakka barrage from 1931 to 2003 is around 186 km^2 (Chattopadhyay, 2003; Iqbal, 2010). Between 1980 and 1999, net erosion downstream of the Farakka barrage to Hardinge

Bridge (in Bangladesh), was 48.5 km^2 on the Indian side and 126.5 km^2 on the Bangladesh side (Sarker, 2004), though no information are available on the amount of land gained at the downstream end.

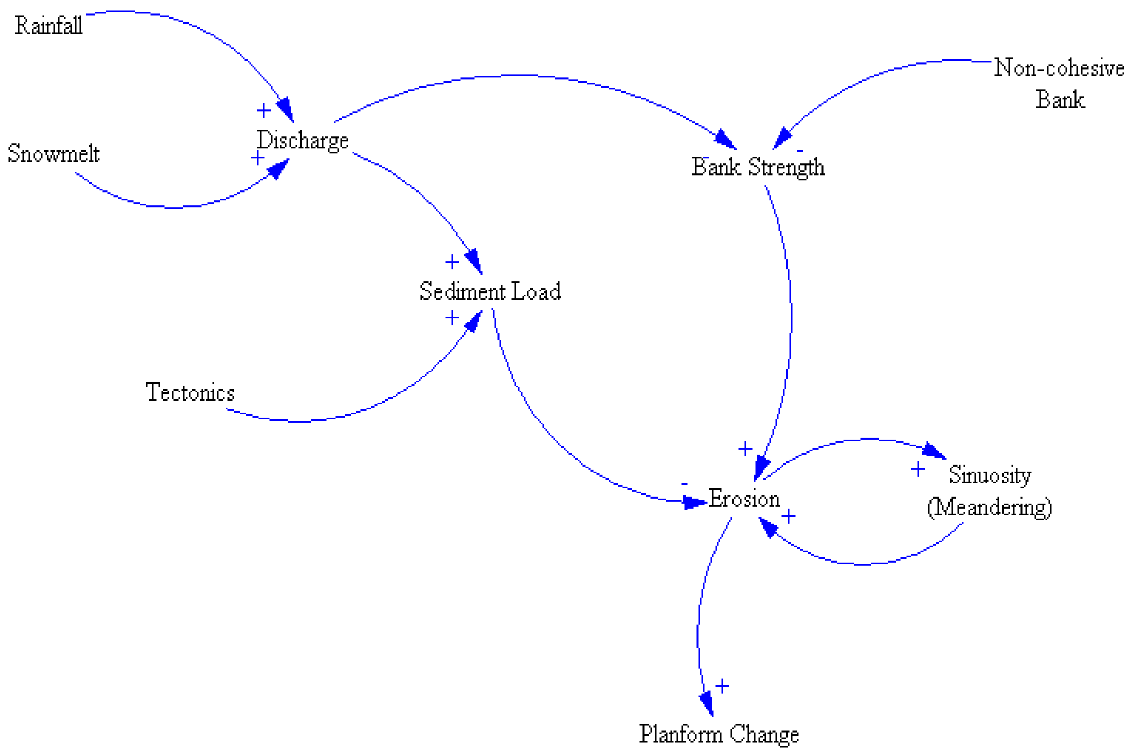

Figure 1-4 Process - Response system depicting bank erosion and planform change

1.3.2 Debate on the causes and effects of the planform change

The Ganga / Ganga – Padma river system in West Bengal, India has a special importance in terms of the Farakka Barrage and existence of Calcutta Port. There are two schools of thought regarding the bank erosion and its association with the barrage which is located across the river at Farakka. The environmentalists (Rudra, 2006, 2009, Mukhopadhyay and Mukhopadhyay, 2007), argue that the increased erosion is attributable to the construction of a barrage which affects the natural flow of the river. They also argue that the river upstream of the barrage will outflank the barrage making it defunct. On the contrary, the engineers involved in the construction of the barrage believe that planning of the barrage was carried out keeping in mind the width of the river as well as the average bed level of the river and the barrage is at the same level as the lowest river bed (Sen, 2008). The design was carried out so that the flow is not affected. The engineers on the other hand attribute the reason for the erosion to the construction of a circuit embankment further upstream of the barrage location around a semi-permanent river island which used to accommodate the excess water during monsoon months as a part of the natural system.

1.4 Research Objective

The present research aims to look more critically into the causes and effects of the planform dynamics of the Ganga-Padma system in its lower reaches and analyse the changes that have taken place in the river over the recorded history until the present. As mentioned already, very few studies have been carried out in this reach of the Ganga-Padma system but lot has been speculated about the river's dynamics in the recent past based on short time period of data. In most of the cases, the Farakka barrage has been projected as the main reason for the river's dynamic behaviour.

Thus the overarching general objective of the thesis is to have a holistic view of the past and present dynamics of the river based on a 38 years period of earth observation data supported by limited ground information as well as sparsely available historical documentations and find out the validity of the speculations about the dynamics of the Ganga-Padma system. The research thus aims to uncover the underlying processes and mechanisms which are active and are most likely the controls of the system. This will enable better management of the river system and forecasting its future planform behaviour.

1.5 Approach to the Research

In the above context, studies on planform change of the river are essential to provide a spectrum of morpho-genetic information over time and space. It can be noted that several studies on fluvial geomorphology focused on change in channel geometry, river banks and flow path in the IGB Plain using historical records, maps, aerial photographs and satellite sensor images (Spring, 1935; Inglis, 1949; Gole and Chitale, 1966; Coleman, 1969; Chitale, 1977; Goswami, 1985; Sarma and Basumallick, 1986; Tangri, 1992; Sinha and Friend, 1994; Jorgensen *et al.,* 1994; Singh, 1996, Sinha, 1996, Goswami *et al.,* 1999, Chakrabarti *et al.*, 2001). However, very few studies have been carried out in the Lower Ganga Plain, especially due to the non-availability of sufficient hydrological data.

Remote sensing is an effective tool, to delineate and monitor the nature and pattern of channel migration over human time scales. It can help to identify related geomorphological and geological features to characterise the morphogenesis of channel migration (Chakrabarti, 1998). Multi–temporal satellite sensor data enable the tracking of river planform through time. Monitoring channel migration is essential for mitigation of hazards that are occurring due to bank erosion. In this context, time-series remote sensing data over decadal time scales are essential to study planform change. In the present day scenario, free availability of Landsat scenes (from mid-2008) has opened up a new era of time series satellite remote sensing studies (Woodcock *et al.*, 2008).

Besides the change detection studies, study on natural meander dynamics of the river system is essential and the mechanism which controls the meander dynamics by means of bank erosion on one hand and cut-offs on the other. Exploring the effects of bifurcations, natural hard banks due to antecedent geology along the river system is essential to understand the dynamics of the river system. Perturbation both upstream and downstream of the river system due to the presence of an impoundment also requires attention, especially as the effect of the barrage constructed in 1975 on the river is a debated issue. Study on the avulsion frequency of the river would also enable exploration of any periodicity in the system or any phase of the meander migration along the river system.

Last but not the least, a study on past migration or avulsion of the river taking into consideration the regional aspects like geology and tectonics would enable a holistic understanding of the dynamics of the river system of the region. The present research is unique in terms of the magnitude of the river studied, its characteristics, the study area (i.e. Lower Ganga Plain) as well as the morphodynamics of the system in the study area which has not been explored in detail earlier. The study is based on almost four decades of satellite sensor data available at regular time intervals which enables a detailed analysis of the dynamics of the river system.

1.6 Organisation of the Study

The research has been presented as individual analysis chapters based on the themes discussed above in section 1.4. A short literature review on planform dynamics of an alluvial system and identifying the factors governing this dynamic behaviour is discussed in Chapter 2. The individual analysis chapters are on related themes and a short review of the literature specific to the research area of the analysis chapters, the research objective and the hypotheses have been discussed in the individual analysis chapters. A description of the study area has also been discussed in the individual analysis chapters along with a regional background.

The first analysis chapter entitled "**Studying decadal changes in the fluvial geomorphology of the River Ganga: Bringing a mega-river to life with Landsat archives**" demonstrates the suitability and limitations of the Landsat time-series to study the morphological characteristics of large rivers in general and the Lower Ganges Plain in particular.

The second analysis chapter entitled "**Criticality in the behaviour of the Ganga-Padma River meanders**" explains the natural meander dynamics of the system and the mechanism which ultimately leads to chute cut-offs. The paper also examines the effect of hard banks due to the antecedent geology and possible perturbation of both upstream and downstream reaches of the river system due to artificial impoundment and its effect on the river dynamics.

The third paper entitled "**Channel pattern recognition and condition for chute cut-off in the Ganga-Padma meanders**" is a continuation of the second analysis chapter and discusses the critical conditions for channel cut-offs to occur. The analysis chapter also discusses the channel pattern of the Ganga-Padma system based on different empirical methods of channel pattern recognition and classification.

The last analysis chapter entitled "**Effect of tectonics and meandering on anabranch evolution following the Ganga–Bhagirathi avulsion"** investigates the factors that led to the moderately paced avulsion of the Ganga–Bhagirathi system to the present Ganga–Padma system and determines why the older channel is still active, leading to an anabranching pattern, contrary to expectations for small and medium rivers.

The thesis concludes with the findings on the dynamic character of the Ganga-Padma system and discusses the scope for further research on predicting the dynamic behaviour of the system as a whole as well as at individual meander bends in the study area.

1.7 Summary

Assessing the planform dynamics of a river system is always a multi-disciplinary task. It requires involvement of geologist, hydrologists, environmentalist, social scientists and engineers. The scope of this research is limited to understanding the factors controlling the planform dynamics of the Ganga – Padma system in the past as well as the present using historical information, time series satellite sensor data and scarcely available hydrological data of the river system. Some morphological aspects of the system will be explored and compared with existing studies carried out on river systems in other parts of the globe.

2 Review of Planform Dynamics of Alluvial Systems

Large alluvial rivers are complex and highly dynamic geomorphological systems with immense cultural, socio-economic and political significance (Harmer *et al.*, 2005). Planform dynamics of these alluvial rivers are a complicated process and vary from one system to another. The rivers adjust their planform based on variation of spatial and temporal controls (e.g. discharge, sediment load, channel morphology and bank-material properties) (Harmar and Clifford, 2006). The planform dynamics of several alluvial river systems are generally accomplished by means of active meandering. Significant research has been carried out to study the inter-relationship of morphology and meander bend evolution by relating them to flow mechanics and sediment transport (Dietrich *et al.*, 1983), but it is difficult to account for different types of meander bends. In addition to planform dynamics of individual river channels, the rivers can also exhibit dynamic behaviour by shifting their course from an existing channel to a new channel, fully or partially depending again on flow dynamics and sediment transport. The process by which rivers exhibit such behaviour is known as river avulsion. Planform dynamics of river systems give rise to various channel patterns and forms and can be broadly classified into straight, meandering and braided (Leopold and Wolman, 1957) although new or transitional or higher order patterns have also been recognised (van den Berg, 1995; Makaske, 2001; Kleinhans, 2010). As a part of this research on understanding the planform dynamics of the Ganga-Padma system, a review of the fluvial geomorphology of alluvial rivers is presented in the following sections.

2.1 Fluvial Geomorphology of Alluvial Rivers

2.1.1 Channel Planform

Channel planform is an important aspect which needs to be understood while carrying out research in the field of planform dynamics. Channel planform is the planimetric geometry of an alluvial channel as seen from above. Planform / pattern of an alluvial river is organised through a feedback between channels, floodplain, bars and vegetation which in turn is controlled by the spatial sorting of bed load and wash load sediments. The width and pattern of a channel is determined by the balance between floodplain formation and destruction (Kleinhans, 2010). The configuration of the channel planform gives rise to different channel patterns.

2.1.2 Channel Pattern

River channel patterns can be broadly classified as straight, meandering and braided as the end member patterns (Leopold and Wolman, 1957; Schumm, 1985; Nanson and Knighton, 1996; Knighton, 1998) although other patterns can co-exist (e.g. anabranching, anastomosing and wandering) (Figure 2-1). The focus of research has always been to identify the variables that describe specific channel patterns. To date there is only a qualitative understanding of the patterns. But these self-organising patterns involve a combined feedback between channel morphodynamics and channel migration. The self-organising patterns also depend on the evolution and erosion of the floodplain (including natural vegetated dikes) during high discharge conditions (Nanson and Croke, 1992; Knighton 1998, Miall, 1996; Bridge, 2003; Fielding, 2008; Kleinhans, 2010). However, this knowledge is based mainly on studies of small and medium sized rivers as well as laboratory flume experiments.

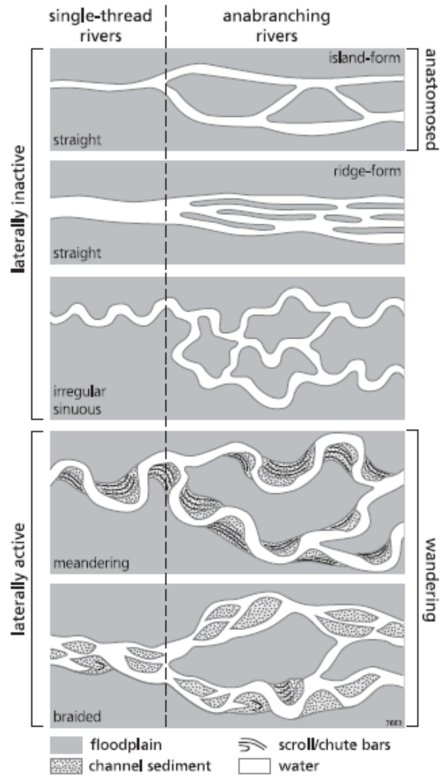

Figure 2-1[2] Classification of alluvial rivers (single channel and anabranching forms). Laterally inactive channels have straight or irregular sinuous pattern whereas laterally active ones have meandering or braided forms (Kleinhans and van den Berg, 2011).

A river is considered as straight when it has a single straight channel and meandering when one single thread shows a sinusoidal pattern. A braided river is one which has

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more than one active channel although an individual channel can be meandering as a single channel river (Leopold and Wolman, 1957).

While considering channel patterns in large rivers it is difficult to apply a simple classification like straight, meandering or braided (Latrubesse *et al.*, 2005). It has been found that in most of the large rivers of the world the anabranching pattern is dominant (Latrubesse, 1992; Nanson and Knighton, 1996; Nanson and Huang, 1999; Makaske, 2001; Jansen and Nanson, 2004) where the river is characterised by multiple channels. Thus the multiple channel characteristics can be considered as boundary between single and anabranching river systems. Some fluvial geomorphologists have classified the anabranching pattern as a separate category (Schumm, 1968; Rust, 1978; Alabyan and Chalov, 1998; Latrubesse, 2008). On the other hand, anabranching rivers have been further re-classified as anastomosing and wandering rivers (Kleinhans and Van den Berg, 2011). Anastomosing rivers are a class of anabranching rivers having low stream power and, thus, tend to have straight or sinuous individual channels (Makaske, 2001). But these channel patterns are not a variant of braided rivers and excludes channel splitting by convex-up bars that characterise braided channels. In addition, anastomosing rivers are laterally inactive unlike braided rivers which are laterally active. Anastomosing channel patterns are result of avulsion (Smith and Smith, 1980; Smith *et al.,* 1997) and are found in floodplains having low gradient. Wandering rivers are another category of anabranching rivers under the classical meandering – braided group having multiple channels. This category has a complicated channel pattern and is considered a transitional pattern between meandering and braided (Neill, 1973; Church and Rood, 1983; Kleinhans and van den Berg, 2011). The above classifications are all based on morphological characteristics of the river.

Though anabranching channel pattern can be considered a major group encompassing variants of multiple channels rivers, but some rivers can be in transition phase from single channel to multiple channel. The river (River Ganga- Padma) under study in the present research can be considered as a *laterally active river with some reaches showing a single thread meandering character while some other reaches showing multiple channels (anabranching character)*. The above definition will be used to describe the channel pattern of River Ganga-Padma in the following chapters. But it can definitely be said that though some reaches of the river shows multiple channels (anabranching pattern) but definitely the system is not anastomosing as the individual channels are laterally unstable.

2.1.3 Channel Pattern Controls

Fluvial systems adjust to a combination of control giving rise to various channel patterns resulting in evolution of floodplain morphology and sedimentology (Latrubesse, 2008). A brief discussion on the various controls is presented below. In fluvial geomorphology as discussed, river channels have been classified as straight, meandering and braided representing a continuum of channel geometry (Leopold and Wolman, 1957; Nanson and Knighton, 1996). The various channel patterns formed or modified from one pattern to another is mainly dependent on the force exerted by the river flow on the banks and the resistance exerted by the bank material to counter the erosion mechanism. This balance is controlled by independent variables like *discharge, slope, sediment load, bed material size, bank composition and strength* (Alvarez, 2005). Initially various empirical relationships were developed to explain the straight, meandering and braided channel pattern based on some of the control variables. The classification was based on channel slope and bankfull discharge and is calculated based on the equation

$$S_b = 0.013 Q_b^{-0.44} \tag{2.1}$$

where S_b is channel slope and Q_b is bankfull discharge.

But Leopold and Wolman (1957) also emphasised that intermediate classes represent natural systems better than a crisp discrimination.

Channel pattern has also been classified based on suspended load dominated to bed load dominated as well as low to high flow strength. Small to large width depth ratio and low to high stability of pattern has also been considered to distinguish between channels (Schumm, 1985). Based on number of co-existing channels, floodplain geomorphology, the flow characteristics, channel width – depth ratio and mode of sediment transport different channel patterns like anabranching, anastomosing and wandering (Figure 2-1) have been proposed (Makaske, 2001; Kleinhans and Van den Berg, 2011).

The qualitative channel pattern classification proposed by Schumm (1985) was modified by relating stream power to amount and size of bed load, width-depth ratio and channel instability. The relation resulted in the emergence of channel patterns like straight, meandering and anabranching for sandy bed load rivers with increasing stream power and straight, slightly sinuous with alternating bars and braided for gravely bed load rivers (Ferguson, 1987).

It was also established that every known channel pattern can be described as a combination of straight, meandering and braided based on low water channel, flood channel and valley bottom. In other words: the channel patterns can be different at different discharge levels (Alabyan and Chalov, 1998). Thus, it can be said that the channel pattern mainly depends on two major factors a) flow strength and b) sediment characteristics (Ferguson, 1987; Kleinhans, 2010). Rational regime models based on theoretical concepts have been able to identify that bank strength is an important factor to understand channel morphology and channel response (Eaton *et al.*, 2004). But the models have limitations if tested on real systems due to constraints on the time scale of change, low discharge fluctuation which is not always the case in real systems. In addition, bank stability where shear stress exerted on the bank must be equal to critical shear stress for bank erosion is unlikely to be found in natural systems. The channel cross-section (which in most natural systems would be asymmetrical instead of trapezoidal shape) employed in the model and the formulation of bed material transport would exhibit both non-equilibrium spatial and temporal variation in a natural system. Finally, the flow resistance equation used in the regime model to predict flow resistance is unable to predict flow resistance which may evolve due to channel sinuosity, bars and other bedforms present in alluvial channels. Generally these factors account for up to 90% of the total flow resistance at bankfull conditions (Millar, 1999), and is likely to play an important part in channel pattern development (Lewin and Brewer, 2001). The theoretical model of Eaton *et al.* (2004) though is not applicable in natural system, but it identifies bank strength which can be related to vegetation on the banks as an important factor for change in channel morphology and channel pattern.

Flume experiments by Tal and Paola (2010) investigated the effect of vegetation on braided morphology to understand interactions among vegetation, sediment, and water in natural rivers. The experiment demonstrated that riparian vegetation on the floodplain can lead to self-organisation of braided channels to form a single thread channel which then maintains itself in a dynamic equilibrium as seen earlier in flume experiments (Tal and Paola, 2007). The experiments showed that riparian vegetation discouraged the coexistence of multiple channels and slowed down the erosion rate, allowing deposition on the opposite bank, resulting in active migration while maintaining a constant width.

A model to predict channel pattern based on median grain size of the bed material, a potential specific stream power parameter related to bankfull discharge or mean annual flood and valley gradient was developed by Van den Berg (1995). He argued that several researchers (Lane, 1957; Leopold and Wolman, 1957; Henderson, 1966, Carson, 1984; Knighton, 1984; Ferguson, 1987; Struiksma and Klaassen, 1988; Bridge, 1993) have classified channel patterns based on flow parameters and in doing so the discriminator of defining the channel patterns required prior knowledge of channel geometry. His model on the other hand is able to predict the equilibrium condition of braided and highly sinuous meandering rivers in unconfined alluvial floodplains. The potential specific stream power was calculated based on the following equation:

$$\omega = \frac{\rho g Q_{bf} S_v}{W} \quad (2.2)$$

where ω is potential specific stream power, ρ = density of water (kg/m^3), g = acceleration due to gravity, Q_{bf} = bankfull discharge, S_c = the channel slope. W is the width which is calculated based on the two regime equation of Lacey (1930); one for sand-bed rivers and another for gravel-bed rivers. His model was tested on 228 datasets and he was able to find a discrimination function to separate out braided and meandering rivers with sinuosity value greater than 1.5. The function could also be used to predict the stability of braided and meandering river patterns with annual flood or bankfull discharges > 10 m^{3}s^{-1} and a median grain size range of 0.1-100 mm. The drawback of the model was that the magnitude of sinuosity could not be predicted as it is influenced by local factors and bank erodibility. Moreover, for calculating potential specific stream power the mean annual flood value is used instead of bankfull discharge which may not be a meaningful substitute for the dominant discharge although it is more pattern-independent than bankfull discharge.

The model was criticised by Lewin and Brewer (2001) and they argued that the channel width considered in calculating the discriminator function was a regime-based estimate and not the actual width of the rivers studied and, thus, this model was unacceptable. They also argued that the value of constant a in regime equation of Lacey (1930) $(W = aQ_{bf}^b)$ used to calculate width was based on values from non–braided gravel-based rivers and, thus, the predicted width would underestimate the width of braided channels. Field data on braided streams (Mosley, 1983) and flume experiments by Ashmore (1991) have shown the value of the constant a to be much higher than that estimated by Van den Berg (1995) thus leading to modification of the discriminator function between two channel patterns leading to inappropriate prediction. Lewin and Brewer (2001) also pointed out that, although the model shows a simple discrimination function to understand pattern transformation; it does not involve any hydraulic considerations (except the width) which may have a considerable influence on the river patterns and their transformation from one to another. Lewin and Brewer (2001) were of the view that greater focus should be placed on the patterning process which leads to pattern scatter on bankfull stream power / bed material size plots. They found that large scale bedform development and stability are important for meandering and braiding patterns and braiding patterns are generally formed at higher shear stress and Froude number.

Van den Berg and Bledsoe (2003) commented on Lewin and Brewer's (2001) criticism and explained that Lewin and Brewer (2001) were correct in pointing out that analysis of bankfull (or annual flood) stream power and grain size alone is insufficient to explain underlying complex processes that result in river patterning. But the intension of their channel pattern stability diagrams were not to simplify complex processes but to have a rough indication of channel pattern when conditions change due to extrinsic and intrinsic drivers. Van den Berg and Bledsoe (2003) substantiated their intension by giving examples of usage of their stability diagram for rehabilitation of distributaries of River Rhine and by predicting their probable channel pattern. They also argue that these stability diagrams are very useful in discriminating classic channel patterns using simple parameters. Van den Berg and Bledsoe (2003) also indicated that present width predictors are not reliable and underpredict or overpredict width of migrating channels as the width predictors were developed for non-migrating sytems. In addition, various hydraulic geometry equations that have been proposed show a positive correlation between bankfull width and stream power, thus making the stream power an appropriate parameter to predict channel pattern.

Van den Berg and Bledsoe (2003) also agree with Lewin and Brewer (2001) that bankfull discharge, Q_{bf}, and bankfull channel width, W, used to define potential specific stream power are inappropriate to predict the width of braided rivers, but they argue that the regime based equation used to predict width were not actual width but reference width. In addition even if the width was biased towards non-braided channels any aim to remove the bias by use of some constants would not change the diagram significantly.

On the other hand, Van den Berg and Bledsoe (2003) disagree with Lewin and Brewer (2001) regarding dismissing of their predictive tools and their class of models. Instead they argue that complex mechanistic models that consume many resources also perform poorly whereas models developed by them can be used effectively for geomorphic assessments for prediction of river and stream behaviour. In addition any predictive tools represent a trade-off between complexity in models and misrepresenting the system of interest.

Kleinhans and Van den Berg (2011) latter modified the channel pattern discriminator model with a lower threshold of channel pattern discrimination and incorporated bar theory and explained that bar patterns can also be predicted from the specific stream power equation of van den Berg (1995). The new flow energy parameter is defined as

$$\omega_{pv} = \frac{\rho g Q S_v}{W_r} \tag{2.3}$$

where ω_{pv} is potential specific stream power, ρ = density of water (kg m^{-3}), g = acceleration due to gravity, Q = mean annual flood / bankfull discharge, S_v = the valley slope (which can be derived from channel slope $S_c = pS_v$ *where* p= sinuosity) and W_r = reference channel width. ω_{pv} is a parameter for the potential maximum available flow energy when the sinuosity of the channel is 1. To keep the reference width W_r independent of the actual pattern dependent width W_a, W_r is derived by the equation

$$W_r = \alpha\sqrt{Q} \tag{2.4}$$

where α = 4.7 for sand with D_{50}< 2mm and α = 3.0 for gravel.

The difference between the updated model and Van den Berg's (1995) model is that the reference width is calculated based on one equation rather than two different regime equations as using two different equations for width prediction has little effect on the channel pattern discriminator. Kleinhans and van den Berg (2011) argued that their model predicts the channel pattern precisely as the width is deliberately predicted incorrectly. Their reasoning was that if actual width is considered then stream power would decrease for rivers which have overpredicted width and *vice versa* resulting in loss of discriminative power. On the other hand, if a pattern independent width predictor is used then for rivers with high width-depth ratio the stream power would be over-predicted and if this stream power were applied to a narrow deep channel it would result in erosion and channel enlargement and the width-depth ratio would increase to the actual value. Kleinhans and Van den Berg (2011) agree with Lewin and Brewer (2001, 2003) that as the width is estimated based on regime-based equations they do not predict the specific stream power correctly. Nevertheless they argue that as the channel width prediction aims to find a pattern independent reference value for channel patterns, the actual width has not been deliberately predicted as the actual width is pattern dependent (Van den Berg, 1995). Based on the above studies it was concluded that there is no definite boundary between categories and they are transitional.

The above discussion on the model developed by Van den Berg (1995) to predict channel pattern based on pattern independent variables followed by criticism from Lewin and Brewer (2001) clearly shows the different approach of researchers to a single problem. But as the reasoning given later by Van den Berg and Bledsoe (2003) and Kleinhans and Van den Berg (2011) indicates that even if some of the arguments given by Lewin and Brewer (2001) are true but still while studying or predicting various channel patterns of rivers it may not be possible to obtain pattern dependent variables like width. Moreover, their model specifically has been developed for predicting width based on pattern independent variables. In such cases regime based equations would be the best option to have a predicted width to calculate stream power and consequently channel pattern. They also show that instead of two different co-efficient (one for sand-bed river and one for gravel-bed river) an average value of the co-efficient is sufficient as it has a little effect on the predicted width.

2.1.4 Bar Pattern

Bars are bedforms with lengths or spacing that scale with channel width (A.S.C.E. Task Force 1966; Bridge 1985, 1993; Carling, 1999). Bars can be non-mobile “fixed-bars” and mobile “free bars”. The “fixed-bars” are alternate and point bars, while the “free-bars” are braid bars and transverse bars (Seminara and Tubino 1989; Carling, 1999). An interrelationship exists between bar formation and planform change (Mosselman, 1995).

Several studies have been carried out on bar forming patterns in meandering and braided rivers. In a meandering river the inner bank may form three main types of bars: scroll bars, chute bars and tail bars (Figure 2-2). Tails bars are generally formed as a result of an obstruction due to woody debris (Edwards *et al.*, 1999, Kleinhans and van den Berg, 2011). From the nature of tail bar formation it can be said that tail bars can be formed both in meandering and braided rivers.

Scroll bars and chute bars are formed at the inner bend of a meandering channel where accretion takes place during peak discharge. The bars are exposed during low stages of the river system. The literature indicates that chute bars are associated with high stream power whereas scroll bars can be linked to both low and high stream power (Kleinhans and Van den Berg, 2011). A scroll bar is formed as a curvilinear ridge in the inner meander bend parallel to the channel. It is sometimes also called a point bar due to its planform which points down channel (Smith, 1974; Church and Jones, 1982). In sedimentology the point bar indicates the accretionary part of an inner meander bend. A point bar generally extends vertically from the deeper part of the channel to the level where accumulation of the floodplain fine sediments starts.

Scroll bars can be “free bars” or “fixed bars”. They can form by various processes (Nanson and Croke, 1992; Bridge, 2003). Dynamic scroll bars are formed by landward migration and coagulation of transverse bars (Lewin, 1976; Ackers, 1982). Stable scroll bars are formed by deposition of fine suspended sediments in the main flow (Nanson, 1980). Active scroll bars can also form if the outer meander bend erodes and creates more space for accumulation in the inner meander bend. This explains the presence of scroll bars both during high and low discharge conditions (i.e. high and low stream power).

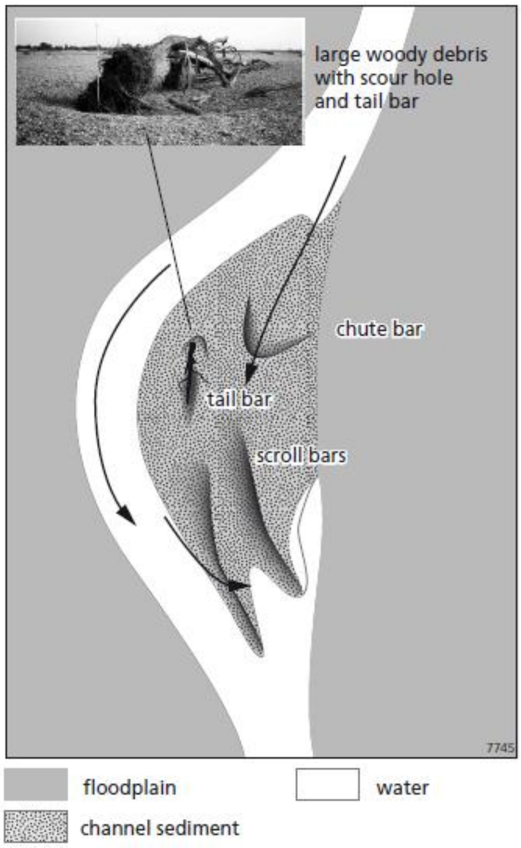

Figure 2-2[3] Sketch of bar formation in a meandering river. Tail bar is formed due to presence of woody debris. Scroll bar and chute bars are related to meander bend and hydrodynamics. A chute cut off is formed by eroding a chute bar (Kleinhans and Van den Berg, 2011).

Chute bars are found both in meandering and braided rivers, although they are more common in braided rivers. Chute bars are horse shoe shaped lobes formed at the downstream end of a chute channel. The flow converges into the chute and then diverges past the lobe allowing it to aggrade (Ferguson *et al.*, 1992; Kleinhans and van den Berg, 2011). Chute channels and bars are also found in the inner bends of a meandering river which is formed during peak discharge (McGowen and Garner, 1970; Gustavson, 1978; Blacknell, 1982; Bridge et al., 1988; Fielding and Alexander, 1996; Bartholdy and Billi, 2002; Kemp, 2004) or reoccurring high flood event (van den Berg and Middlekoop, 2007) . They are also found in rivers with low stream power where

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they occur as imprints from former braided patterns (Marston *et al.*, 1995). When a chute grows and results in a chute cut-off a new braid is formed. Experiments have shown that chute cut-offs result in initiation of transition of a meandering river to a braided river (Friedkin, 1945). Chute cut-offs are also an indicator for active braiding (Ashmore, 1991).

Some studies have shown that chute bars and scroll bars do not exist simultaneously in the inner bends of a meandering channel (McGowen and Garner, 1970; Nanson, 1980; Blacknell, 1982; Brierley and Hickin, 1991; Kemp, 2004) while other studies have indicated their presence in the same point bar (Lewin, 1976; Bridge *et al.*, 1988; Fielding and Alexander, 1996). A classic example of both bars existing simultaneously can be found in an 18th century map of the River Rhine at the Dutch-German border (Kleinhans and Van den Berg, 2011).

Thus, based on channel pattern and the occurrence of bars and their relation to stream power it can be said that there are four categories of channel pattern based on energy of flow, but the boundaries are transitional:

- immobile rivers without bars.
- meandering rivers with scroll bars.
- meandering rivers with chute bars .
- rivers with braid bars.

2.1.5 River Metrics

To compare channel patterns and planform changes of a river, it is necessary to discuss a suite of river metrics to obtain insight into the river morphology and the underlying processes that are active in the system.

2.1.5.1 Sinuosity

Sinuosity of a river is one of the most important characteristics of a river channel pattern. Sinuosity is measured as the (Figure 2-3) ratio of the stream length along the centre of the channel to the valley length (Hooke, 1977; Brice, 1984). Leopold and Wolman (1957) proposed that if the sinuosity of a river is > 1.5 then the river can no longer be considered as straight and should be classified as meandering. But, this two fold classification was found to be insufficient to describe a range of patterns existing in nature. Schumm (1963) recommended a new classification (five types) based on sinuosity values ranging from 1.1 to 2.3. Brice (1984) modified this with additional categories such as sinuous canaliform, sinuous point bar, sinuous braided and non-sinuous braided. Based on past studies and various classification systems it can be said that the boundary between two different channel patterns is gradual. Sinuosity of some rivers has been found to change with time depending on human intervention, discharge and sediment load (Hooke, 1977; Sarker, 2004; Alvarez, 2005).

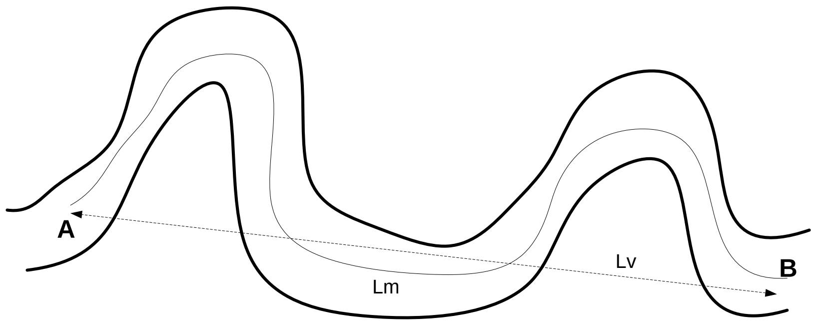

Figure 2-3 Geometric feature of a meander indicating the sinuosity which is the ratio of meander length L_m to the valley length L_v

2.1.6 Cut-offs and Avulsions

The primary mechanism by which a river changes its planform are island formation from mid-channel bars, lateral migration, cut-offs and avulsion. Cut-off and avulsion involves switching of channel position (Brook and Luft, 1987; Hooke, 1987; Alvarez, 2005). But the major difference between cut-off and avulsion is the scale of the two processes. Channel relocation by cut-offs are related to meander bends while avulsion results in relocation of an existing channel of a river to a new channel.

Cut-offs as mentioned above occurs at meander bends and can be classified into neck cut-off and chute cut-off. Neck cut-offs are produced by breaching of a narrow gap between adjacent channel bends. Chute cut-offs are caused by scouring of the floodplain in an inner bend leading to the formation of a new channel. Neck cut-offs are formed when the rivers are highly sinuous and the floodplains have very low slope. Chute cut-offs are formed when the floodplain is poorly vegetated, and the sediments are erodible and non-cohesive (Lewin, 1977; Alvarez, 2005).

Avulsion is a natural process by which a river relocates itself, usually during high discharge time, and diverts out of a present channel to a new permanent channel in the adjacent floodplain. The duration of avulsion can vary from a short period of time (28 years) (e.g. Kosi river, India) to long periods of time (e.g. over 1000 years for the Missisippi river). Avulsions are generally found in aggrading floodplains (Slingerland and Smith, 2004; Abbado *et al.*, 2005).

Avulsions can be full or partial (Figure 2-4) where in the first case the parent channel is abandoned downstream of the bifurcation and in the second scenario the new channel co-exists with the old ones (Heller and Paola, 1996). Partial avulsions give rise to anastomosing channels if the divided channels rejoin downstream. Avulsion usually initiates as a crevasse when the natural or artificial levee is breached by the water channel and sediment are deposited on the floodplain. The crevasse in some cases, when takes a part of the flow of the water from upstream, results in a bifurcation. The flow which has been diverted due to the crevasse can result in abandoning of the older channel and the whole of the flow going through the new channel. Thus avulsion is caused at the bifurcation formed due to the crevasse. Avulsion can also result if the sediment coming from upstream is not distributed equally into the two channels created at the bifurcation resulting in changes in discharge, slope or cross-section leading to changes in carrying capacity of the channel. The initiation of the crevasse leading to the avulsion is generally triggered by flood but can also be because of neotectonic movements, log jams, bank failures or bar migration downstream blocking one of the channels (Jones and Schumm, 1999). However, the location where the avulsion will occur will be determined by factors like channel geometry, bank stability, floodplain topography as well as the confluence with one of the trigger mechanisms. The outer bends of meanders where flow velocities are high and weak areas in the channel bank are the potential locations (Chrzastowski *et al.*, 1994, Smith *et al.*, 1998).

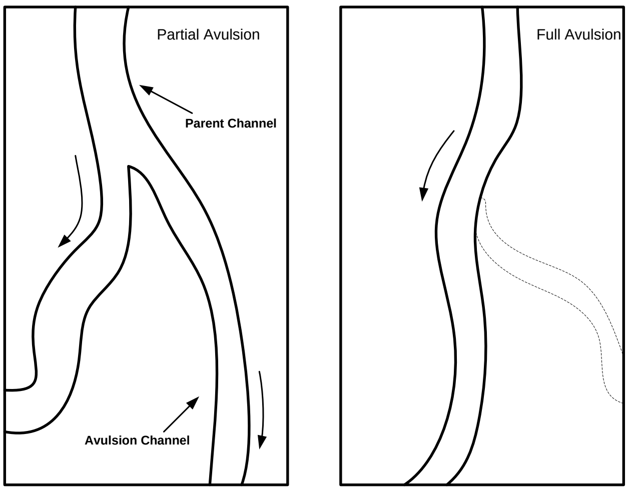

Figure 2-4 Schematic diagram showing partial and full avulsion (after Slingerland and Smith, 2004)

Recently, some researchers have proposed the term ‘soft avulsion’ when no channel abandonment takes place and the path of the maximum sediment flux shifts from one active channel to another (Edmonds *et al.,* 2011). This has been classified as a new class of avulsion where existing channels are exploited instead of creation of new channel (Jerolmack and Paola, 2007). This process is used by delta network to uniformly fill space without abandoning and creating channels (Edmonds *et al.,* 2011).

In the present study, chute cut-off has been considered the process by which the river self-organises itself in the various reaches. The chute cut-offs have been considered synonymous with 'soft avulsion' as chute channel and the main channel are simultaneously active in the Ganga –Padma system and there is not usually a simple abandonment of the main channel in favour of the new channel. Thus the term chute cut-off or 'soft avulsion' would be interchangeably used in the analysis section of this thesis. Only in case of formation of a new course by partial or full abandonment of an existing channel the term avulsion would be used.

2.1.7 Meander Migration

Meander migration is a process by which a river changes its planform. Rivers which are actively meandering, adjust their planform depending on spatial and temporal variation in discharge, sediment load, channel morphology and properties of bank material. The water coming from the upstream reach is directed towards the outer bend of a meander by centrifugal force leading to super elevation of water level. This leads to erosion in the outer bank and the sediments are transported to the inner bend. Theory suggests that the maximum erosion will be just downstream of the apex resulting in down valley translation of the meander bend. Four models have been identified by which a meander migrates; translation, rotation, extension and a combination of the three (Hooke, 1980). Extension refers to growth of the meanders whereas translation indicates the migration of the meander bends.

Channel geometry is an important parameter on which the migration rate depends. The radius of curvature also affects meander migration (Leopold and Wolman, 1957). The ratio of the radius of curvature to the width of a channel determines the tightness of a bend or bend curvature. The migration rate is dependent on the tightness of the bend. In temperate rivers, it has been found that a bend curvature ratio of 2.0 to 3.0 maximises the migration rate (Nanson and Hickin 1983; Begin 1986; Biedenharn *et al.*, 1989; Thorne 1992). Several models have been developed on meander migration based on fundamental physics (Howard, 1992) and probability (Furbish, 1991; Stolum, 1998) which showed that a variety of bend shapes and sizes can evolve. Although not investigated much as a parameter of a meander migration model, due to the non-availability of suitable data, geology and neotectonics play an important role in meander migration especially due to their influence on channel slope (Schumm and Khan, 1972), as well as sediment production and storage (Murphy, 1983; Hudson and Kesel, 2000; Harmar and Clifford, 2006).

2.2 Summary

This short review of fluvial geomorphology indicates that the above characteristics of an alluvial river deserve attention. The Ganga-Padma system, thus, has been studied in relation to the above discussed aspects of fluvial geomorphology to characterise its behavioural pattern as well as to provide insights into the morphological processes which may be responsible for its changing pattern. An attempt has been made to utilise Earth observation data and limited hydrological data to understand the above morphological processes occurring in the system.

3 Studying decadal changes in the fluvial geomorphology of the River Ganga: Bringing a mega river to life with Landsat archives[4]

3.1 Introduction

Satellite sensor data are used widely to study Earth surface processes such as glacier flow (Kääb, 2005), surface and internal processes occurring in volcanoes (Zebker *et al.*, 2000), coastal and estuarine processes (Cracknell, 1999) and fluvial systems (Smith, 1997, Chakrabarti *et al.*, 2001, Hughes *et al.*, 2006, Boruah *et al.*, 2008, Jung *et al.*, 2010). Satellite sensor data are particularly suitable for monitoring changes in river planform, especially for large and highly mobile rivers, due to the potentially large area covered, synoptic view and repeatable data acquisition capability (Leys and Werrity, 1999; Collins *et al.*, 2003, Mount *et al.*, 2003, Mount and Louis, 2005). As rivers are continuous systems, true documentation of their structure and function requires a continuous time-series of data (Lane *et al.*, 2010) over a range of temporal and spatial scales (Fonstad and Marcus, 2010). Fluvial geomorphologists attempting to model the long-term dynamics of meandering rivers have documented the difficulties caused by the limited availability of continuous datasets (Stølum, 1998). Thus, satellite sensor data have great potential for providing standardised mapping of river planform at regular intervals (Smith, 1997, Stølum, 1998).

The era of space-based Earth observation at a spatial resolution relevant to the mapping and monitoring of mega-rivers started in 1972 with the launch of the first Landsat satellite carrying the multispectral scanning system (MSS) sensor with a spatial resolution of 80 m. In 1982, the Thematic Mapper (TM) sensor was added to the Landsat platform and in 1999, Landsat 7 carried the Enhanced Thematic Mapper (ETM+) sensor, both having a spatial resolution of 30 m (Mika, 1997, Williams *et al.*, 2006). The availability of spatially continuous, synoptic and temporally repetitive data in multi-spectral mode created a new capability for studying the Earth's surface and the processes occurring on it. But until mid-2008, cost restricted access to archival Landsat data, limiting the ability of the scientific community to study and monitor the planet's surface (Woodcock *et al.*, 2008). In mid-2008 the Landsat data archive was made freely available to the global community via the internet by NASA and USGS enabling the

[4]© 2012 Taylor & Francis (This chapter has been published as Niladri Gupta, Peter M. Atkinson & Paul A. Carling (2013): Decadal lengthchanges in the fluvial planform of the River Ganga: bringing a mega-river to life with Landsatarchives, Remote Sensing Letters, 4:1, 1-9. DOI: 10.1080/2150704X.2012.682658).

scientific community to reconstruct changes on the Earth's surface due both to natural and anthropogenic causes.

The focus of this analysis chapter is one of the Asian mega-rivers, the River Ganga, and, in particular, a section of the river upstream and downstream of the Farakka Barrage (Figure 3-1). A limited number of studies have been carried out on this section of the river system, but only over short time periods (Chakrabarti 1998, Chakrabarti *et al.*, 2001, Sarker, 2004). Here, Landsat images supplemented by Indian Remote Sensing (IRS) images were processed to produce a time-series over a longer period spanning nearly 40 years.

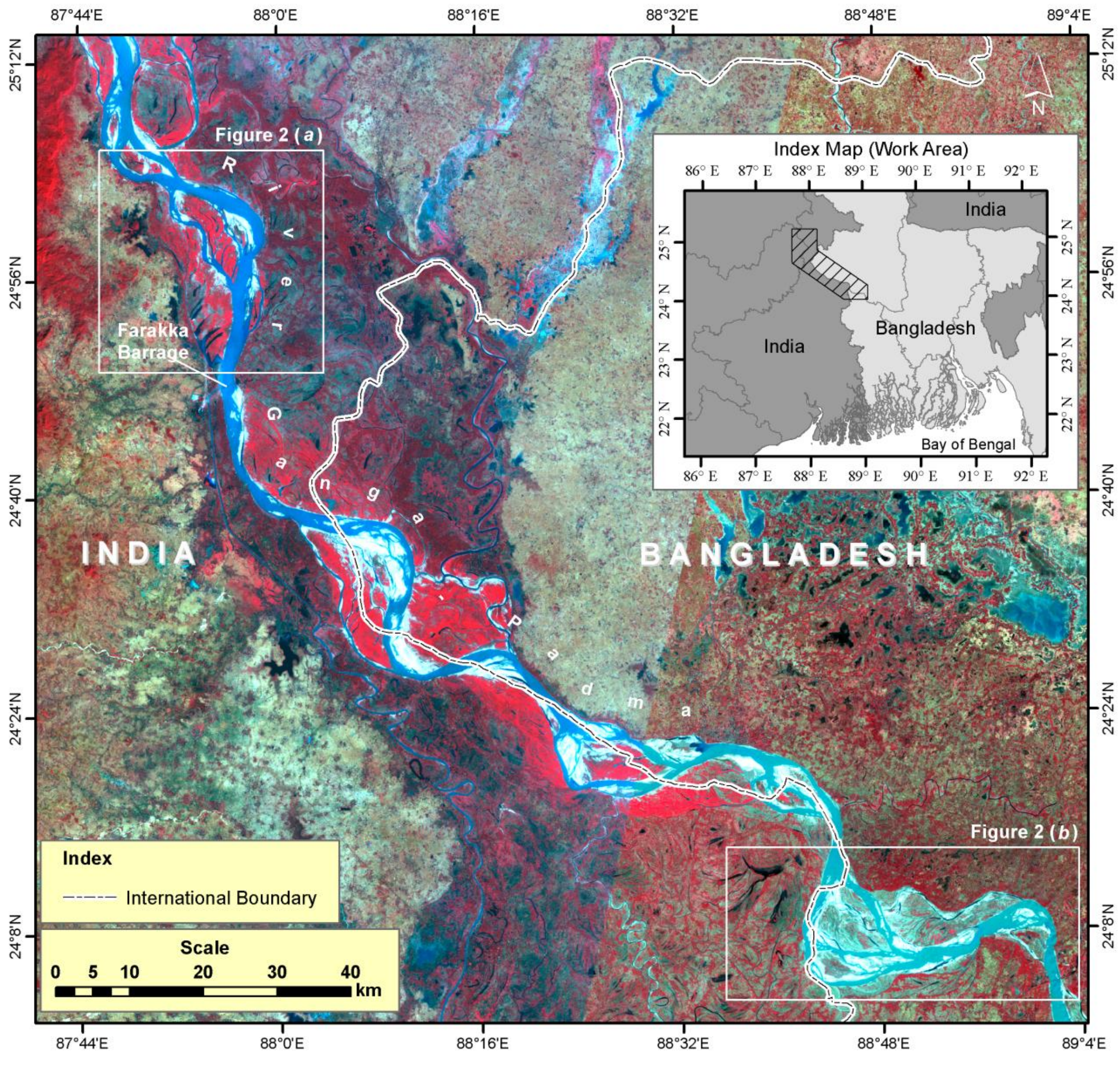

Figure 3-1[5] Mosaicked Landsat ETM+ image (17 November 2000 / 10 December 2000) showing the section of the River Ganga in India and Bangladesh used in this research. The image is a standard false colour composite where the Red Green and Blue band has been assigned Green, Red and NIR colours respectively.

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The present study area as seen in Figure 3.1 exhibits around 4 meanders. These meanders have similar characteristics as the meanders further downstream inside Bangladesh till the Ganga-Padma system meets the River Yamuna (R. Brahmaputra). The river flows through similar floodplain geology (Figure 4.3). Thus the present study area can be considered as a representative of the whole lower reach of the Ganga-Padma system starting from the point where it enters West Bengal, India and joins the R. Yamuna in Bangladesh to form the R. Meghna.

The main objectives of this research were (i) to reconstruct the specific planform changes occurring in the lower reaches of the Ganga from 1972 to 2010 using satellite imagery, (ii) to highlight the utility and limitations of the Landsat archive for this purpose and the processing steps necessary in constructing a useful time-series and (iii) to provide a geomorphological interpretation of the dynamic pattern revealed here for the first time, including discussion of the potential effects of the Farakka Barrage which was constructed in 1975.

3.2 Data

A major problem with the Landsat archive is gaps in the time-series for regions outside the USA. The study area was covered by two scenes from the Landsat archive (path/ row: 148/43 and 149/43 of Landsat 1, 2 and 3 MSS; path/row 138/43 and 139/43 of Landsat 7 ETM+). As the river is a mobile system and major changes occur during the monsoon season (June to September), cloud-free post-monsoon images were required annually to capture the inter-annual variability in the system. Archival data for the study area were available for 1972, 1975-1979 and then continuously from 1999 to 2010. However, it was found that the data for the period 1976-1979 were either available for one of the two scenes only or had significant cloud cover in one of the scenes. Thus, the data for 1976-1979 were unusable. A major gap existed until 1999 as the Landsat MSS or TM data post-1979 were collected by a different ground station outside the USA and the dataset from this ground station was unavailable in the Landsat archives (Roy *et al.*, 2010). Thus, this gap period (1976 to 1999) was filled from the archives of IRS programme which launched its first mission, IRS 1A, in 1988. The study area was covered by two scenes of the Indian Remote Sensing (IRS) programme (path/ row: 18/51 and 19/50 of the IRS 1A/1B Linear Imaging Self Scanner (LISS) I; 107/54 and 108/54 of IRS 1C LISS III). From 1999, Landsat archival data were available for the whole region. In total, 4 Landsat MSS (1972, 1973, 1975), 24 Landsat ETM+ (1999 - 2010), 2 IRS IA LISS I (1988), 4 IRS 1B LISS I (1992, 1994, 1995) and 2 IRS 1C LISS III (1998) images were used. Besides filling up of the gap in the Landsat archive using IRS imagery, presence of information gap due to scan line errors in Landsat ETM+ data after May 31, 2003 was also partially corrected using overlapping data.

3.3 Study Design

Remote sensing provides an excellent source of data to measure the properties of natural fluvial systems through time. However, observed remotely sensed images are a function of many variables, some relating to the scene of interest, and others relating to atmospheric effects, to the characteristics of the sensor and to the sampling framework (e.g., spatial resolution). It is necessary to control these confounding factors if meaningful comparisons are to be made through time between image-based maps of planform constructed from different sources of imagery. To separate desired signal from unwanted confounding factors, the conceptual model used in remote sensing of: scene model, atmosphere model, sensor model and image model (Woodcock *et al.,* 1988) is adopted here and elaborated below.

3.3.1 Remote Sensing Models

3.3.1.1 Scene Model

A scene model represents the ground reality from which remotely sensed measurements are derived to create an image (Woodcock *et. al,* 1988). The primary interest in this research is change in river planform. Within the scene, the planform of a river at a given point in time is dependent on many factors which include confounding influences such as discharge (and consequently stage). Inter-annual change of discharge; while fundamentally an integral part of the scene of interest will not be useful from the present point-of-view (it would be ideal if discharge was identical between years). Thus, controlling for stage becomes important to allow comparison between inter-annual maps of planform.

3.3.1.2 Atmospheric Model

Satellite sensor data are affected by atmospheric interference on the signal (e.g., as a function of scattering due to aerosols). Thus, atmospheric correction is one of the most important pre-processing steps in quantitative remote sensing (Yang and Wen, 2010); this is particularly important where images are to be compared quantitatively in a time-series.

3.3.1.3 Sensor Model

Sensor models are required in order to understand the functional relationships between the image plane and the ground space (Tao *et al.*, 2000). While physical models are possible, generalised (statistical) models that allow transformation of image coordinates to a coordinate system representing the ground space are more common. The present research not only involved data from different sensors (Landsat

MSS and TM), but also from different platforms (Landsat and IRS) and, thus, the generalised sensor model was suitable. The Landsat MSS and TM data were already georectified and projected into the UTM WGS 84 system as individual bands in Geotiff format. However, the IRS sensor data were not geometrically corrected. To allow comparison between different sensor data geometric correction of the IRS data was necessary.

3.3.1.4 Image Model

A fundamental characteristic of satellite remote sensing data is the spatial resolution, which depicts the unit area on the ground that is measured and represented in the satellite sensor image (Townshend, 1980). Thus spatial resolution can be considered analogous to the scale of observation (Atkinson and Tate, 2000). While for most ground measurements the scale of observation is variable, for satellite sensor data the scale of observation is fixed by the sensor characteristics (Woodcock and Strahler, 1987; Atkinson 1997). Importantly, the observed image is a function of both the properties of interest in the scene, confounding factors such as the atmosphere as described above, and the sampling strategy, which in remote sensing is fundamentally determined by the spatial resolution. Thus, it is vital to control for the effect of spatial resolution if data are to be compared in a time-series. Analysing time-series data with varying spatial resolutions without prior equalization of the level of thematic content and spatial detail would confound monitoring (Petit and Lambin, 2001).

3.4 Data Processing

Based on the above conceptual model, a series of data processing steps were carried out to standardize the data for further analysis.

3.4.1 Controlling for Discharge

As the planform of a river at a given point in time is dependent on discharge (and consequently stage) it was necessary to control for stage to allow comparison between years. The ideal scenario would be to have images with identical discharge in all years, which in reality is not possible. To control for discharge, the images in the time-series were acquired within the dry period from November of one year to May of the next year when there is little if any change in planform and the stage is fairly low and constant from year to year. The majority of images were acquired in November or December when the stage is sufficient to fill the main channel. During November and December the area is generally cloud free, as it is the dry season. In some instances, however, extensive cloud cover existed during these two months or data were unavailable. In such cases, data between the months of January and May of the next year were considered as the low-flow period extends through these months. To check for flow level stability, discharge data from the Farakka gauging station covering a 24 year period (Appendix 8.2 – 8.3) from 1949 to 1973 were obtained from the Global Runoff Data Centre (Koblenz, Germany) and examined (Figure 3-2).

3.4.2 Georectification

All images in the time-series were transformed to a common coordinate system representing the ground space. The Landsat MSS and ETM+ data were already georectified and projected into the UTM WGS 84 system. However, to allow comparison between different images the IRS data were geometrically corrected. The Landsat ETM+, November 2000 image was considered as the base image and all other images of Landsat MSS and ETM+ were georectified to the November 2000 image. Any differences with respect to the November 2000 image in the positions of permanent features in the MSS and ETM+ images were corrected by polynomial georectification (image warping coupled with pixel re-sampling) based on ground control points (GCPs) (Hughes *et al.*, 2006). The IRS data were co-registered to the Landsat ETM+ November 2000 image by taking around 50-60 GCPs using the same polynomial georectification process.

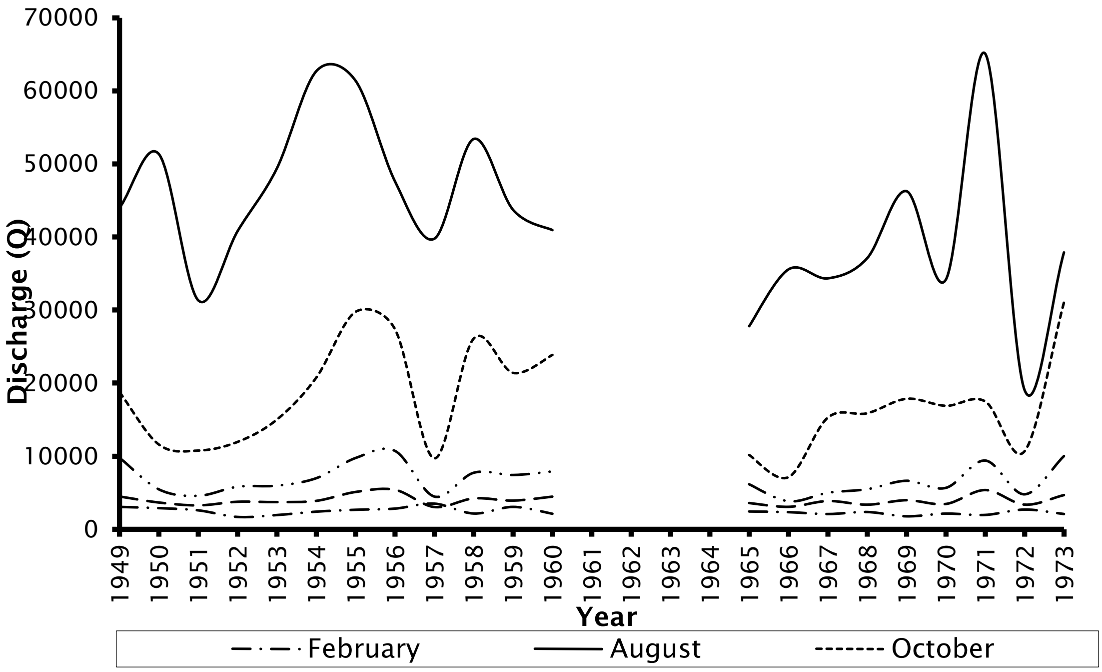


Figure 3-2 Monthly average discharge for several months plotted against year from 1949 to 1973 for the Ganga-PadmaRiver (Data Source: GRDC, Germany).

The process involved three steps (i) matching the GCPs with common features in the base layer, (ii) transforming the GCPs to the UTM WGS 84 coordinate system and (iii) pixel re-sampling. The GCP selection was conducted following a published technique

(Campbell, 2002; Richard 1986). The GCPs were distributed evenly to provide a stable image warp (Leys and Werrity, 1999). When choosing GCPs, both hard (e.g. road crossings, canals) and soft points (corners of waterbodies, features with fuzzy edges) were considered. Hard points should be considered in preference to soft points to increase georectification accuracy (Hughes *et al.*, 2006), but as the environment was riverine not all soft points could be excluded. Polynomial transformation was carried out on all the images, including the unregistered IRS sensor data. During polynomial transformation, a least-squares function was set between the GCPs of the unregistered or incorrectly registered satellite sensor data and the base data. The differences in location between GCPs on the transformed layer and the base layer were represented by the root-mean-square error (RMSE) equation (Slama *et al.*, 1980):

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(X_{s,1,i} - X_{r,2,i})^2 + (Y_{s,1,i} - Y_{r,2,i})^2}{n}} \quad (3.1)$$

where X_s and Y_s are coordinates of the points on the source image; X_r and Y_r are the identical points on the transformed satellite sensor image and n is the number of points on the image. The average RMSE of the whole image was less than 1 pixel. Re-sampling of the pixels then was conducted using the nearest neighbour function as it retains the original pixel values (Hughes *et al.*, 2006).

3.4.3 Controlling for Variation in Spatial Resolution

As the time-series data from the Landsat and IRS archives spanned a 38 year period, the research required the use of images of multiple spatial resolutions varying from 80 m to 30 m (Landsat) and 72.5 m to 23.5 m (IRS). Thus, it was, necessary to standardise the spatial resolution so that meaningful comparisons could be made (Ham and Church, 2000; Petit and Lambin, 2001). To facilitate comparison between images of different dates all fine spatial resolution data were converted to a uniform 80 m spatial resolution, using pixel averaging, bringing all the data over the time-series to the same level of spatial generalization. This meant that the spatial complexity was reduced in some images, but the spatial resolution was adequate to reveal the major thematic and spatial characteristics required for this research (Weibel and Jones, 1998).

The archival Landsat data and IRS data pre-1998 were of 80 m and 72.5 m spatial resolution, respectively. As no TM data were available of the study site from 1990 to 1998, these were replaced by IRS 1A, 1B LISS I data of 72.5 m and IRS 1C LISS III of 23.5 m spatial resolution, respectively, from 1988 onwards. The images available were coarsened to 80 m spatial resolution by digitising the data at the original spatial resolution, rasterising the vector representation, and upscaling the data to a spatial resolution of 80 m by simple averaging (Figure 3-3).

3.4.4 Vectorisation

Initially, to extract the wetted channel and the non-wetted channel areas within the river a supervised classification technique was tested on data for a single year (Downward *et al.,* 1994). Such automated classification was found to be unsuitable as the bankline and channel bar boundaries could not be extracted accurately due to mixed pixels and similarities in the reflectance of the sand in the point bars and sand splays in the riparian zone on one hand and low lying high moisture laden areas and water channel area on the other hand. To reduce the discussed classification errors, the river bankline and channel bars were extracted by manual digitization of the whole river reach within the study area for all the available satellite sensor data series (Figure 3-4). The vectorisation of the data at their original spatial resolution enabled to extract the river bankline as well as the boundary of the bars with enhanced accuracy. Thus the vectorisation of the data was carried out followed by rasterisation and then upscaling of data to coarser resolution for analyses.

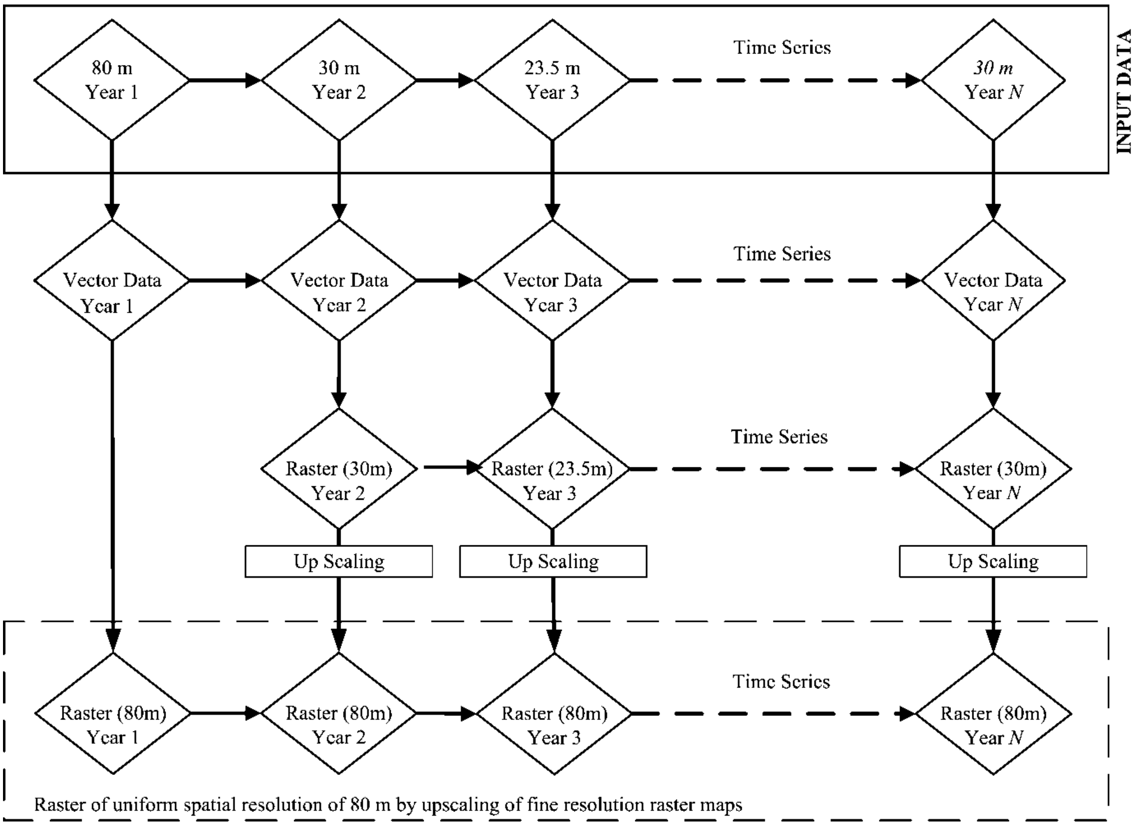


Figure 3-3 Schematic diagram showing the processing steps used to convert all available data to a uniform spatial resolution of 80 m.

The river in the study area was digitised in each year as a feature class (line), in a geodatabase, by inserting coordinates or nodes at close intervals to minimize digitising line generalization. As a result, the individual feature class was in the same projection system as the satellite sensor data (UTM WGS 84). The banklines, as well as the channel bar boundaries, were digitised as polylines in ArcGIS and the data were checked for cartographic accuracy and spatial topology errors such as undershoot, overshoot and unresolved line segment intersections. The feature classes were then converted into polygons for each year and stored in a geodatabase as a year-wise feature class (polygon). These polygons were then classified into two categories: (i) water channel and (ii) sand. The river in the study area is characterized by multiple channels i.e. an anabranching pattern (Nanson and Knighton, 1996). As the multiple channels were fully interconnected, water channels were represented by a single polygon.

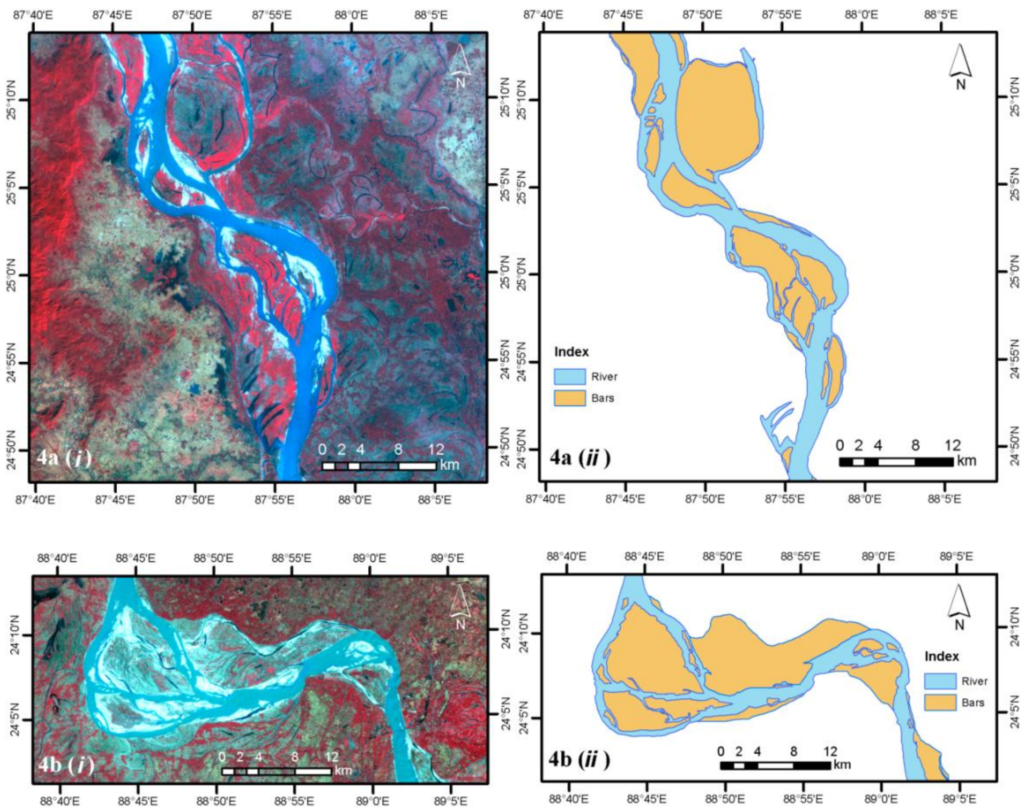


Figure 3-4[6] a(i) Landsat ETM+ image of 17 November 2000 and 4a(ii) corresponding manual digitisation; 4b(i) Landsat ETM+ image of 10 December 2000 and 4b(ii) corresponding manual digitisation. The problem of water on the floodplain is apparent in 4a(i), confounding automatic classification. The manual digitisation 4a(ii) and 4b(ii) enabled understanding of planform dynamics as seen in Figure 3-7. Figure 4a (i) and 4b (i) are standard false colour composites where the Red Green and Blue band has been assigned Green, Red and NIR colours respectively.

3.4.5 Vectorisation *vs* Digital Image Classification

Traditionally, digital image classification techniques like unsupervised or supervised classification should have been a preferred method for extraction of the water channel area as well as the sand bars. But these techniques are unable to extract information with high accuracy level due to spectral confusion amongst the wet areas in the flood plain and the boundary of the water channel area. The ox-bow lakes in the flood plain though can be easily identified due to their very low reflectance but the main aim of this study was to extract bankline of the river system at the highest possible accuracy level over the whole time series long with the bar boundaries within the river system.

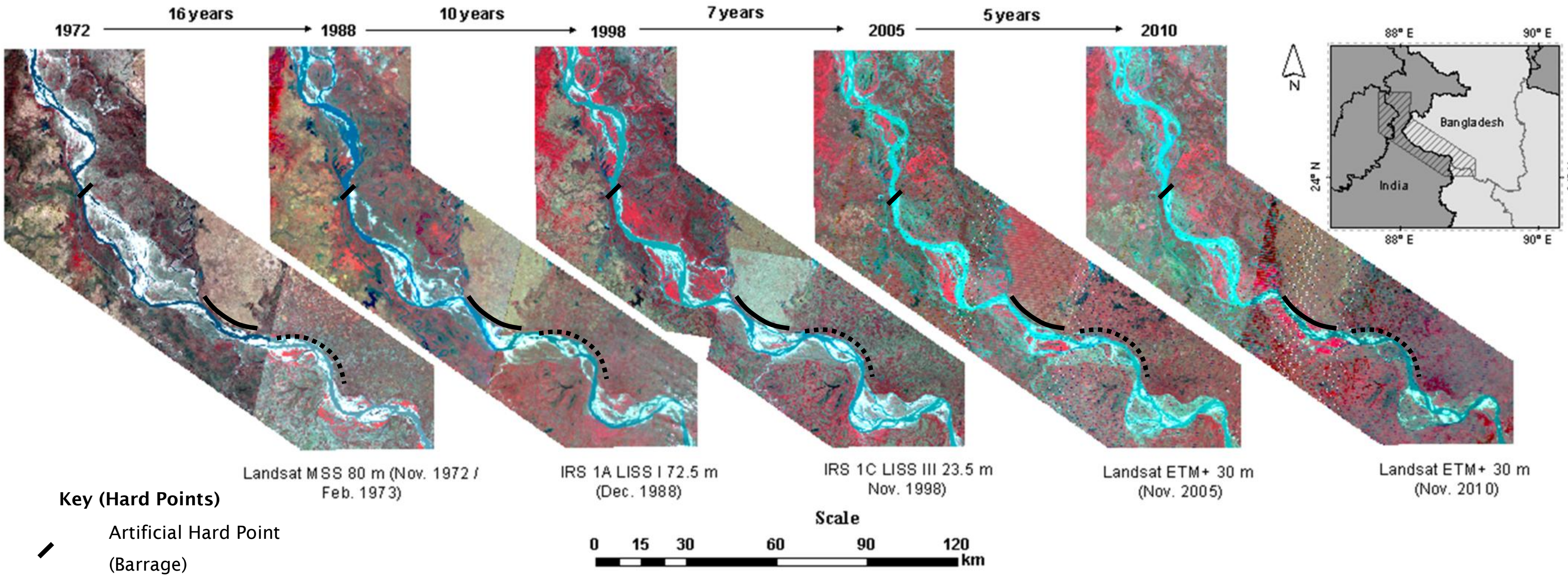
Dynamics of wetlands in river floodplain have been studied using rule based classification techniques like Normalised Difference Water Index (NDWI) to demarcate wetland boundaries (McFeeters, 1996). As the aim of the study was not to explore dynamics of wetland in river floodplain, so the above method was not explored. Some studies recently have used unsupervised classification methods alongwith neural network technique to delineate river banklines (EGIS, 2002; Baki *et al.*, 2012). In the present study, as digital classification technique did not yield encouraging results for the whole reach of the study area, manual digitsation technique was chosen. It requires mentioning that image classification technique did yield result in the lower reaches of the study area but not along the whole reach. The main issue was mixing of the wet pixels in the floodplain with the wet pixels of the river boundary as well as the point bars and the sand splays along the bank. Better image classification algorithms were required for uniqueness of part of the study area but were not within the scope of the present research.

3.5 Geomorphological Interpretation

The sequence of co-registered images brings the Ganges river system to life, revealing a cyclic pattern in the study area (Figure 3-5 and Figure 3-6) (also see animation in CD).The river started as a single thread channel in 1972, and then started meandering at four locations controlled by some natural and artificial hard points. After approximately a 17 year period in 1992, chute cut-offs are observed at multiple locations almost simultaneously. The chute cut-offs grew in size while the existing meanders narrowed, leading ultimately to complete closure by the process of aggradation around 2005. This led to the river returning to a planform similar to that present at the beginning of the study period. Morphological modification of river channels by means of chute cut-offs as observed and explained above have been recently termed as soft avulsion or mild avulsion (Edmonds *et al.*, 2011).

A similar dynamic behaviour has been observed in other mega-river systems of the world especially in the tropical regions (Rutherford, 1994, Stølum 1998) although the time taken for completion of the channel adjustment process varies from one system to another. The dynamics of the river system have a morphological interpretation in relation to the geology of the area, as well as natural and artificial hard points existing in the region, especially the Farakka Barrage. The Farakka Barrage was commissioned in 1975 to divert a part of the discharge of the River Ganga through an artificial feeder canal to rejuvenate the Bhagirathi-Hooghly system which was historically the main channel of the River Ganga. A major effect of the barrage was observed just downstream of the barrage due to force feeding of water released from the barrage through one of the two existing downstream channels leading to closure of the other channel (Figure 3.5 where two channels are seen to exist just below the Farakka barrage in the 1972 satellite sensor data while the left channel is absent from 1988 onwards). Effects upstream of the barrage were also observed in terms of shifting of the meander bend further upstream with respect to the pre-barrage location (Figure 3-7). The shifting of the meander upstream can be interpreted as due to blocking of a freely swinging river. The river adjusts to the creation of hard point by shifting its pre-barrage meander further upstream as a number of embankments created along with the barrage restrict the free growth of the meander. The natural hard points created by geologically older formation (Barind formation) restrict the river from changing its bankline over the studied time series (Figure 3.5). Similarly the river has been seen to have no bankline change along the left bank near Rajshahi town in Bangladesh where a century old embankment exist. These dynamics are revealed here for the first time using the time-series data available from the Landsat archive.

The time-series of the River Ganga reveals that the river exhibits a self-organising behaviour trying to attain dynamic equilibrium, as observed by Schumm *et al.* (1994) in the River Mississippi, USA and by Hooke (2003) in the River Bollin, UK. Chute cut-offs occur after the bend radius reaches a critical value. The sinuosity of the river, thus, reduces after an initial increase. The river is likely to then increase its sinuosity again and oscillate within a critical value to maintain its self-organised state as observed by Stølum (1998) in his simulation model. This behaviour may be one part of the cycle of attaining dynamic equilibrium: self-organising criticality may have been attained in earlier periods before the era of satellite remote sensing. But SOC is difficult to prove due to lack of enough data st spread over a longer time period. Thus, the meander evolution can also be interpreted as a simple threshold response of a system where the chute cut-off occurs when the sinuosity reaches a certain critical value based on sediment flow and discharge from the upstream direction. The data also reveal the effect of the natural hard banks along the left bank in the lower reaches where erosion is concentrated along the right bank. The reaches just above and below the barrage reveal the effects of barrage management, especially in the lower reach where water has been force fed through one channel.



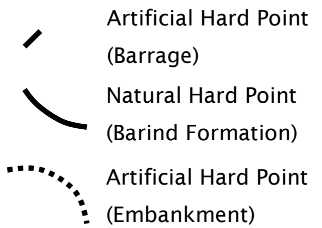


Figure 3-5[7] Sequential changes in the River Ganges over a 38 year period.

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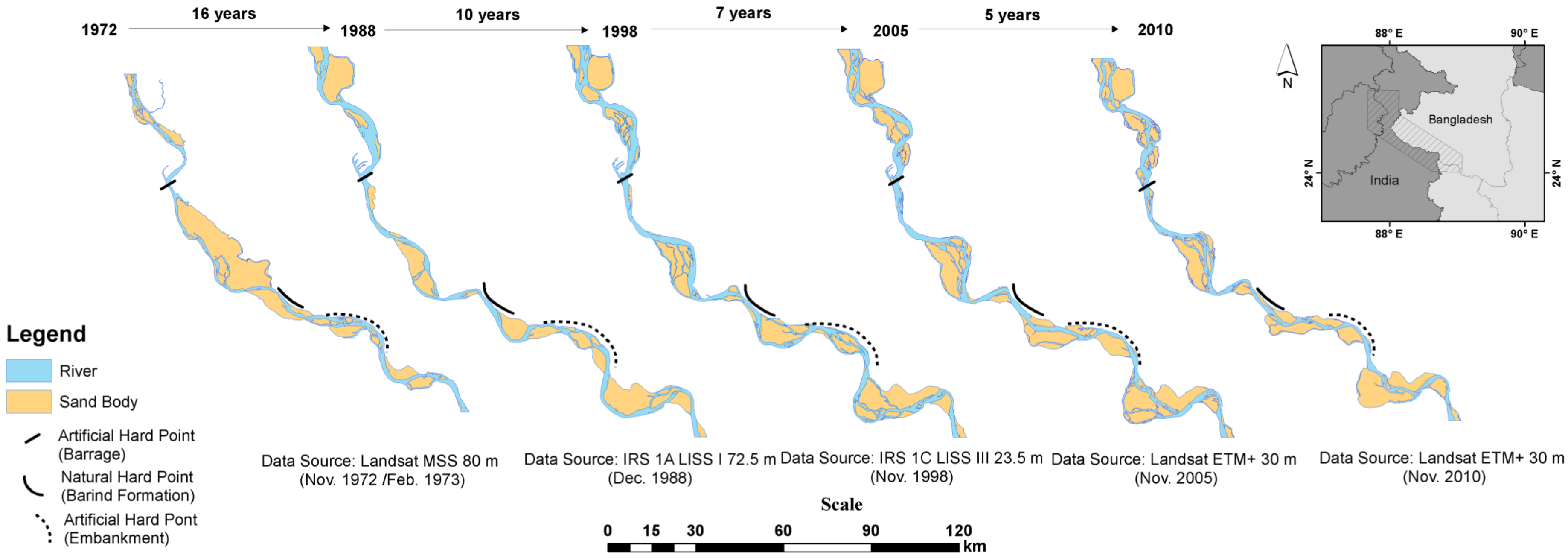

Figure 3-6 Sequential change of the Ganges over a 38 years period (Digitised from Landsat and IRS sensor data).

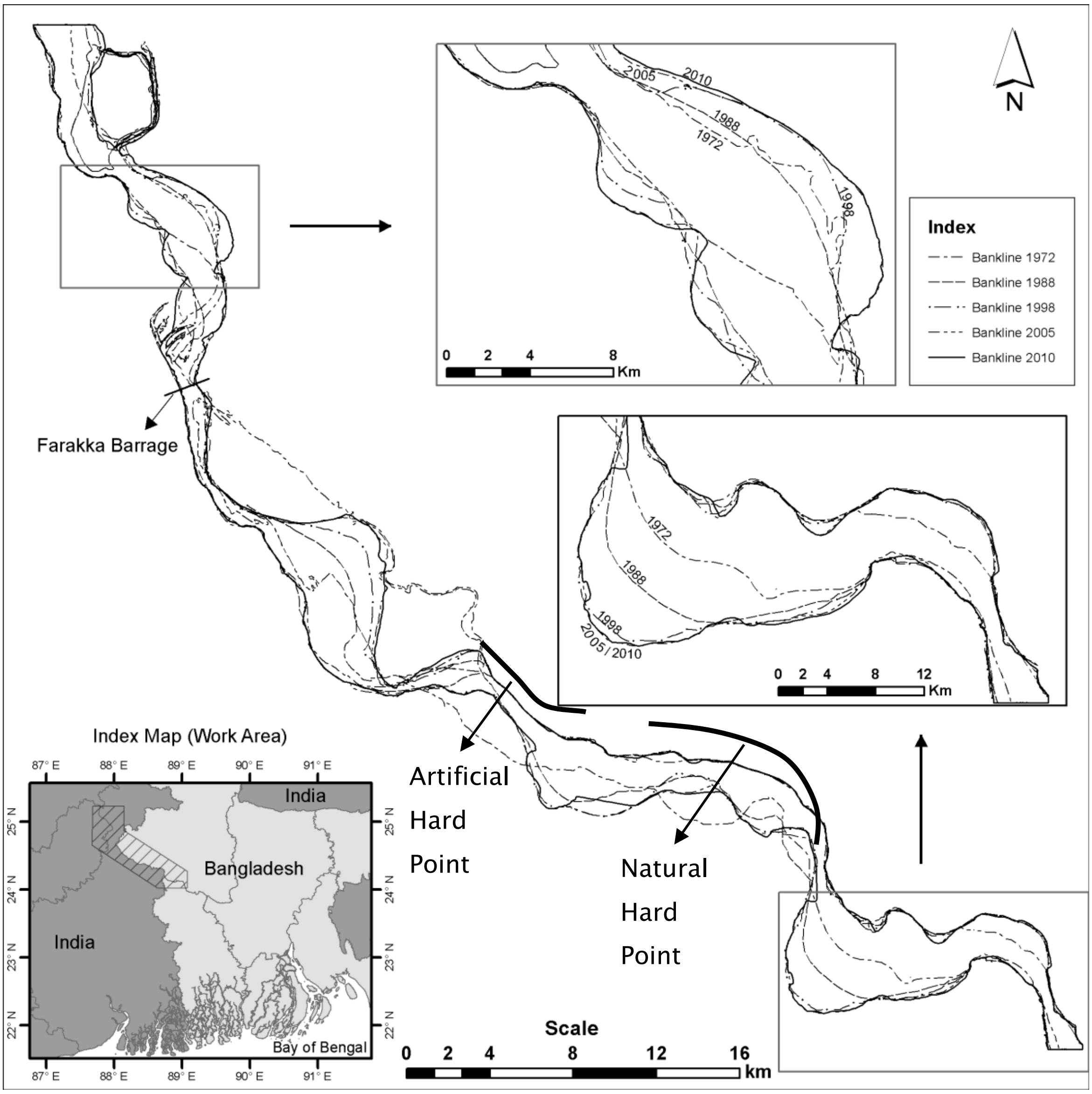

Figure 3-7[8] Planform dynamics of the River Ganga as observed from the manually digitised planform maps. The inset figures show the meander dynamics in two sections of the river in the study area over a 38 year period.

The time-series data also give some insights into bar dynamics in the river system as well as aggradation and erosion at bifurcations, where one bifurcate carries the main discharge and the other bifurcate collapses as it becomes plugged by the sediment load coming from upstream.

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3.6 Discussion

According to Latrubesse *et al.* (2005) knowledge of tropical river systems is limited due to their size and distribution over a large extent. Related to this, ground data for various tropical rivers are limited. Thus, the Landsat and other remote sensing archives provide an effective source of data to study the morphodynamics of large river systems, especially in tropical regions. The availability of sequential archival data has opened a new avenue for fluvial geomorphologists to study the large river systems of the world.

Gaps in the Landsat time-series, especially if working in areas outside the North American region, are a concern and additional data (e.g., IRS archive data in the present study) are likely to be needed to create the continuity of time-series exemplified here. In creating a time-series from multiple sensors, issues related to georectification and varying spatial resolution need to be addressed. In the present study, we used a manual data extraction technique to ensure the high quality of the data produced as well as uniqueness of the study area which restricts usage of digital classification technique. However, the process is time intensive and better image classification algoritms should be explored in the future as has been done by researchers studying the River Brahmaputra (EGIS, 2002; Baki *et al.*, 2012).

3.7 Conclusion

The Landsat archive was used to characterise the dynamic behaviour of the River Ganga and reveal the cyclic processes (morphological evolution) occurring within the system. The river exhibits a self-organising behaviour in which it periodically reaches a critical value of sinuosity (refer to p. 68) at which point one or more chute cut-offs are triggered. It is notable that this periodically repeating pattern is fixed locally by hard points in the geology (refer to p. 62), and by the Farakka Barrage, such that it is likely that this pattern will persist, at least in the short-term. The information provided here has increased understanding of the behaviour of the river Ganga and mega-rivers more generally. It also has implications for local planners and decision-makers. Specifically, local concerns over the potential lateral migration of the river Ganga and consequent erosion and loss of productive land are unlikely to be realised given the research presented here. Instead, a periodic repeating pattern in which the river is constrained to reworking old material has been demonstrated.

4 Criticality in the behaviour of the Ganga-Padma River meanders

4.1 Introduction

The future planform dynamics of a river system are governed largely by the present planform characteristics of the meanders (Gűneralp and Rhoads, 2005). Extensive research has been carried out on the characteristics and dynamics of meandering rivers (Brice, 1974; Hickin, 1974; Ferguson, 1975; Carson and Lapointe 1983; Nanson and Hickin, 1983; Hooke 1995), but the mechanisms involved are still not completely understood (Gűneralp and Rhoads, 2005). In particular, long-term meander dynamics on large river systems are difficult to study by empirical means (Stølum, 1998). It has been found that historical maps spanning over eight centuries provide limited information on long-term meander dynamics because of the low temporal frequency of updates (Lewis and Lewin, 1983; Gagliano and Howard, 1984; Walters and Simons, 1984; Braga and Gervasoni, 1989). Similarly, repeat aerial surveys with frequent temporal intervals do not exist, limiting the ability to study planform dynamics over a long time period (Stølum, 1998). However, the availability of satellite sensor data at regular and frequent intervals for almost four decades has great potential for increasing our understanding of the natural cycle of meander growth, formation of chute cut-offs and ox-bow lakes in the large river systems of the world. The present study makes use of the available Landsat archive over a span of 38 years to study the meander evolution of the lower reaches of the Ganga system.

4.1.1 Meanders and chute cut-offs

River meanders and the resulting channel migration have been analysed due to their unique forms, dynamics and the changes they bring about in the floodplain as a result of their movement (Hooke, 2003). Meanders in rivers have been studied with a focus on their regularity and their morphological stability or steady-state forms (Langbein and Leopold, 1966). The evolution of meanders initially was explained by bar theory of Hansen (1967) and Callander (1969) which treated meandering as formation of alternate bars in a straight alluvial channel with non-erodible banks. Fredsoe (1978) developed the theory incorporating friction, inertia due to transverse velocity and sediment transport to explain bar instability giving rise to predicting capability as to whether channel will be straight, will form alternate bars or will braid. According to the theory the ability to form alternate bars gave rise to meandering channels (Blondeaux and Seminara, 1984). The bar theory over time changed to bend theory by Ikeda *et al.* (1976) followed by Ikeda *et al.* (1981) in which the restraint on the fixed side wall in the bar theory was relaxed and it was found that bend amplitude grew when the stability of a sinuous channel with erodible banks was tested (Ikeda *et al.*, 1981)

Over the years, the focus shifted to meander instability, the resulting complex forms and the processes which govern the theory of development of the unstable meanders (Hickin, 1974; Carson and Lapointe, 1983; Stølum, 1996). Meander instability can be defined as the process by which a meander grows by bank erosion and then relaxes by means of cut-offs influenced by various local geomorphic variables. In many unconstrained systems the meander changes in dimension, shape and is rarely the meander bend is consistent leading to an unstable state. In addition it can also be said that meander development is an expression of planform instability where a small localised perturbation spreads in upstream or downstream direction or both (Lanzoni and Seminara, 2006). Research based on conceptual and graphical models indicate that meander development is an asymmetrical process as sinuosity which is a measure of the state of a fluvial system transforms the system from a straight course or ordered state (axial symmetry) to a curved course or less ordered state (axial asymmetry). Stability analysis of a sinuous channel with erodible banks was used to delineate bend instability (Ikeda *et al.,* 1981) and the evolution of meanders. The study was based on bend theory rather than the bar theory of the past, and it was shown that for alluvial rivers both bend theory and bar theory operate on a similar scale (Ikeda *et al.,* 1981). The bend theory explains the observation of Kinoshita (1957) that alluvial rivers with small or moderate curvature contain only point bars whereas in torturous bends alternate bars may be superimposed on a single point bar.

The non-linearity in meander development was validated by research based on field data which showed that the non-linearity can be explained by a relationship between the rate of movement and radius of curvature (Hickin and Nanson, 1975; Nanson and Hickin, 1983; Hooke, 1991, 1997). In fact, meander behaviour can be considered within a phase space of sinuosity and rate of movement (Hooke, 2003), as change of radius of curvature is usually associated with a change in sinuosity.

4.1.2 Concept of self-organised criticality (SOC) and complexity

Self-organised criticality (SOC) had been conceptualised to create a link between a complex phenomenon occurring in nature and simple laws of physics/or one of the underlying processes (Bak and Tang, 1989; Bak and Chen, 1991; Bak, 1996; Winslow, 1997). The model evolved from the 'dancing landscape model' of Bak and Kaufmann which was modified to show not only the state of SOC but also the transition phase from an initial non-self-organised state to a state of SOC (Bak, 1996). The theory states that large interactive systems self-organise into a critical state governed by a power law. It also says that once the system is in this state, any small perturbation will lead to a chain reaction affecting any number of elements in the system.

The concept is most commonly explained by the sand pile experiment (Winslow, 1997) in which a single grain of sand is added at a regular interval to a pile of sand in a sand box. Initially the sand grains drop on the experimental sand pile without any effect increasing the slope of the pile. After a certain time interval, the slope locally reaches a critical value leading to an avalanche filling up the empty area of the box. If more sand grains are added, the sand box will overflow resulting in a scenario of gain or loss of sand. When the addition and loss of grain are equal then according to theory the sand pile has reorganised to a critical state. Any addition of sand grain may or may not result in an avalanche but eventually an avalanche will occur. The theory puts forward that (i) the next avalanche can be of any size but will occur following a power law, (ii) the interaction of individual sand grains will be dictated by simple physical laws and the system will self-organise to a critical state following these laws and (iii) avalanches will not be periodic.

Though this experiment is over simplification of processes occurring in complex natural system, the SOC concept may be applicable to model a natural system although noisy conditions prevailing in natural systems. For example, the SOC concept has been tested on magnitude and frequency of earthquakes and the Gutenberg-Richter relationship (Gutenberg and Richter, 1956), which describes the magnitude and frequency, has a power law distribution. The SOC can thus be validated in a natural system even with the existence of noise in the system.

4.1.3 Meandering and self-organised criticality

Meandering rivers reach a SOC resulting in complexity in the system where the river oscillates in space and time from a chaotic state to an ordered state (Stølum, 1996). The river increases its sinuosity by means of meandering (chaotic state) until it reaches a threshold where it self-organises by means of cut-offs to reach a low sinuosity value (more ordered state). Simulation models based on fluid mechanics theory have showed that meanders initially exhibit an increase in sinuosity from sub-critical state tending towards a state of criticality, then give rise to complexity by oscillating by means of cut-offs (Stølum, 1996) and meander regrowth. The cluster of cut-offs generally occur when the meander reaches the critical point. Stolum's (1996) model exhibited occurrence of bend growth followed by cut-off to maintain self-organisation. This process enables maintenance of steady state of the critical sinuosity (Hooke, 2007). In longer time periods of model simulation, Moorman (1990) found cyclicity and periodicity in the fluctuations of sinuosity. However, identification of SOC in nature requires evidence of meander evolution through extended time periods which in most cases is unavailable, or meander evolution is too slow to allow meander evolution and cut-off to be observed through more than one cycle (Hooke, 2003). Exceptionally, Hooke (2003) carried out a study on meander evolution in the River Bollin in Cheshire, NW England investigating a period of 160 years and tested for SOC. It was found that bend curvature increases until it reaches a critical value of sinuosity when clusters of neck cut-offs take place and the channel passes through a period of apparent channel disorganisation before stabilising after absorbing the effects or transmitting and distributing the effect of channel disorganisation along the course. Hooke (2003) observed that the sinuosity value attained immediately before cut-off is lower than the critical value of 3.14 suggested by Stølum (1996) through his simulation which was considered to be operating in unconfined alluvium. The difference in the critical value of the model and real system was explained by the fact that in natural systems river banks or terraces can be partially responsible for constraining loop development, resulting in cut-offs at lower critical sinuosity value after which self-organisation takes place through oscillations. Thus, river systems exhibit evidence of self-organisation corroborating simulation models (Moorman, 1990; Stølum, 1996), indicating that the self-organisation process is dynamic in nature and the critical value of sinuosity varies within a range after which self-organisation process initiates (Hook, 2003). Similar patterns of self-organisation have been exhibited for the River Mississippi using sinuosity data pertaining to periods of time prior to its artificial cut-offs (Schumm *et al.*, 1994). A hypothetical phase plot of meander behaviour based on bend curvature and rate of movement (Figure 4-1) shows a non-linear relationship and the different phases of the meander evolution. The specific nature of the cyclicity and periodicity will depend on variation in bank material, vegetation and other local factors (Hooke, 2003). Stølum (1996) indicated that the critical value of a reach will also depend on valley width and will be higher in unconstrained meanders and lower in constrained meanders. In ideal situation constrained meanders may never reach the critical value for cut-off, but in reality the meanders will ultimately reach a stage (over a longer time period) where it will have a cut-off or else it will be considered a straight river with a sinuous channel rather than a laterally migrating meandering river. However, other factors like geology and tectonics also have an influence on meander development (Schumm *et al.*, 1994; Goswami *et al.*, 1999). Thus the phase space diagram of meander pattern behaviour can be developed further by incorporating these limits and constraints.

4.1.4 Channel pattern reorganisation due to meanders and chute cut-offs

In the process of reaching a state of SOC meandering rivers may also change from one channel pattern to another. Chute cut-offs which takes place in confined sections of meandering rivers are also a manifestation of a change from a meandering to an anabranching / weakly or moderately braided river system (Friedkin, 1945) and are considered an important process in the initiation of active braiding (Ashmore, 1991). Chute bars may be eroded to form chute cut-offs and the new channel formed due to a cut-off may be considered a braid. The channel curvature determines the configuration of the chute bars. The chute bars are formed along with the scroll bars on point bars in the channel. If the meander bend is tighter the chutes tend to cross cut most of the point bar. Figure 4-2 shows a schematic diagram of the various bars and the cut-offs discussed here. Chute cut-offs tend to form at relatively high stream power (Kleinhans and Van den Berg, 2011). The spatial scale takes into consideration the ratio of river depth and friction coefficient while the temporal scale is proportional to the square of the spatial scale divided by the width of the river, longitudinal velocity and the erodibility coefficient (Camporeale *et al.,* 2005). Thus, these scalars indicate that the characteristics of the bank material, river depth and river width are important factors controlling the long-term self-organising condition of a meandering river.

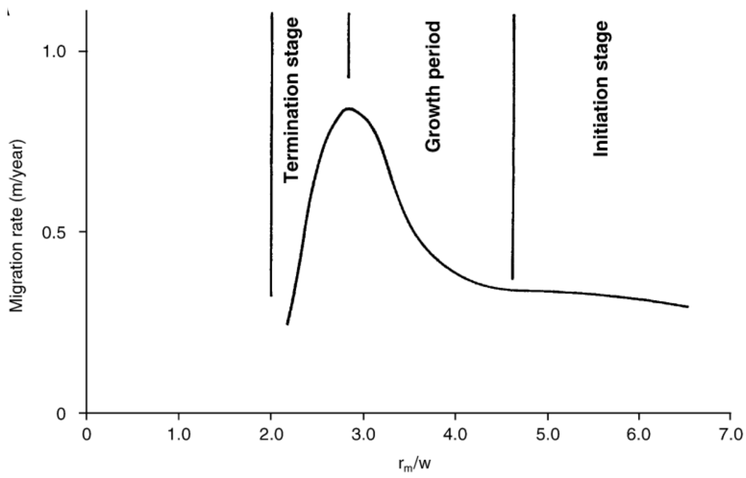

Figure 4-1[9] A hypothetical phase plot of meander behaviour based on bend curvature and rate of movement (Hickin, 1978).

4.1.5 Upstream influence on meandering rivers

River meandering has been classified as a sedimentary process at the spatial scale of the channel width which expresses itself by the formation of bars (Lanzoni and Seminara, 2006). Lanzoni and Seminara (2006) attempted to find out if the upstream can influence the evolution of the planform of a meandering river when the downstream of a meander bend is constrained. Laboratory experiments in erodible channel with constant curvature and non-erodible bank connected by straight channel

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both up and downstream of the curvature showed downstream influence with the formation of a stationary bar downstream of the entrance to the bend as well as downstream of the exit of the bend (Struiksma *et al.,* 1985). However, further experiments have shown that if the channel is wide enough then the presence of a bend generates an influence on the upstream reach by means of damped spatial fluctuation of bed topography along the inner and outer banks in the upstream reach (Zolezzi and Seminara, 2001). Thus, it can be said that an upstream bend steers the flow over some downstream distance resulting in erosion or closure of chute or meander channels.

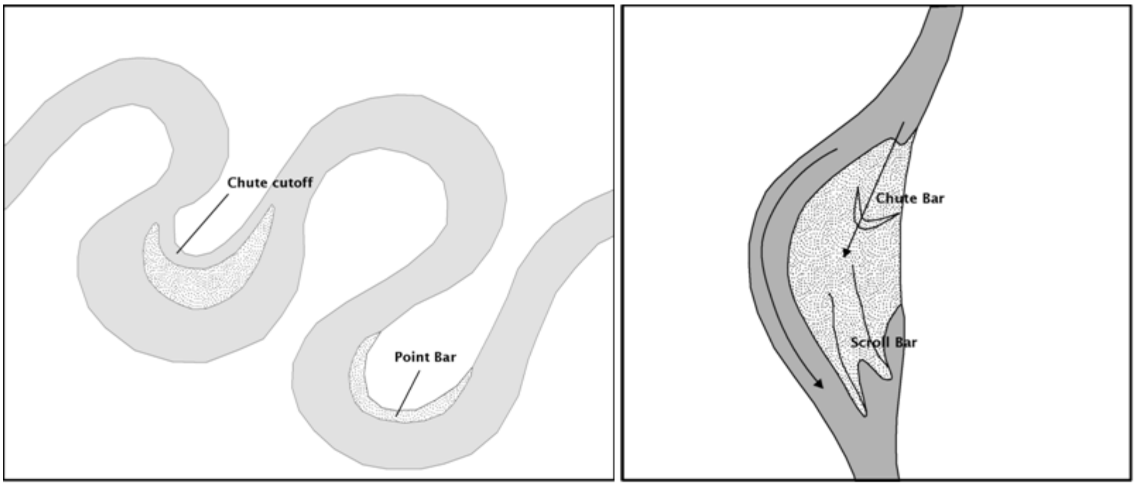

Figure 4-2 Schematic diagram of point bar, chute bar and scroll bar occurring in a meandering river channel and chute cut-off which leads to meander evolution.

4.1.6 Effect of bends at bifurcation

The formation of a chute cut-off when the meander bend reaches the critical value leads to the formation of a bifurcation at the cut-off location. If a bend exists above the bifurcation then the division of water and sediment between the two branches will be influenced by the bend characteristics. The bifurcations developed due to a chute cut-off are unstable in the sense that as one channel grows and the other reduces one of the channels receives less sediment than its transport capacity leading to erosion of its banks while the other receives more sediment than its transport capacity and gradually aggrades and shallows (BollaPittaluga *et al.,* 2003). The division is conditioned primarily by the gradient advantage of the enlarging branch, the bend conditions at the bifurcation and bar dynamics in the upstream reach (Miori *et al.*, 2006; Kleinhans *et al.*, 2007).

4.1.7 Objective

Based on the above background on meander evolution, chute cut-offs, self-organising criticality, upstream influence on bends and the influence of bends at

bifurcation, the present research focused on interpreting the meander dynamics of the lower reaches of the River Ganga-Padma over a 38 year period. A conceptual model was developed based on graphical information from the sensor data and quantitative information on river metrics like sinuosity. This conceptual model was then used to explain the behaviour of the river system of reaching a threshold for cut-off to occur and self-adjustment including evidence for self-organising criticality and the attempt of the river to reach dynamic equilibrium. In addition the effect of other natural and anthropogenic factors on the dynamics of the river system has also been explored.
The objectives of the present research were three fold. The first objective was to explain the natural meander dynamics of the system including chute cut-offs and the mechanism which controls the meander dynamics which will ultimately lead to chute cut-offs. The second objective was to examine the effect of hard banks due to the antecedent geology on the river dynamics in some reaches of the river system. The third objective was to examine the possible perturbation of both upstream and downstream reaches of the river system due to the construction (1975) of the Farakka barrage. Time-series satellite sensor data show that water was released from the barrage through one of the two bifurcating channels located just downstream of the barrage location which previously existed as a natural course of the river, leading to a situation where the upstream forcing in the planform evolution of meandering rivers can be explored.

4.2 Study area

4.2.1 Study site

The study area (Figure 4-3) is located in the eastern part of India covering the districts of Malda and Murshidabad in West Bengal and part of the Bengal Plain of the Indo-Gangetic alluvial tract (Singh, 1987). In the study area, the Ganga-Padma river system borders the Himalayan Foredeep Zone in the north and the Shelf Zone and Mid-Basinal Zone (west and east of the Bhagirathi-Hooghly River, respectively) in the south (Refer to Figure 6.2) (Ghosh and Majumder, 1990). The river Ganga enters the state of West Bengal, India from the north-west from the Chotanagpur plateau fringe and flows into the alluvial plain in a south-east direction and further downstream splits into two branches. The main eastern-southeastern branch (known as the Ganga-Padma River) flows into Bangladesh and joins the River Brahmaputra (known as the River Yamuna in Bangladesh) and together proceeds into the Bay of Bengal as the River Meghna. The other branch flows south into the Bay of Bengal as the River Bhagirathi-Hooghly.

The river Ganga is characterised by changes in its course over historical time scales, particularly in its seaward reaches before it enters the Bay of Bengal. The river is prone to bank erosion during high discharge leading to changes in its planform. Lateral migration results in loss of villages and towns and loss of agricultural land as the river flows through one of the most densely populated regions of the world. The lateral migration of the river has been observed to be from west to east upstream of the barrage and from east to west downstream of the barrage.

Research indicates that the geological character and neotectonism of this region may be responsible for changes in the river planform over time (Seijmonsbergen, 1999). Major seismic activity in the past has brought about drastic shifts in the tributaries of the river Ganga (Bhattacharya, 1959). For example, a major former Ganga tributary (River Teesta) changed its course, and is presently a tributary of the river Brahmaputra, due to major seismic activity in the mid-1800s (Bhattacharya, 1959, Chowdhury and Kamal, 1996). However, the effect of tectonics on the planform dynamics of the Ganga-Padma river system is beyond scope of this chapter.

The basic hydrological properties of the system are summarised in Table 4-1. The three major Himalayan Rivers, the Ganga, Brahmaputra and Indus, are the most sediment-laden in the world (Milliman and Meade, 1983); they carry 1.8 Gtonnes yr^{-1} of suspended sediment (about 9% of the total annual load carried from the continents to the oceans worldwide) and have a combined runoff of 1.9×10^3 km^3 (Meybeck, 1976; Hasnain and Thayyen, 1999). The River Ganga itself carries a sediment load of 729 million tonnes yr^{-1} (Abbas and Subramanian, 1984; Wasson, 2003), recorded upstream of the Farakka Barrage in the study area, while in the downstream reach it carries a sediment load of 300-500 million tonnes yr^{-1} measured at Hardinge Bridge in the study area (Sarker, 2004). The balance sediment load is partly deposited in the barrage reservoir and another passes downstream through the link canal. The large sediment production is attributed to the Himalayan catchment and the monsoonal rainfall which triggers extensive erosion. Besides heavy rainfall which produces the sediment load, snow melt also contributes flow and tonnes of additional alluvium to the tributaries and ultimately to the vast river bed of the Ganga (Froehlich and Starkel, 1993; Latrubesse *et al.*, 2005). The river system is about 1.4 km to 2 km wide at its narrowest points in the study area and varies from 10 km to 13 km wide at its widest sections. The channel bars are also about 0.7 km to 1.5 km wide and sometimes even larger. The channel pattern of the river is mainly meandering with anabranching pattern (multiple channel) within some reaches

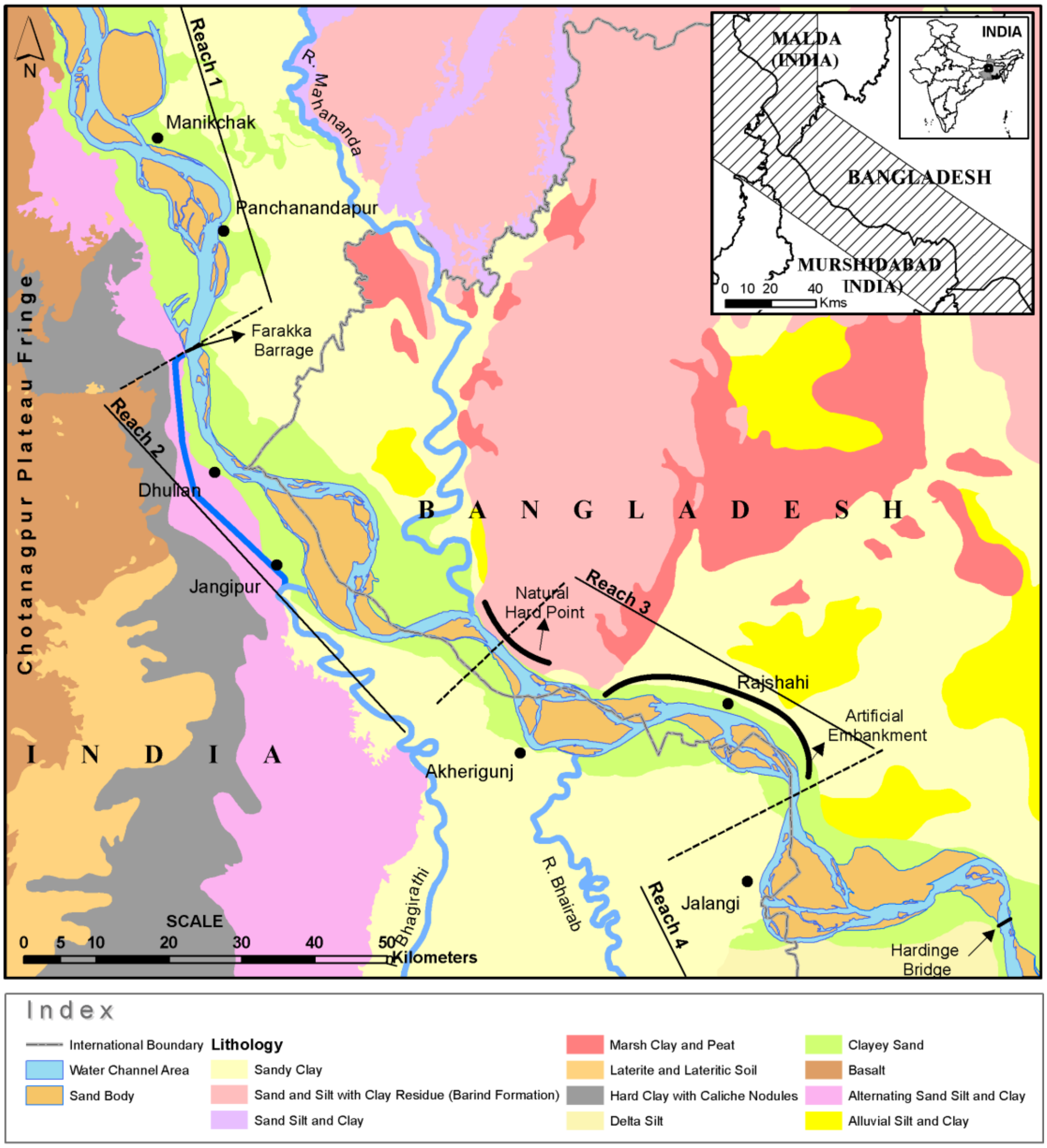

Figure 4-3 Geological setup and location of the study areain West Bengal, India. (Source: GSI Quadrangle map of 1:1,000,000; GSB Geological map of 1:1,000,000 scale and updated from Landsat ETM+ November 2000)

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Table 4-1 Hydrological parameters of the Ganga - Padma system

Parameter	Values (approx.)
Mean annual discharge	12100 $m^3\ s^{-1}$
Mean bankfull discharge	60000 $m^3\ s^{-1}$
Valley gradient	5 cm km^{-1}
Bed sediment particle size (D_{50})	0.14 mm
Meander wavelength	5 km
Channel depth	16 – 20 m

4.2.2 History of river planform dynamics and bank erosion

River bank erosion and lateral migration are chronic problems both upstream and downstream of the Farakka barrage along most of the 207 km length of the river being studied. The upstream length of the river in the study area is about 59 km north of the Farakka barrage and the downstream length of the river in the study area is around 148 km from Farakka barrage to about 8 km downstream of Hardinge Bridge in Bangladesh (Sarker, 2004). In the recent past, bank erosion and the rate of change has increased resulting in a loss of agricultural land of about 3 km^2 to 3.5 km^2 annually upstream of the Farakka barrage in the study area of this research (Chattopadhyay, 2003). The total loss of land in the study area upstream of the Farakka barrage from 1931 to 2003 was around 186 km^2 (Chattopadhyay, 2003; Iqbal, 2010). Between 1980 and 1999, net erosion downstream of the Farakka barrage to Hardinge Bridge (in Bangladesh) within the study area, was 48.5 km^2 on the Indian side and 126.5 km^2 on the Bangladesh side (Sarker, 2004).

A comparative study by Parua (2009) of the Survey of India toposheet of 1924, 1939, 1948-49, 1956 and 1961-62 revealed that the river had a meandering pattern and the pattern changed over the surveyed time period. The main flow of the river was along the right bank above the present barrage location and on the left bank below the present barrage location during 1939. The pattern reversed in 1948-49, but returned to the 1939 pattern again in 1956 and did not change much until 1961-62 at which time there was some evidence of a trend of return to the 1948-49 pattern with increased river bank erosion (Parua, 2009). Presently the main flow is along the left bank upstream of the barrage and the along the right bank just downstream of the barrage (although just downstream of the barrage the right bank flow is forced by the barrage).

4.2.3 Farakka Barrage

A major barrage was commissioned in 1975 on the River Ganges at Farakka to create a perennial head-water supply from the River Ganges to the River Bhagirathi-Hooghly through an artificial feeder canal (Mazumdar, 2005; Parua, 2009; Rudra, 2010).

There are two schools of thought regarding the effect of the barrage on the increased rate of bank erosion both in the upstream and downstream reach of the study area. Social scientists argue that increased erosion is attributable to the construction of the barrage which affects the natural flow of the river (Rudra 2006, Mukhopadhyay and Mukhopadhyay, 2007). However, the engineers involved in construction of the barrage are of the view that the concrete barrage floor was constructed close to the average bed level of the river such that during maximum flood of 760 x 10^3 m^3 s^{-1} (Sen, 2008), the water level will rise by a maximum of 0.025 m (above the pre-barrage level) in the upstream direction. The flow control arising due to rise in water level of 0.025m would not enhance the existing bank erosion in the upstream reaches. However, regarding enhanced erosion in the downstream reach in the immediate vicinity of the barrage, some engineers feel that the non-operation of the barrage gates along the left bank may have enhanced bank erosion along the right bank upto a distance of around 30 kilometres downstream of the barrage as the left channel below the barrage became inactive due to siltation (Parua, 2009).

4.3 Methodology

A time-series of satellite sensor data (Landsat and IRS) was digitised and analysed using overlay analysis and geomorphological river metrics calculated. The data were used to build a conceptual model of river evolution by means of meandering and chute cut-off. Non-availability of satellite sensor data prior to the construction of the barrage meant that river characteristics prior to the barrage were obtained from the literature. A set of aerial photographs of November 1966 (approx. 1:60,000 scale) were used to represent the pre-1972 period (Geological Survey of India Archive), although the dataset was incomplete downstream of the barrage as the international boundary of India and Bangladesh passes through the river system.

4.3.1 Time series satellite sensor data

United States Geological Survey (USGS) Landsat Multispectral Scanning System (MSS) and Thematic Mapper (TM) data of 80 m and 30 m resolution for the study area were available from 1972 onwards with a gap during some specific years (Roy *et al.* 2010). In this research, the gaps were filled using data from the Indian Remote Sensing (IRS) programme satellite sensors which data were procured from the Indian Space Research Organization. The study area was covered by two scenes of Landsat MSS and TM data as well as by the IRS LISS 1 and LISS III data. The IRS, MSS and TM sensors data were of different spatial resolutions and so all data were aggregated to the resolution of MSS (80 m). By combining the different sources of sensor data (i.e. Landsat and IRS), a total of 38 years of data was assembled. The details of the data used for the present study are given in Table 4-2.

The sensor data used were mainly for November or December of each year when the area is generally cloud free, as it is the dry season. In some instances, however, extensive cloud cover existed during these two months or data were unavailable. In such cases, data between the months of January and May of the next year were considered as the low-flow period (November to May) extends through these months.

4.3.2 Data Processing

4.3.2.1 Controlling for Discharge

To control for discharge, the images in the time-series were acquired within the dry period from November of one year to May of the next year when the change in planform is negligible and the stage is from low to moderate and fairly constant from year-to-year. The majority of images was acquired in November or December when discharge is sufficient to fill the channel. To check for flow level stability, discharge data available from the Farakka gauging station covering a 24 year period from 1949 to 1973 were examined (GRDC, Germany). The data indicate that discharge was sufficient to fill the channel during November and December; the main periods of image acquisition.

4.3.2.2 Planform map generation

Georectification was carried out using established methods by matching the common permanent features in the time-series dataset to analyse channel position over time (Hughes *et al.*, 2006). The Landsat TM, November 2000 image was considered as the base image and all other images of Landsat MSS,TM and IRS were georectified to the November 2000 image. The images were corrected by polynomial georectification (image warping coupled with pixel re-sampling) based on ground control points (GCPs) (Hughes *et al.*, 2006). The GCP selection was conducted following a published technique (Richards 1986; Campbell, 2002). Both hard (e.g. road crossings, canals) and soft points (e.g. corners of waterbodies) were considered as GCPs as the environment was riverine and not all soft points could be excluded.

To reduce classification errors arising from digital image classification, the river bankline and channel bars for the whole river reach within the study area were digitised manually for all the available satellite sensor data at their original spatial resolutions. The vector data were then rasterised and then upscaled by simple averaging to ensure retention of detail at the original spatial resolution for use in future research. At the boundaries of the in-channel bars and sand splays the bankline was drawn by judging the location of the river bankline with reference to the data of previous year and the data of the next year. Although errors may exist they are thought to be negligible for the present analysis as the bank line changes at these locations were within a few metres and cannot be interpreted as the spatial resolution of the images was much coarser in comparison.

4.3.2.3 Computing erosion and aggradation

The river in the study area was divided into four reaches. Changes in the planform of the Ganga-Padma system were observed in these four reaches from north to south:

1. Manikchak-Panchanandapur section (Reach 1),
2. Dhulian – Jangipursection (Reach 2),
3. Rajshahi-Akherigunj section (Reach 3) and
4. Jalangi section (Reach 4)

as seen in Figure 4-3. The amount of erosion and aggradation was computed for every time step for the whole time series at these four reaches. The division of the reaches noted above was decided based on hard points located along the river. The first hard point was the Farakka Barrage while the other two hard points were straight sections of the river system (downstream of the barrage) where migration over the time series was observed to be negligible.

Raster analysis was carried out for each time step using the spatial analysis tools of ArcGIS to find the gain or loss in land area along the left and the right bank for each reach. Difference images were created for each time step and the net gain or loss of land per year was calculated for each bank and plotted to indicate the trend of bank migration in each reach. The average bank net gain or loss over the complete time-series was considered as a reference point and values above or below this level indicate years with high or low rates of erosion.

4.3.2.4 Analysing river metrics

Quantitative river metrics may lead to greater understanding of the processes underlying planform changes and the evolution of meanders in a river system. In this research, the sinuosity of the system over the time series was considered. The sinuosity of a channel indicates its geometry in plan and provides a measure of the degree to which a channel departs from a straight-line course (Ghosh, 2000). As the calculation was carried out on time-series data (Table 4-2), a semi–automatic method was devised to generate the channel centre line (channel length) of the river reaches using Arc-GIS Model Builder and the Arc-Scan utility. Sinuosity was calculated based on the equation (Leopold and Wolman, 1957):

$$S = \text{channel length} / \text{valley length} \tag{4.1}$$

The sinuosity of each individual reach was plotted against time to provide insight into the evolution of meanders.

Table 4-2 Archival Landsat and IRS data used for the research

Index: LM1: Landsat 1 MSS; LM2: Landsat 2 MSS; IRS 1AL1: Indian Remote Sensing Satellite 1A LISS 1; IRS 1BL1: Indian Remote Sensing Satellite 1B LISS 1; IRS1CL3: Indian Remote Sensing Satellite 1C LISS 3; L71: Landsat ETM+

Satellite Sensor - Bands	Date	Path / Row	Resolution (m)	Satellite Sensor - Bands	Date	Path / Row	Resolution (m)
LM1 - B456	19721123	148 / 43	80	L71 - B432	20021123	138 / 43	30
	19730222	149 / 43	80		20021029	139 / 43	30
LM2 - B456	19751117	148 / 43	80		20031110	138 / 43	30
	19751118	149 / 43	80		20031203	139 / 43	30
IRS1AL1 - B432	19881216	18 / 51	72.5		20041112	138 / 43	30
	19881217	19/ 50	72.5		20041119	139 / 43	30
IRS1BL1 - B432	19921104	18 / 51	72.5		20051115	138 / 43	30
	19921127	19/ 50	72.5		20051106	139 / 43	30
IRS1BL1 - B432	19941122	18 / 51	72.5	L71 - B432	20061118	138 / 43	30
	19950426	19/ 50	72.5		20061024	139 / 43	30
IRS1CL3 - B432	1998	107/54	23.5	L71 - B432	20071121	138 / 43	30
	1998	107/55	23.5		20071112	139 / 43	30
	19991115	138 / 43	30	L71 - B432	20090110	138 / 43	30
	19991106	139 / 43	30		20090117	139 / 43	30
L71 - B432	20001117	138 / 43	30	L71 - B432	20091126	138 / 43	30
	20001210	139 / 43	30		20091203	139 / 43	30
	20011120	138 / 43	30	L71 - B432	20101129	138 / 43	30
	20011026	139 / 43	30		20101104	139 / 43	30

4.4 Results

4.4.1 Qualitative analysis of planform dynamics

A qualitative analysis of the planform dynamics for each of the four reaches was undertaken by visual interpretation of the sequential planform maps generated from the time-series data. The first two reaches exhibited meander migration mainly towards the left bank while the last two reaches exhibited major migration towards the right bank. The observations are recorded below in detail.

Reach 1: In the Manikchak-Panchanandapur section (Figure 4-4a) visual observation and qualitative analysis of the time-series data indicated active erosion in this section along the left bank of the Ganga-Padma system. The morphological arrangement of the older meander scrolls indicates erosion of these scrolls by the river during its lateral migration. A north-easterly migration is evident in this section. The river exhibits its meandering nature with the outer bend towards the left bank in the aerial photograph of 1966 (also observed by Parua, 2009 in the 1961-62 topographic sheets). The bar dynamics of the river also have an influence on the morphological changes which can be observed in the system. In 1972 a point bar was located on the left bank and consequently the main flow of the river was along the right bank of the river. The point bar was about 13 km long and 2 km wide and can be observed flanking the left bank until 1975. As a result of this the water flow was directed along the right bank and the width of the water channel, thus, increased towards the right bank. A gap exists in the time series from 1975 until 1988. In 1988, the point bar on the left bank was completely removed, most probably due to high discharge. After 1988 a bar was deposited along the right bank opposite the location of the point bar that was flanking the left bank earlier. The bar gradually increased in length and width and disintegrated into three major bars. As a result of the increase in bar width and its disintegration, the main flow of the river was pushed towards the left bank increasing the meander migration at the outer bend which continued until 2004. The lateral migration was significant during the year 1997 where an analysis of pre-monsoon and post-monsoon data (April and November) indicates a shift of about 700 m in one rainy season (Figure 4-5). From 1999 onwards (after almost 11 years) the effect of the migration of the outer bend along the left bank was observed annually based on the time series data. Some older meander scrolls were found to be re-occupied by the migrating river indicating bank erosion and loss of land (Figure 4.5). The right bank started migrating towards the west from 1999 onwards until the end of the study period (December 2010). It was also observed that the point bar which was washed away in the 1988 image was seen to reoccur at the same location from 1999 onwards which gradually moved downstream flanking the left bank. From 2006 onwards the main flow of the river was located towards the central channel and the left bank was occupied by two major bars; this led to the outward migration of the right bank just upstream of the barrage and the main channel occupied some abandoned channels. A major river island exists at the top of the reach which has an influence on the flow pattern and bar development in the river as it is bounded by an embankment. The circuit embankment protecting the river island has been breached during peak discharge.

Reach 2: The Dhulian – Jangipur section (Figure 4-4b) of the study area was also modified over the time series. The older course of the Ganga, which is presently the Bhagirathi-Hooghly system, also bifurcates from this reach and is joined by the feeder canal from the Farakka Barrage. Before the construction of the barrage the river used to bifurcate into two branches with a semi-permanent bar in-between and join again further downstream. The remnant can be observed in the satellite sensor data of 1972 and 1975. The channel along the left bank was partially active until 1975 which can be seen from the satellite sensor data. However, the 1988 satellite sensor data shows the channel area to be covered with intense agricultural activity and the existence of a narrow water channel which joins the River Mahananda further downstream. However, from 1992 onwards due to aggradation, the channel has filled with sediment and a remnant channel exists today. It seems that the water release mechanism from the barrage is the primary cause of the flow being directed through one channel. Though in Figure 4.4b it seems that the left channel is a narrow channel but in aerial photograph of 1966 the channel could be seen as a major channel. The channel had actually narrowed down in 1972 satellite sensor data due to the barrage construction activity in progress. As a result of the closure of one of the channels the main flow is directed towards the right channel with erosion continuing until 1998. Further downstream, the left bank was affected by severe erosion. The outer bend along the left bank migrated outwards at a considerable rate from 1998 until 2005. The migration rate until 1999 was ~0.5 $kmyr^{-1}$. The river in this section was characterised by multiple channels showing an anabranching pattern. At the downstream boundary of the reach the left bank is joined by the River Mahananda. Bank erosion is also observed just upstream of the confluence of the River Mahananda with the Ganga-Padma system. The hard point on the left, downstream of the confluence (boundary of Reach 2-Reach 3) consists of the comparatively hard geological formation known as the 'Barind formation'. Geologically, this is older alluvium deposited during the Pleistocene which is well oxidized, reddish in colour and mottled containing ferruginous and calcareous nodules.

Reach 3: The third reach of the study area (Figure 4-4c) is around Akherigunj, India located on the right bank and Rajshahi, Bangladesh located on the left bank. The migration of the river in this reach is towards its right bank in two separate sections. The time-series satellite sensor data show that the river had a straight course in 1972 and 1975, but in 1988 there is evidence of erosion on the right bank at both locations. The first section of the reach eroded considerably and the off take point of one of the distributaries, the River Bhairab located 6 km upstream of the present mouth, shifted in a south west direction as the meander migration occupied the older meander scrolls around the distributary channel. The meander migration continued until 2005 with two channels bifurcating at a major mid channel bar. Until 1998 the left bank channel was the minor channel and the right bank channel was the major channel. From 1999 onwards until 2001, the left bank channel increased in width and both the channels had similar dimensions during this period. From 2002 onwards the right bank channel of the bifurcation slowly diminished in size and around 2006 closed down due to the bar which developed at the pinch point; gradually from 1998 and substantially from 1999 until 2002. The developing bar pushed the main channel towards the left bank by increasing flow resistance leading to soft-avulsion. This resulted in straightening of the river course by way of chute cut off or soft avulsion after 30-32 years. Incidentally, left bank erosion was not considerable for two specific reasons. In the first section of this reach the left bank is bounded by the relatively hard geology of older 'Barind Formation' alluvium (Figure 4.3). Consequently, the meander bend just upstream of the reach could not develop due to the hard point and the water was pushed towards the right bank. Secondly, Rajshahi, a major historical city located further downstream of the 'Barind formation', was protected by an artificial embankment from 1857. It is a 17 km long embankment with a height of 21 m above MSL with a top width of 3.26 m and a bottom width of 47.5 m (unpublished BWDC Report, 2000). The embankment was an earthen embankment with silt-sand composition which was later strengthened with concrete block mattresses in 1999-2001 after breaches at various locations due to floods in 1998 (Monir and Khan, 2004). The embankment continues until the downstream boundary of Reach 3. The 'Barind formation' and the embankment protecting the Rajshahi city and its surroundings prevents the river from eroding the left bank along most of Reach 3 and the high discharge during the monsoon season is diverted towards the right bank eroding it leading to the meander migration. A mid-channel bar further downstream, near the bifurcation of the two threads, migrated downstream after 1998 due to high discharge (due to the monsoon 1998) and is presently located along the banks of Rajshahi city. Consequently, the river now has a low flow channel along the left bank. A qualitative analysis of the reach from 1972 to 2010 indicates a low sinuosity which increases gradually and reaches a peak around 2002 and then reduces abruptly.

Reach 4: In the Jalangi section, the overall migration of the river is along the right bank of the river in a southerly direction. In 1972 the river had a meandering configuration with a high meander wavelength. The bend along the right bank developed into a tight bend which continued until 1998. From 1998 onwards due to the sharp meander bend and gradient advantage, a channel started developing cutting the bar along the inner bend by way of chute cut-off. The migration of the outer bend along the right bank reduced after the chute cut off. The outer bend along the left bank further downstream started migrating from 1988 onwards in the same phase as the outer bend along the right bank. The migration continued until 2006, with a lull in-between, after which the meander migration along the left bank stopped completely. In the first bend the river exhibits a anabranching pattern (semi-braided) due to the presence of several channels (formed as chute cut-offs) separated by mid channel bars. From 1998 until 2006, similar to Reach 3, the right bank channel of the first meander bend diminished in size while the chute channel increased in dimension. These trends ultimately led to closure of the right bank channel and domination of the chute channel resulting in a near straight course of the system. In the migration process the river has engulfed the older meander scrolls near the bifurcation point of the River Mathabhanga (another distributary of the Ganga-Padma system downstream of the River Bhariab) as seen in the time-series data (Figure 4-4d). The outer bend of the river further downstream in the reach did not migrate beyond the point it reached in 2006. Similar to Reach 3 a qualitative analysis of the time-series data indicates that the sinuosity increases from an initial low value and then falls abruptly from the moment of the chute cut off.

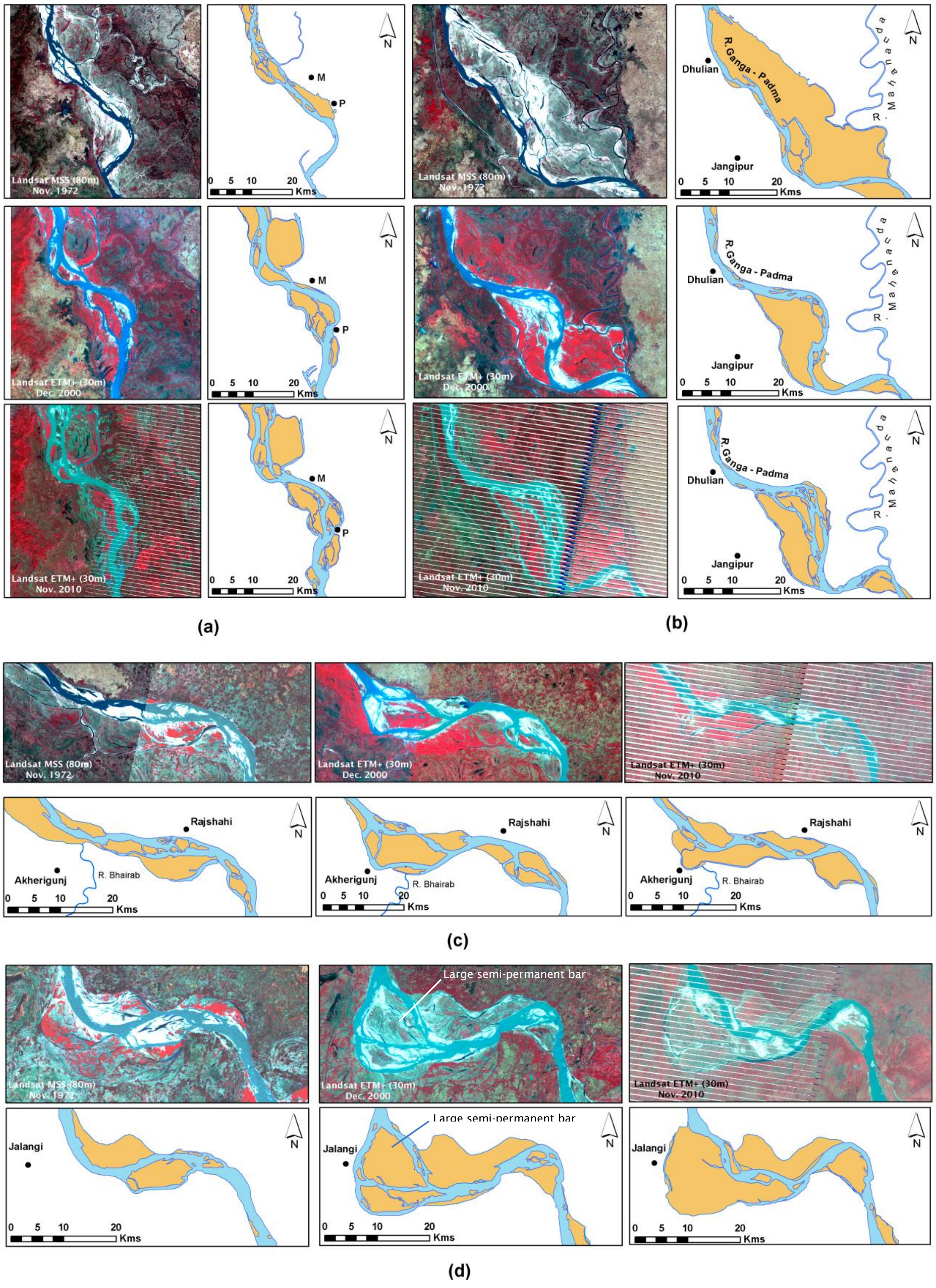


Figure 4-4(a) Changes in the planform of the Ganga-Padma system within Reach 1 from 1972 – 2010. M represents Malda and P represents Panchanandapur (b) Changes in the planform of the Ganga-Padma system within Reach 2 from 1972 – 2010. (c) Changes in the planform of the Ganga-Padma system within Reach 3 from 1972 – 2010. (d) Changes in the planform of the Ganga-Padma system within Reach 4 from 1972 – 2010.

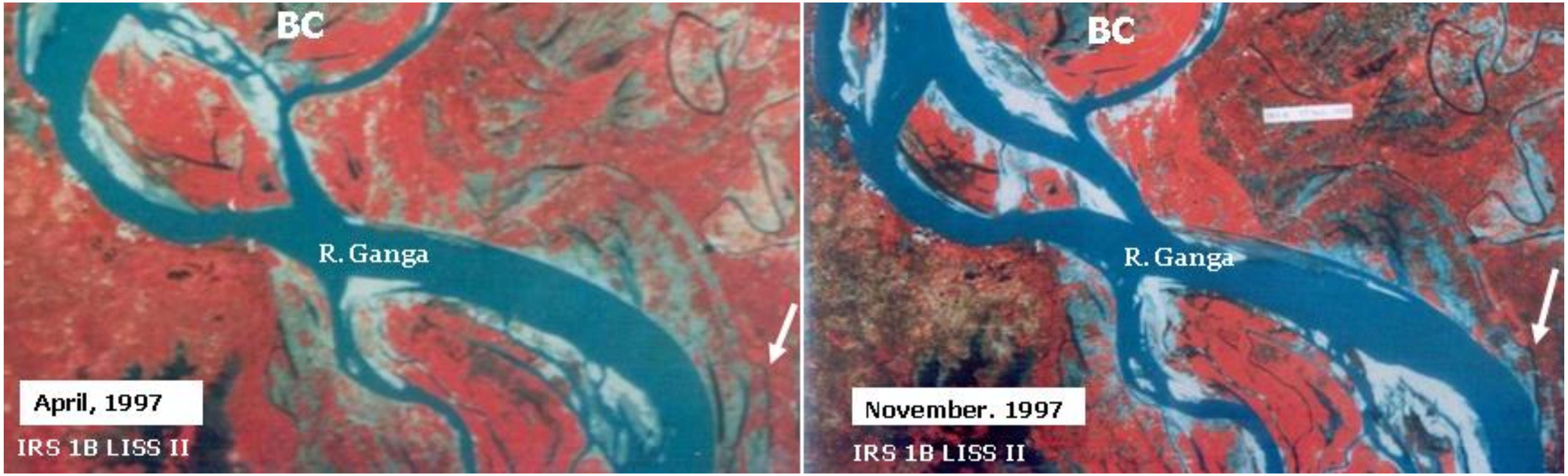


Figure 4-5 Satellite sensor data of the River Ganga south of Bhutnir Char river island (BC) in Manikchak–Panchanandapur section, Malda district for April 1997 and November 1997. An abandoned spill channel (active flood plain of historic times) is marked with a white arrow. The total shift of the river in one rainy season in 1997 is about 700 m.

4.4.2 Quantitative analysis of planform dynamics

4.4.2.1 Gain or loss of land area

An analysis of gain or loss of land was undertaken to ascertain if a trend exists in erosion or aggradation of the banks. As the time-series was not continuous until 1998, the pre-1998 changes were displayed as an average across the relevant years. This approach is the most accurate and appropriate representation of the available data graphically, but one should remember that an average may miss important inter-annual changes. The results were plotted reach-wise by incorporating the actual gain or loss of land (as points) and the net gain or net loss of land over the time period (as bars).

In Reach 1 (Figure 4-6) until 1998, the left bank (blue bar) exhibits an alternate decrease and increase of net land loss while the right bank (pink bar) exhibits an initial decrease of the net loss of land until 1992 after which the right bank exhibits a net gain of land and then in 1998 the right bank again exhibits a net loss of land. Post 1998 until 2007, the left bank exhibits alternate net loss and net gain of land while the right bank exhibits a similar trend until 2003. After 2003 the right bank exhibits a net loss of land which reduces until 2006 and thereafter the net loss of land again shows an increasing trend. In Reach 2 (Figure 4-7) the left bank (blue bar) initially shows a net gain of land (> 10 km^2) which continues until 1988, but considerable net gain can be associated to the closure of one of the channels just downstream of the barrage as indicated in Section 4.1.7. In 1972-1975 the left bank exhibits a net loss of land (> 5 km^2) which reduces until 1998. After 1998 the left bank again shows a considerable net loss of land (> 20 km^2) which again reduces until 2004. The net loss of land along the left bank from 2005 onwards shows an alternate increase and decrease until 2007. The right bank (pink bar) on the other hand shows an initial net loss which converts into net gain in 1988 and then from 1988 until 1998 the right bank shows a net loss of land (<5 km^2). From 1998 until 2007, the right bank shows an alternate net loss and net gain of land. The net loss or net gain was of approximately equal proportion for each alternating year. Reach 3 (Figure 4-8) does not exhibit any trend of net gain or net loss of land. The initial net loss of the right bank (pink bar) is considerable (> 15 km^2) but overall in this reach the right bank exhibits more net loss of land compared to the left bank (blue bar). In Reach 4 (Figure 4-9) the right bank (pink bar) exhibits a steady net loss of land from 1972 until 2000 during the migration of the meander in a south westerly direction. After 2000 it exhibits a steady net gain of land until 2003, after which it again shows a net loss of land. The left bank (blue bar) on the other hand does not show any trend of gain or loss of land, though at the initial phase it exhibits a net loss of land which changes to net gain until 1998. Post 1998, the net loss or gain of land reduces considerably until 2007, though it does not follow any specific trend.

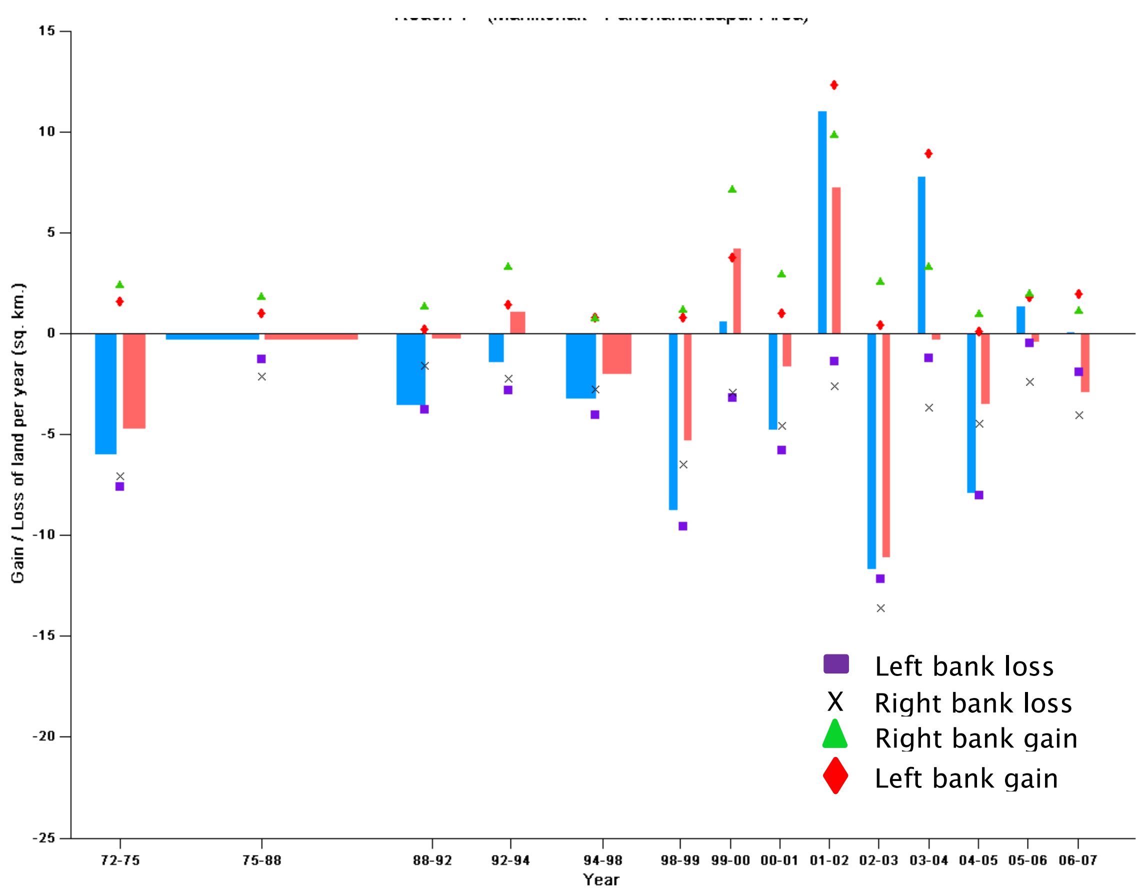


Figure 4-6 Net gain / loss of land within Reach 1 from 1972 – 2007. The points depict the actual loss / gain of land and the bars depict the net loss / gain of land. The blue bar represents the left bank and the pink bar represents the right bank.

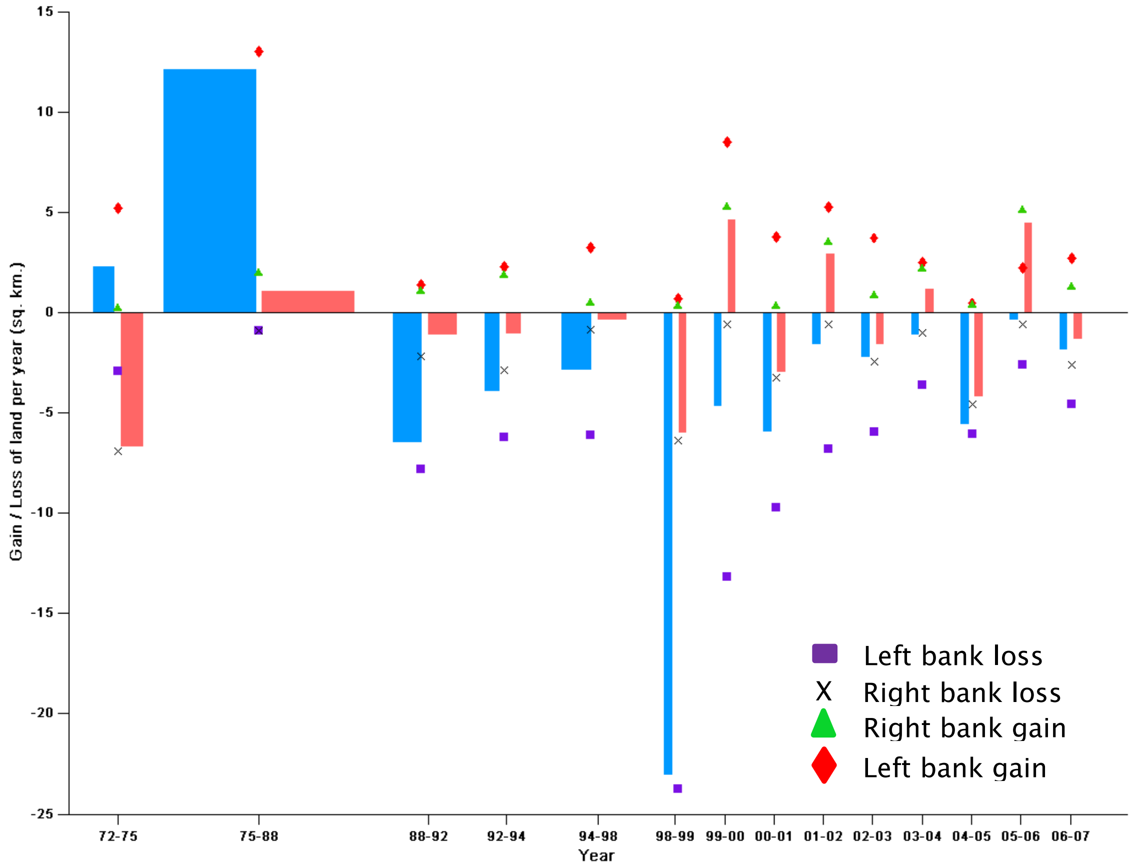


Figure 4-7 Net gain / loss of land within Reach 2 from 1972 – 2007. The points depict the actual loss / gain of land and the bars depict the net loss / gain of land. The blue bar represents the left bank and the pink bar represents the right bank.

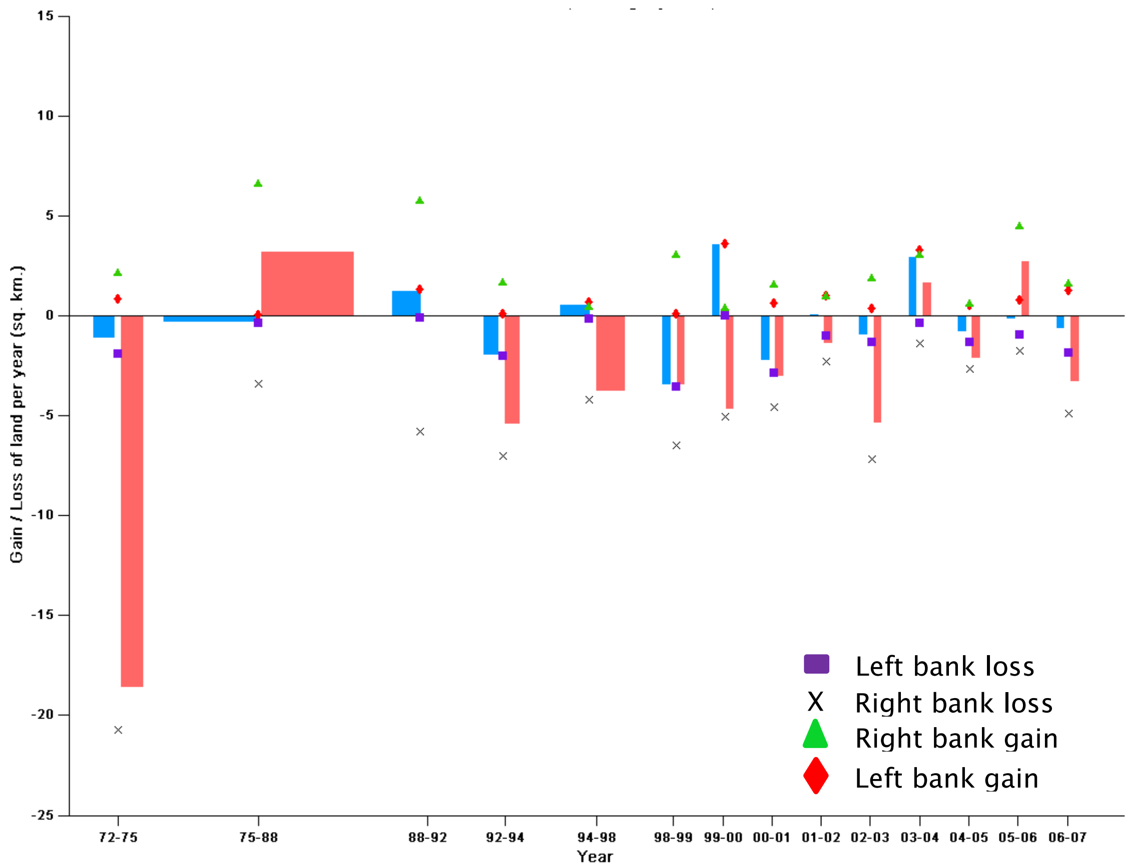


Figure 4-8 Net gain / loss of land within Reach 3 from 1972 – 2007. The points depict the actual loss / gain of land and the bars depict the net loss / gain of land. The blue bar represents the left bank and the pink bar represents the right bank.

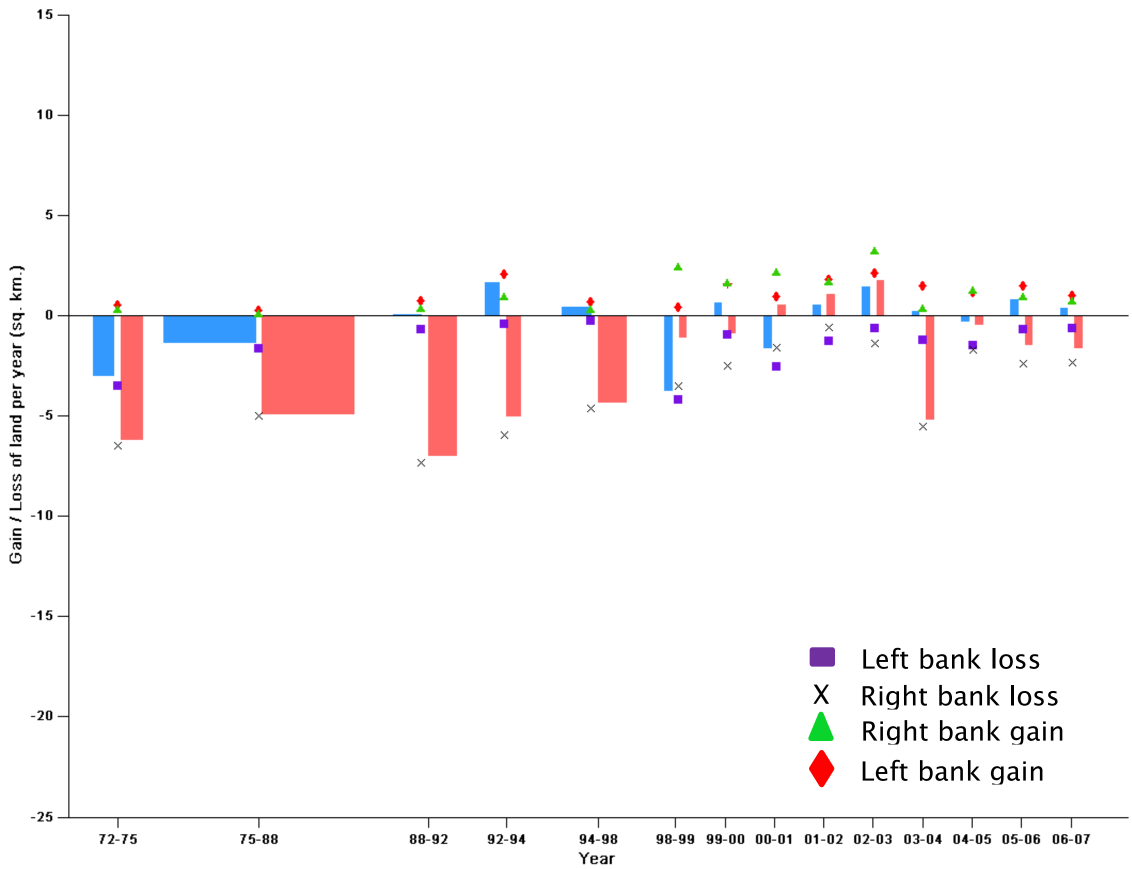


Figure 4-9 Net gain / loss of land within Reach 4 from 1972 – 2007. The points depict the actual loss / gain of land and the bars depict the net loss / gain of land. The blue bar represents the left bank and the pink bar represents the right bank.

4.4.2.2 Sinuosity

The change in sinuosity of the river system was analysed quantitatively over the period of data availability for each individual reach to provide insights into the planform dynamics, as discussed by Hooke (2003). By observing the time sequence data, three different scenarios of change in sinuosity were conceptualised (Figure 4-10). In the first scenario, the river exhibits an increase in sinuosity which drops suddenly as the channel straightens itself due to a chute cut-off. In the second scenario, the sinuosity increases in phases where the chute channel starts to become sinuous before the previous sinuous channel is closed by sedimentation. In the third scenario the sinuosity increases and then reduces due to chute cut-off and then again increases in phases when the river meanders migrate in the opposite direction. The results for the individual reaches are given in Table 4-3 and Figure 4-12 (see also animation in CD).

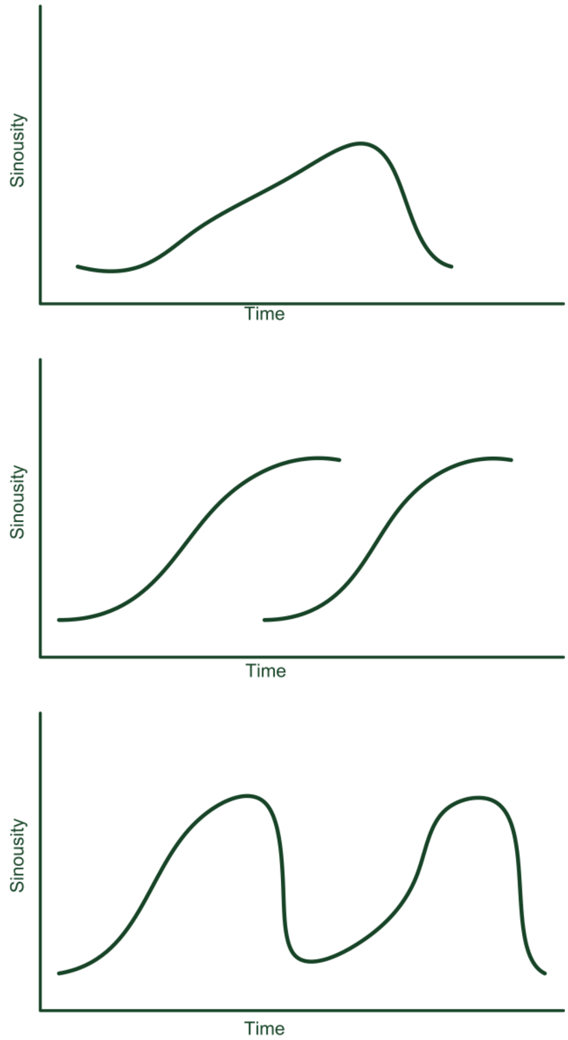


Figure 4-10 Conceptual plots of sinuosity in the Ganga-Padma system.

The results indicate that in Reach 1 the sinuosity of the river increases from 1992 onwards with stable periods in-between before increasing once again (Figure 4-12a). After 2007 the river shows a considerable decrease in sinuosity and again stabilises between 2008 and 2010. The minimum and maximum sinuosity varies between 1.17 and 1.29. In Reach 2, the sinuosity increases considerably until 1994 after which it decreases and then again increases from 1999 onwards (Figure 4-12b). After 2006 sinuosity decreases and then increases from 2008 onwards. The minimum and maximum values of sinuosity are 1.17 and 1.38, respectively. In Reach 3, the sinuosity increases until 2001 after which it drops and the meandering channel dries up due to aggradation. The chute cut-off occurs in 1992 which grows gradually and shows an increase in sinuosity as seen in Figure 4-12c along with the increase in sinuosity of the major channel. After 2001 the chute channel takes over as the main channel. The minimum and maximum sinuosity is 1.09 and 1.30, respectively, for the older channel and 1.10 and 1.17 for the growing chute channel during the study period. Thus the sinuosity curves match the second scenario of the conceptual model (Figure 4-10).

Reach 4 also exhibits a similar sinuosity trend to Reach 3 (Figure 4-12d) and corroborates the observation of the time sequence data. The sinuosity increases until 2002 and then decreases and ultimately the channel diminishes due to aggradation. The chute channel grows parallel to the main channel from 1995 onwards in Reach 3. The reason for the parallel development can be attributed to the large semi-permanent bar (Figure 4.4d) located just south of the chute bar in Reach 4 which may have been difficult to erode.

Table 4-3 Change in sinuosity of the four river reaches in the study area

Year	**Sinuosity**					
	Reach 1	**Reach 2**	**Reach 3**	**Reach 3 (Chute)**	**Reach 4**	**Reach 4 (Chute)**
1972	1.17	1.17	1.09		1.20	
1975	1.17	1.17	1.09		1.29	
1988	1.18	1.21	1.24		1.49	
1992	1.18	1.25	1.25	1.10	1.51	
1994	1.20	1.29	1.27	1.11	1.56	
1998	1.21	1.27	1.28	1.11	1.67	1.34
1999	1.24	1.27	1.27	1.13	1.68	1.33
2000	1.24	1.31	1.31	1.14	1.69	1.36
2001	1.24	1.31	1.32	1.18	1.70	1.38
2002	1.24	1.34	1.31	1.16	1.72	1.40
2003	1.27	1.34	1.30	1.16	1.64	1.28
2004	1.27	1.37		1.15	1.67	1.31
2005	1.28	1.38		1.16	1.69	1.35
2006	1.28	1.37		1.16		1.37
2007	1.29	1.32		1.16		1.32
2008	1.23	1.36		1.18		1.35
2009	1.22	1.36		1.17		1.35
2010	1.23	1.35		1.17		1.35

4.4.2.3 Periodicity of meander migration

The observed changes in the planform for consecutive years over the whole time series reveal a periodicity. The individual reaches behave independently separated by the hard points. Reaches 3 and 4 exhibit similar behaviours subject to chute cut-off processes while Reaches 1 and 2 exhibit individual characteristics without chute cut-offs. A visual interpretation of Reaches 3 and 4 shows that the planform has a straight configuration in 1972 which then migrates laterally and meanders along the right bank as the river is constrained by hard geology and an artificial embankment on the left bank. The lateral migration of the meander is terminated by a chute cut-off when the bend radius of the meander reaches a threshold value. The bend radius is normalised by width of the river to formulate the dimensionless radius of curvature. The meanders evolve until they reach the threshold dimensionless radius of curvature of around 2.0 when the chute cut-offs takes place. The chute channels then grow in width while the meander channels diminish in width by the process of aggradation, and the river returns to a near straight course as seen in the 2010 satellite sensor image. This periodicity of straight to meandering and then straight again was supported by the quantitative data generated from the sinuosity analysis which shows an increase in sinuosity and then a gradual decrease at the end of the study period (Figure 4-12c, d). In Reaches 1 and 2, periodicity was also observed in the formation of a bar along the left bank of the river. In Reach 1 the meander migrates along the left bank and after reaching a threshold sinuosity value of around 1.29 – 1.37, instead of chute cut-off, it is observed that the migration is in the opposite direction downstream, just above the barrage, leading to a sequence of increase in sinuosity, followed by a decrease and then an increase again. In Reach 2, just downstream of the barrage, the flow is forced along the right bank due to the barrage operations and the effect of forcing the water through a specific path is observed further downstream by way of meander migration along the left bank. In Reach 2, the channel migrates to a certain limit until 2010. In both Reach1 and Reach 2 the sinuosity shows cyclic pattern in terms of increase in sinuosity, then a decrease and then increase again but overall the sinuosity shows an increasing trend and few years before the end of the time series (around 2008) there is an effective fall in sinuosity values and this can be inferred as the start of the next cycle of overall decreasing sinuosity (Figure 4-12a,b). Inferences based on the gain or loss of land, changes in sinuosity, periodicity of migration and their relation to river morpho-dynamics are discussed below.

4.5 Discussion

4.5.1 Explaining the meander dynamics and chute cut-offs

The meander dynamics and the cut-offs occurring need to be examined based on the spatial and temporal characteristics of the channel change. As seen from the results of the four individual reaches that the river meanders and sinuosity of the channel increases to a certain critical value when the river relaxes itself by chute cut-off or by formation of bend along the opposite bank. Various explanations can be put forward for the morphological evolution of this system. While explaining such morphological evolution we have to keep in mind that the river is bounded in most of the reaches either by artificial or natural hard points.

One of the most likely explanations is that the river has a very high rate of migration and as a result it rapidly reaches the threshold value of sinuosity i.e. within few decades (38 years) and then relaxes itself by means of chute cut-off (Reach 3 and Reach 4) or by alteration of meander loop (Reach 1). As we know that the data window of the present research falls within the adjustment period of the river system, as a result it is a bit difficult to show more than one cyclic pattern of the river in which a rapid adjustment takes place in a specific time interval. But some evidences of rapid adjustment can be found in the literature (Parua, 2009) where study on topographical sheet from 1924 – 1962 shows multiple alteration of meander loop over a period of few decades (discussed further in Section 4.5.2). The cause of this high rate of migration can be attributed to the annual monsoon during which the river carries 70% of its annual discharge as well as sediment load. Studies in the lower Mississippi river (Harmer and Clifford, 2006) from 1765 to 1975 (with special emphasis on the pre modification period of 1765-1930) using sequential maps shows that the sinuosity increased and then after reaching a threshold decreased again and related this change to basin condition and the results agreed with earlier studies carried out by Walter and Simons (1983). Studies carried out in River Puerco in Cuba (Love, 1992) shows a rapid adjustment of the river by means of cut-off on reaching a threshold value. The study shows that threshold of cut-off can be reduced by erosion or anthropogenic influences and though cut-off can occur at moderate flow condition but subsequent high flow condition enable the river to adjust to the upstream and downstream condition to attain a dynamic equilibrium. Studies by Schumm and Khan (1972) on laboratory models and relating the results to channel pattern changes in River Mississippi (Schumm, 1973) have shown that every fluvial systems changes their channel pattern and modify the landscape based on thresholds of geomorphic variables like valley slope, discharge and sediment load. The river Mississippi has been found to alter its channel pattern based on critical values of slope of the valley floor. When the critical value of slope of the valley floor is attained the channel pattern changed from straight to meandering and again after reworking of the valley floor it again reached a threshold value of slope when the river changed from meandering to braided pattern. The attainment of near threshold value may be due to low or moderate events but change of the pattern may be due to a major flood event. Thus attainment of threshold value is due to intrinsic factors but the change from one pattern to another is due to external factors. Similarly in the present study the evolution of the meanders can be seen as a system attaining geomorphic threshold and on reaching a critical value of sinuosity adjusts itself by chute cut-off to attain dynamic equilibrium. The process is supposed to go in a cyclic manner though we are able to observe only one cycle.

One of the other explanations for the meander behaviour where it results in a chute cut-off on reaching a critical sinuosity value could be based on the self-organising criticality (SOC) as explained by Hooke (1995, 2003) based on her study on River Bollin, UK and by Stølum (1996) in his quantitative model of non-linear dynamic theory. The major differences between the studies carried out by Hooke (2003, 2004) and the present dataset under investigation are the time period of data availability. Hooke (2003) had a data set spanning over 160 years in comparison to the present dataset spanning over a 38 year period. The other difference is the scale of the rivers considered. The river examined by Hooke (2003, 2004) was a small or medium river of the temperate region with width of few tens of metres whereas the Ganga-Padma system is a large river with widths of few kilometres. Hooke (2003, 2004) observed a single cycle on River Bollin spanning over 160 years in which initially (early part of the study period) some cut-offs occurred when the system was in the sub-critical state and then the river system reached a critical state when a cluster of cut-offs took place. Based on the observation made in a small or medium river (River Bollin), it can apparently be assumed that the whole process of an ordered state to a sub-critical state to a chaotic critical state is supposed to take much longer time in a large river system like the River Ganga. Thus the cut-offs we are observing in the River Ganges may be part of the sub critical phase because the River Ganga does reset in the 38 years of observation period. On the other hand it can also be said that Ganga-Padma being a large river, the volume of discharge and sediment load coming from upstream will be few hundred times than that of River Bollin and so the river will reach the chaotic state faster but due to constraint of long term planform data availability it becomes difficult to explain the meander evolution of the system in light of SOC. The study area is covered with several older meander scrolls and ox-bow lakes, as seen in the IRS LISS III sensor data (Figure 4-11), and based on this observation, it can be inferred that the older scrolls may be remnants of a phase when the river reached criticality leading to formation of the cluster of cut-offs as was seen in River Bollin at the end of the available dataset by Hooke (2003, 2004). The change in sinuosity, where it reaches a critical value, calculated from the Landsat sensor data for a 38 year period is part of the self-organisation process post attainment of criticality. The river is again in a sub critical state and is moving towards the threshold of a critical state sometimes in the future. But the older meander scrolls seen in the satellite sensor data (Figure 4-11) can also be interpreted as remnants of the river system operating under a different regime and not part of the present cycle. In addition historical evidences show that the river had a three stage change in its course before it came to the present configuration and older meander scrolls are evidence of those phases (Sengupta, 1969; Roy 1952). Thus due to non-availability of enough data it becomes difficult to interpret the system behaviour in terms of SOC.

If we observe the change in sinuosity only over the time period of study in all the reaches of the River Ganga (Figure 4-12), we note that in all the four reaches, the sinuosity reaches a maximum value after which it shows a decreasing trend. This reduction in sinuosity after reaching a maximum value can be interpreted as the attainment of criticality of the system as shown by Hooke (2003, 2004) in River Bollin and by Stølum (1996) in his simulation model. But it would be difficult to interpret this attainment of critical value in terms of SOC as quantitative evidence of pre and post SOC conditions are unavailable for the Ganga-Padma system.

In terms of critical sinuosity value, Stølum (1996) in his simulation showed that the critical sinuosity value is 3.14 in unconfined alluvium at which cut-off would take place and then the self-organisation process starts. Hooke (2003, 2004) showed that in River Bollin the critical sinuosity value at which cut-off occurs is about 2.92 as the system is constrained by terraces. But in Ganga-Padma system the peak sinuosity values in the four reaches varies between 1.3 to 1.69 which is much lower than the critical sinuosity value observed by Hooke (2003, 2004) and Stølum (1996). The difference in the peak sinuosity value can be due to the presence of hard geology in the lower reaches of the study area, low gradient of the river as well the bank characteristics (soft banks). It has been observed that in River Yampa near Hayden Colarado, the river is characterised by chute cut-offs at a sinuosity value of 1.7 (Howard, 1997). Though the difference in the critical sinuosity value can be explained by variation in floodplain parameters but relating it to SOC is difficult. More data on cut-off occurrence and power law relation is required to explain SOC in Ganga-Padma system. It addition it requires mentioning that a study on Lower Mississippi River using 120 years of data does not show any evidence of SOC though it shows evidence of increasing sinuosity followed by relaxation (Harmer and Clifford, 2006). Evidence of SOC has been found in the Yellowstone River basin where the number of bank failures and their magnitude show a power law relation (Fonstad and Marcus, 2003). According to Frascati and Lanzoni (2010) evidence of SOC in meandering rivers in the field remain unresolved due to non-availability of long term data showing signature of chaotic behaviour. Thus in the present Ganga-Padma system evidence of SOC cannot be proved with enough confidence though relaxation of meanders after attaining a critical value of sinuosity can be seen distinctly. This phenomenon can be part of self-adjustment of the system following the principles of complex response of fluvial systems to geomorphic thresholds with an aim to attain dynamic equilibrium.

The sinuosity values further show that the meandering (or increase of sinuosity) of the river does not occur in phases and each reach adjusts independently of the neighbouring reach. This can be explained by the fact that the behaviour of each reach is controlled by the pinch points (natural or artificial) present in the study area which resets the system reach by reach. In Reaches 3 and 4 although the reduction in sinuosity starts from 2002, Reach 3 stabilises faster than Reach 4. Thus, the straightening occurs in phases. In Reaches 1 and 2 the impoundment (Farakka barrage) seems to have some influence on the meanders just upstream and downstream of the barrage. However, the upstream meander seems to be affected more due to the embankment around the river island upstream of the barrage which actually directs the discharge towards the left bank. The sinuosity plots of Reaches 1 and 2 suggest attainment of criticality followed by relaxation of the meanders almost simultaneously. Both the plots (Figure 4-12a, b) show a similar behaviour as the hypothetical phase plot of meander behaviour based on bend curvature and rate of movement (Figure 4-1).

The availability of Earth observation data for four decades has enabled analysis of the planform evolution of a large river system. Though some signatures related to SOC was evident based on insights derived mainly from simulation models (Moorman, 1990; Stølum, 1996; Frascati and Lanzoni, 2010) and small and medium sized rivers with extended hydrological and planform data records (Sapozhnikov and Foufoula-Georgiou, 1997; Hooke, 2003, 2004), but due to non-availability of long term planform records of Ganga-Padma system existence of a chaotic behaviour in the system could not be established. It can be more confidently said that the observations made in the satellite sensor data (older meander scrolls) and sinuosity results indicate that the river has a cyclic behaviour. The system starts from a straight configuration (based on 38 years of data), reaches a threshold value of sinuosity when it undergoes a chute cut-off or meander switching and goes back to its original state. The whole process is accomplished in a 38 year period though it may extend a few more years for all the reaches (e.g. Reach 4) to reset.

4.5.2 Evolution of the meander based on bend theory and bar theory

The meander evolution can also be analysed based on bar theory and bend theory. As discussed already bar theory was initially formulated to understand meanders. A meandering channel was visualised as a channel with alternate bars but later bend theory was incorporated to explain meandering of a river. Bend theory states that the bend curvature is characterized by a point bar and the location of the point bar is determined by the curvature of the bend whereas in bar theory location of alternate bars is not predetermined (Ikeda *et al.*, 1981).

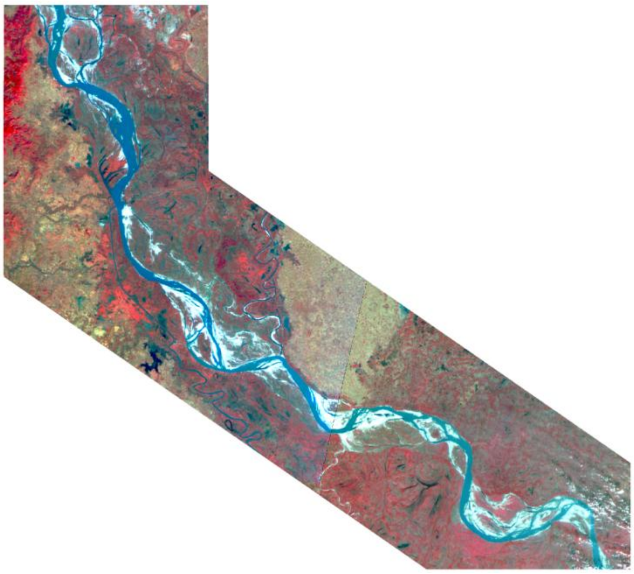


Figure 4-11 Presence of older meander scrolls and ox-bow lakes as observed in IRS LISS III data (November 1998) in the four reaches indicating SOC prior to the observation period of the time series data.

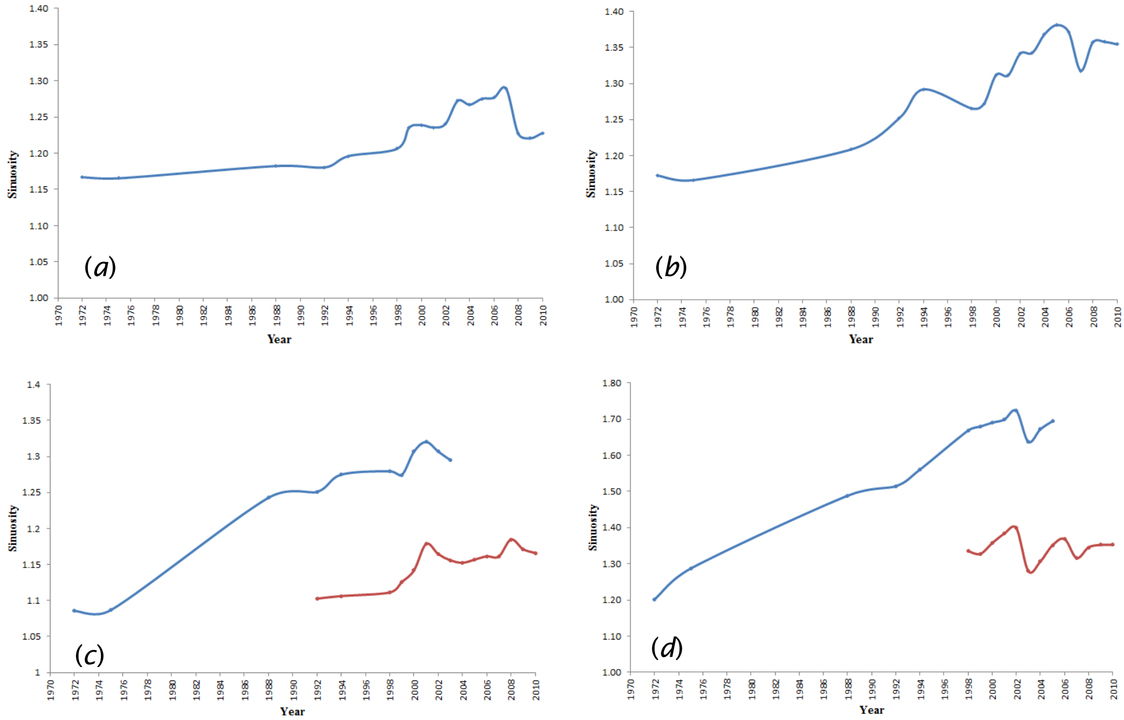


Figure 4-12(a) Actual change in sinuosity of Reach 1 from 1972 – 2010. (b) Actual change in sinuosity of Reach 2 from 1972 – 2010. (c) Actual change in sinuosity of Reach 3 from 1972 – 2010. (d) Actual change in sinuosity of Reach 4 from 1972 – 2010. The sinuosity pattern in all the reaches shows the channel reaching a phase of self-organising criticality.

Thus bar theory is dependent on inertia and friction rather than curvature while it is opposite in case of bend theory. But experiments by Hooke (1975) have shown that point bars exist in case of moderate curvature streams making the bend theory more applicable for meandering rivers. In addition, in case of torturous meanders, according to Kinoshita (1957) point bars are superimposed by several alternate bars. In the present Ganga-Padma system, throughout the study area the meander curvatures are characterized by point bars on the inside of each bend. In all the reaches under study the sinuosity of the bends does not increase above 1.69 which can be considered as gentle or regular bend because torturous bends have a sinuosity of around 2.3, or greater, according to Schumm's (1963) classification. Thus the evolution of the meanders of the Ganga-Padma system in the study area can be related to the principles of bend theory based on bend sinuosity and bar characteristics.

4.5.3 Effect of the barrage on planform dynamics

It has long been debated whether the increase in sinuosity of the river leading to bank erosion in the study area has been caused by construction of the Farakka barrage which acts as a hard point leading to destabilisation of the system. It has been argued, as for example in Reach 1, that impoundment of the river and the subsequent rise in bed level due to accumulation of silt has led to a reduction in the cross-sectional area of the river. It is argued that this reduction in cross-sectional area has led to a reduction in the carrying capacity of the river. This may be a factor which has enhanced the meander bend eroding its left bank leading to an increase in its sinuosity upstream of the barrage, although it cannot be said that the barrage is the only reason. Similar effects have been observed upstream of the Coho Dam, on the Huron River in north-central Ohio where, after construction of the Coho Dam, channel sinuosity increased due to increased deposition in the channel (Evans, *et al.*, 2007). A similar increase in sinuosity was also observed upstream of a dam on the Black River in the Upper Connecticut River watershed (Magilligan *et al.*, 2008). Although an increase in the pond level of river was observed, the barrage may not be the only reason for the increase in sinuosity. The meandering nature of the river was observed in aerial photographs from 1966 as well as satellite sensor data from1972. The barrage was commissioned in 1975. Thus, even before the construction of the barrage the river was meandering and would have further increased its outer bend even if the barrage was not present. Moreover, a study by Parua (2009)based on topographical sheets from 1924 to 1962 showed that the river meanders and changes it loop along the left and right bank alternately. The 1962 configuration was similar to the 1924configuration when the meander bend was along the left bank. However, it can be added that the migration time period may have been shortened by the impoundment and the migration has shifted upstream of the location where it was taking place in 1966 and

1972. Similarly, downstream of the barrage it was observed that streams degrade progressively due to low sediment supply, with a lowering of the river bed over a large distance until a new state of equilibrium is reached, as observed downstream of Foote Dam on the Au Sable River and Junction Dam on the River Manistee in Michigan, USA (Lane, 1934), Fort supply Dam on the N. Canadian River in New Mexico, Texas (Coldwell, 1947), and Denison Dam on the Red River at the border between Minnesota and North Dakota (Hathaway, 1948). Similar downstream degradation was observed below barrages, but the time span for the degradation is limited as seen in the case of the Esna Barrage and the Naga-Hammadi Barrage on the River Nile in Egypt (Mostafa, 1978; Abul-Ata, 1980). It was observed that downstream of many barrages in India the river changes its planform instead of lowering its bed (Ahmad, 1961; Galay, 1983). Regarding the downstream reach (Reach 2) of the Ganga-Padma system, it was reported that the increase in sinuosity may be attributed to the fact that after construction of the Farakka barrage the supply of sediment as well as the supply of water reduced, especially during the dry season, and the river, instead of lowering the bed, significantly increased its sinuosity to reduce the slope (Sarker, 2004). In addition, water was released from the barrage only along the right channel, thus, leading to a forced fixing in Reach 2. This contributed to some erosion along the right bank, but the major influence was along the left bank further downstream leading to meander migration to a considerable extent as seen from the loss of land as well as the qualitative observation of the time sequence data.

4.6 Conclusion

Analysis of the river over a 38 year period, along with historical records and information from the literature representing earlier periods, suggest that the river has changed its planform periodically. Such changes can be placed in the context of non-linear dynamical theory and SOC. Non-availability of long term planform data restricts the evidence of SOC in the system but can be due to response to geomorphic thresholds. Although the data analysed up to 2010 show that the river is moving towards a straight course, especially in Reaches 3 and 4, it will meander again and erode its banks over the next few decades. It will also likely be influenced by the amount of discharge during the peak flow period in each year, although a lack of discharge data meant that the effect of inter-annual variation in discharge on morphodynamics could not be analysed here. The meander evolution also follows the principle of bend theory of Ikeda *et al.* (1981) based on bend sinuosity and bar pattern and relating it to observations made by Hooke (1975).

Natural hard points (e.g., the Barind formation) and embankments influenced the migration of the river along one bank to a greater extent rather than the other.

Moreover, the hard points and embankments along the river's course act as constraints to lateral migration such that the river is locked in to a long-term periodic pattern of evolution in a dynamic equilibrium system. This conclusion has important implications for planners who may fear lateral migration and consequent loss of agricultural land. It means that the evolution of the river is constrained and largely predictable.

The Farakka barrage itself does not appear to be responsible for the system's dynamic behaviour, as the river already had a periodic dynamic behaviour as documented in the literature (Colebrooke, 1801; Parua, 2009). Nevertheless, management of the barrage has had some local influence on river evolution. The closure of one of the channels just downstream of the barrage location due to release of water through some selected gates led to a scenario of forcing from upstream direction through one particular channel influencing the planform evolution of the meanders downstream of the river. This may have led to increased erosion downstream of the barrage. Operational management of the barrage may need a critical review with a view to better management outcomes on the Ganga-Padma system.

5 Channel pattern recognition and condition for chute cut-off in the Ganga-Padma meanders

5.1 Introduction

The importance of thresholds in Earth system dynamics had been recognised by Schumm (1973). In geomorphological systems thresholds are either extrinsic or intrinsic and contribute to change in morphology of the system under study (Schumm, 1979). According to Schumm (1979) although changes in the landform may be progressive, until the landform reaches a critical state, rapid adjustment will not take place in the system. For the case of river channels, changes in planform due to climate change, for example, that might lead to changes in river discharge may be considered as an example of change induced by extrinsic factors. On the other hand, progressive increase in channel sinuosity leading to sudden development of cut-offs in a meandering reach that result in an overall straighter channel can be viewed as due to intrinsic factors.

Thus, in the case of rivers, it can be inferred that crossing of thresholds (intrinsic or extrinsic) from one process domain to another may lead to channel pattern change in which avulsion may play a significant role as an intrinsic response. For any one driving parameter, the threshold values thus need to be identified as they may vary from one system to another or, indeed, they may prove to have similar values when considered in a scale-independent framework from one system to another regardless of system scale.

5.1.1 Empirical determination of channel pattern changes

Alluvial channels usually are categorised as straight, meandering, braided and multi-channel (anastomosed; anabranching) from empirical and theoretical considerations (Leopold and Wolman, 1957; Ferguson, 1987; Nanson and Knighton, 1996), but these channel patterns may be regarded as a continuum of planform change that may or may not be separated by physical thresholds. Temporal adjustments to the channel patterns, for example from meandering to straight, or meandering to fully braided, may be characterised by transitional states like weakly developed braiding and the presence of chute channels (Kleinhans and Van den Berg, 2011). Although adjustments in channel patterns and their style of evolution very commonly are related to the development of specific bar characteristics, nevertheless simple channel parameters often can be used to predict channel patterns despite the underlying complexity of bar-channel-floodplain interactions (Kleinhans and van den Berg, 2011) though some researchers have reservation on these models (Lewin and Brewer, 2003; refer page 16).

The advantage of using simple predictors is generally twofold. Firstly it shows that the channel pattern is a simple emergent property of the underlying complexity taking place in the system and secondly the simple channel pattern predictor are useful tools which can be used for river renaturalisation processes (Van den Berg and Bledsoe, 2003). In addition, large river systems change their channel patterns from one form to another and these simple predictors can be used to provide hypotheses for the change. The simple predictors are based on pattern-independent boundary conditions of median grain size of the river bed (D_{50}) and a potential specific stream power and can be explained by the relation given in equation 2.3.

In spite of the capability of these methods to predict the discriminator of the meandering and braiding pattern in unconfined alluvium these methods are unable to predict higher order multi-channels like anabranching (anastomosing) or wandering patterns as they are unrelated to stream power (Kleinhans and van den Berg, 2011). Four stability fields can be distinguished based on the discriminator in the empirical diagram. The thresholds of change of one channel pattern to another are not hard thresholds and can be considered only as indicative thresholds of occurrence of a specific channel pattern. This is because just above the discriminator both the new channel pattern as well as the channel pattern from the preceding stability field exists together due to lag effects and indeed the actual transition may occur below the indicative threshold.

5.1.2 Mobility number and channel pattern evolution

Anastomosing rivers are characterised my multiple channels, sometimes separated by stable vegetated islands (Nanson and Knighton, 1996; Makaske, 2001; Jansen and Nanson, 2004). As discussed in section 5.1.1 river channel patterns, mainly braided, meandering and their variants can be determined by empirical means but channel patterns like anabranching, anastomosing or wandering cannot be determined by this method. The non-applicability of the empirical methods to determine anabranching or anastomosing pattern arise from the fact that the higher level multi-thread property of the above channel pattern is not related to stream power (Kleinhans and van den Berg, 2011). On the other hand the anastomosing channel pattern can be considered as patterns evolving due to low stream power incapable of sufficient channel mobility (Makaske *et al.*, 2002) and is likely to be resulting from avulsions driven by overloading of sediment upstream or aggradation of channel bed (Abbado *et al.*, 2005). Although, it has been argued that the anabranching pattern is an equilibrium state which has been attained by a combination of flow strength, sediment transport and vegetation (Nanson and Knighton, 1996; Jenson and Nanson, 2004); recent studies based on regime theory (Desloges and Church, 1989; Millar, 2005) have been able to discriminate between anabranching and braiding thresholds incorporating bank strength, grain size as well as discharge (Eaton *et al.,* 2010). Existing models on equilibrium channel morphology (Parker *et al.*, 1998; Dade, 2000) are unable to predict occurrence of anabranching channel pattern, though in combination with mobility number it can qualitatively predict their occurrence.

Studies carried out by Jerolmack and Mohrig (2007) have shown that avulsion is associated with aggradation of the channel bed and they derived the time period of lateral migration and aggradation of a channel to find a critical mobility number (discussed in section 5.3.4). They found that if mobility number $M >> 1$ then the river is supposed to be a laterally moving river sweeping the flood plain while if $M << 1$ then avulsion are likely to be frequent leading to multiple channels being active in parallel (Makaske, 2001). According to them if $M=0$, then transition between single and multiple channels is expected.

5.1.3 Radius of curvature and its effect on meander migration

Alluvial rivers meander by the process of erosion and deposition along their banks. The rate of erosion and the resulting migration of a river channel are controlled by two opposing factors (a) shear stress exerted by the water flow on the banks and (b) the resistance offered by the bank material (Alvarez, 2005). The shear stress is controlled by the channel planform as well as the shape of the cross section while the resistance is controlled by the cohesive strength of bank material (Williams, 1986; Chang, 1988). Studies have exhibited that the rate of migration is inversely proportional to silt-clay content of banks (Daniel, 1971) and directly proportional to discharge (Hooke, 1980).

Migration rate of a river channel has been found to have a relation with channel geometry. Channel migration has been found to be affected by radius of curvature of the channel (Leopold and Wolman, 1957). Radius of curvature (r) is a measure of the tightness of a specific meander bend and is represented by a circle around a meander bend as shown in Figure 5-1. The radius of curvature is scaled to channel size or channel width (w) and expressed as a ratio r/w and is called the bend curvature (Alvarez, 2005). The lower the value of the bend curvature ratio the tighter is the bend.

Migration rate has been found to be related to bend curvature and thus the tightness of bend. The relationship between bend curvature and meander migration were tested on temperate rivers e.g. Beatton River, British Columbia and it was found that a critical value of *r/w* of 2.0 to 3.0 showed a maximum migration rate after which erosion decreased (Hickin and Nanson, 1984).

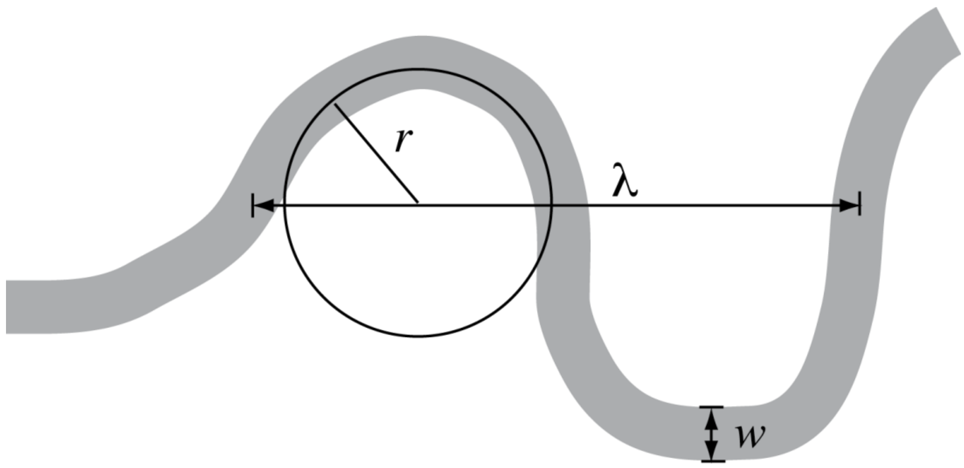


Figure 5-1 Radius of curvature (*r*) of a meandering channel of wavelength (λ) and channel width (*w*).

5.1.4 Critical condition for channel cut-off

Meandering rivers change their path by an important mechanism of bend cut-offs. If a meander bend cut-off develops by progressive migration of an elongated bend that intersects the existing channel a neck cut-off occurs (Zinger *et al.*, 2011). On the other hand if a new channel is formed by erosion across the neck of a bend it is called a chute cut-off (Lewis and Lewin, 1983).

Although, cut-off is a process by which a meandering channel evolves, the condition for a cut-off to occur will vary from one system to another. Sometimes the conditions for avulsion are defined as due to accretion within the channel (Jerolmack and Mohrig, 2007) that forces overbank flows, but more usually tightening channel bends deepen on their outer banks (Seminar, 2006; Nittrouer *et al.*, 2011; their fig 15) and it is the consequent increasing flow resistance within the bend that causes an elevation in the outer bank flow level, increased bank erosion, and subsequent chute cut-off (soft avulsive) event. Thus the critical condition for channel cut-off can be determined for each bend and depends on channel geometry and discharge. It can be determined, in part; by the ratio of width and radius of curvature *w/r* where *w* is the channel width and *r* the radius of curvature. For cut-off to occur the river must flow overbank and avulse by rapid erosion of the levée and floodplain surface. The minimum condition for overbank flow is bankfull discharge augmented by any super-elevated flow on the outer bank of the river. If the bankfull flow velocity is low then super elevation above the 'horizontal' water surface will also be low which is unlikely to cause a cut-off.

As discussed earlier that migration of a river system is controlled by two opposing forces and erosion outside of the bend will occur if the force is sufficient to entrain bank material. Flow resistance in the bendway will reach a maximum as the radius of curvature reaches the minimum value. Determining the addition of form resistance induced by bends is complex (Chang, 1983). However, for illustrative purposes we can utilise the simple procedure of Leopold *et al.* (1960). Any river channel has a threshold limit to adjust the flow resistance by increasing sinuosity and it reaches a stage where cut-off takes place and the river aligns itself to a lower sinuosity value.

5.1.5 Objective

The present research has two main objectives. First to analyse channel patterns based on established empirical methods and to determine the evolution of channel pattern in alluvial river systems. The second objective is to determine the critical condition for chute cut-off to occur in certain reaches of the Ganga-Padma system. A combination of hydrological data from literature, satellite sensor data and empirical methods were used to explain the channel pattern evolution in the Ganga-Padma system and the condition for chute cut-off to take place.

5.2 Study area

The present study has been conducted in the Lower Ganga Plain covering parts of the state of West Bengal, India and parts of Bangladesh. To study the channel pattern the study area of the River Ganga was divided into two sections (i) upstream of the Farakka barrage and (ii) downstream of the barrage. The research on the condition for chute cut-off to occur has been conducted along four reaches in the above two sections in the study area. Reach 1 is located upstream of the barrage and Reach 2, Reach 3 and Reach 4 are located downstream of the barrage (Figure 5-2). The Ganga River in the study area flows through the alluvial plain of the Bengal basin and is characterised by lateral migration. Due to the presence of erodible bank material, the rivers in the Bengal basin respond to large changes in discharge and sediment load by shifting their courses and/or dramatically changing their morphology and bed forms. Evidence of planform changes includes abundant ox-bow lakes, scroll bars and abandoned channels throughout the flood plain of the Ganga-Padma river system (Kale, 2002). The hydrological characteristics in the two sections of the study area are given in Table 5-1. The discharge data pertain to the Farakka barrage in West Bengal and at Hardinge Bridge in Bangladesh (Sarker, 2004; Singh *et al.*, 2007). There are four meanders in the study area as seen in Figure 5-2 and amongst them two of the meanders in Reach 3 and Reach 4 are characterised by chute cut-offs. The behaviour of the meanders in

Reach 1 and 2 are somewhat influenced by the Farakka barrage located at the upstream boundary of Reach 1 and Reach 2.

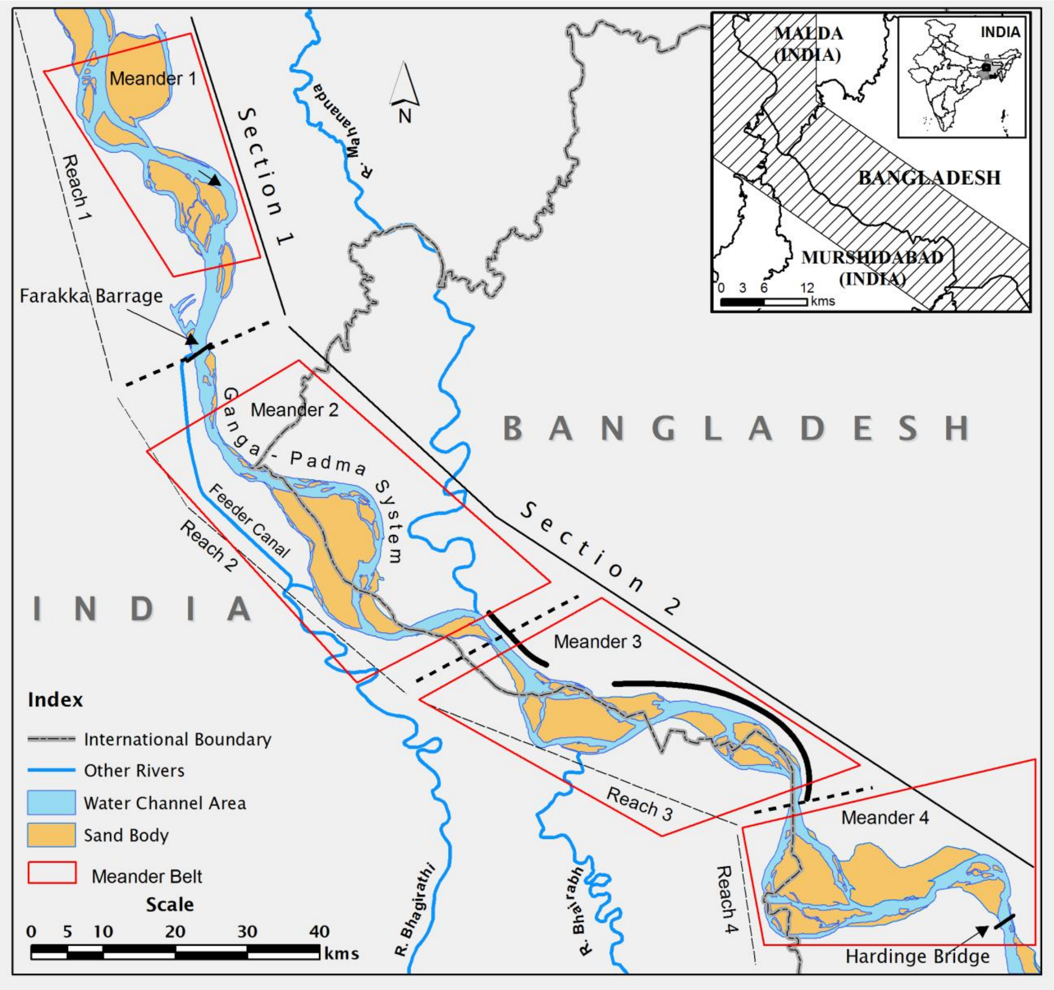


Figure 5-2 Study area of the research

Table 5-1 Channelcharacteristicsof the Ganga-Padma system at Farakka barrage, India and Hardinge Bridge, Bangladesh

Location	Mean annual flood Q_{af} (cumec)	Width (W_a) (Km)	Grain size of river bed D_{50} (mm)	Valley Slope S_v (cm/km)	Sinuosity	Depth of channel (m)
Farakka Barrage	59960	2.2	13	5	1.21	20
Hardinge Bridge	54966	1.6	14	3	1.37	15

5.3 Methods

The study was designed to calculate the relevant metrics related to channel pattern change, meander migration and conditions for channel cut-off. The methodologies used to study the metrics were applied to each of the four reaches in the study area.

5.3.1 Potential specific stream power

The variables required to calculate the potential specific stream power were mean annual flood discharge (Q_{af}), median particle size (D_{50}) of the channel bed, valley slope (S_v),channel slope (S) and sinuosity ($P=S/S_v$); Data were collected with reference to the actual width of the river (W_a) measured from satellite sensor data of a single season of a particular year (November 2000 in case of Ganga – Padma system) and depth of the river (h), median particle size (D_{50}) and the mean annual flood discharge (Q_{af}) as seen in Table 5-1. The width of the river is defined as the point on either side of the river where floodplain vegetation starts and a marked change of gradient is observed between the floodplain and the river course. From satellite image gradient change is difficult to measure so the endpoint of floodplain vegetation on either side has been considered as the bankline and the width has been measured by considering a line at 90º to the river course. But the accuracy of measurement is depended on the satellite image resolution. The other required variables were calculated using the relations reported in section 2.1.2. The potential specific stream power is calculated based on the van den Berg equation 2.2. The potential specific stream power is plotted against median grain size (D_{50}) in the diagram of Kleinhans and van den Berg (2011). Mean annual flood discharge was used as a variable for calculating the potential specific stream power for near-bankfull overbank flows as it is less dependent on channel pattern than bankfull discharge. Bankfull discharge is dependent on width and depth of the channel and varies somewhat throughout the study area.

5.3.2 Sinuosity

The sinuosity of the river at each of the reaches was calculated separately. As in Reach 3 and Reach 4 chute cut-offs were observed so the sinuosity calculation had to be carried out for both the 'main' meandering channel thalwegs ignoring any chutes and also for the courses through the chute cut-offs to have an understanding of sinuosity changes before and after cut-offs (Figure 5-3). Based on the above observation of the chute cut-off the sinuosity was calculated based on the centre line of the main channel as well as the minor or chute channel at the beginning of the available time series and the main channel and the closing channel at the end of the available time series. The valley distance was measured from the starting point of the reach to the endpoint of the reach connected by a straight line or in other words the shortest distance between the starting of the reach and end of the reach.

5.3.3 Mobility Number

Mobility number (section 5.1.2) is the ratio of the time scales of avulsion and lateral migration (Jerolmack and Mohrig, 2007). The time scale of lateral migration (T_c) *was* calculated based on the following relation:

$$T_c = \frac{B}{v_C} \tag{5.1}$$

where *B* is the bankfull width and v_c is the bank erosion rate. T_c was calculated for each set of available data over the whole time series from 1972–2010. The mobility number was calculated for each of the four reaches. To calculate T_c an average width of the river was determined from 1972 – 2010 based on measurements at five locations in each of the reaches. Similarly, the average erosion rate of the each river reach was calculated based on erosion at multiple locations over the each reach.

In Reach 1 the time scale of avulsion was at first calculated based on deposition rate at the reservoir upstream of the Farakka barrage based on the following relation

$$T_A = \frac{\bar{h}}{v_A} \tag{5.2}$$

where T_A is the time scale of avulsion, $\bar{h}$ is the time required by river to aggrade one average channel depth and v_A is the aggradation rate. For Reach 2, 3 and 4 the time scale of avulsion T_A was calculated based on the observation from the time series satellite sensor data when the chute channel becomes the main channel. Based on the above calculations the mobility number (*M*) was calculated based on the relation

$$M = \frac{T_A}{T_C} \tag{5.3}$$

where T_A is the time scale of avulsion and T_c is the time scale of migration. The mobility number was calculated for each set of available data (Table 4.1) of the whole time series from 1972–2010.

5.3.4 Parker's theoretical stability criterion

Parker (1976) developed a stability criteria (ε) to predict the channel character and differentiate when a river will be braided or a single channel with sinuous or straight planform. The Parker's theoretical stability criterion (ε) was calculated for both peak and mean annual discharge:

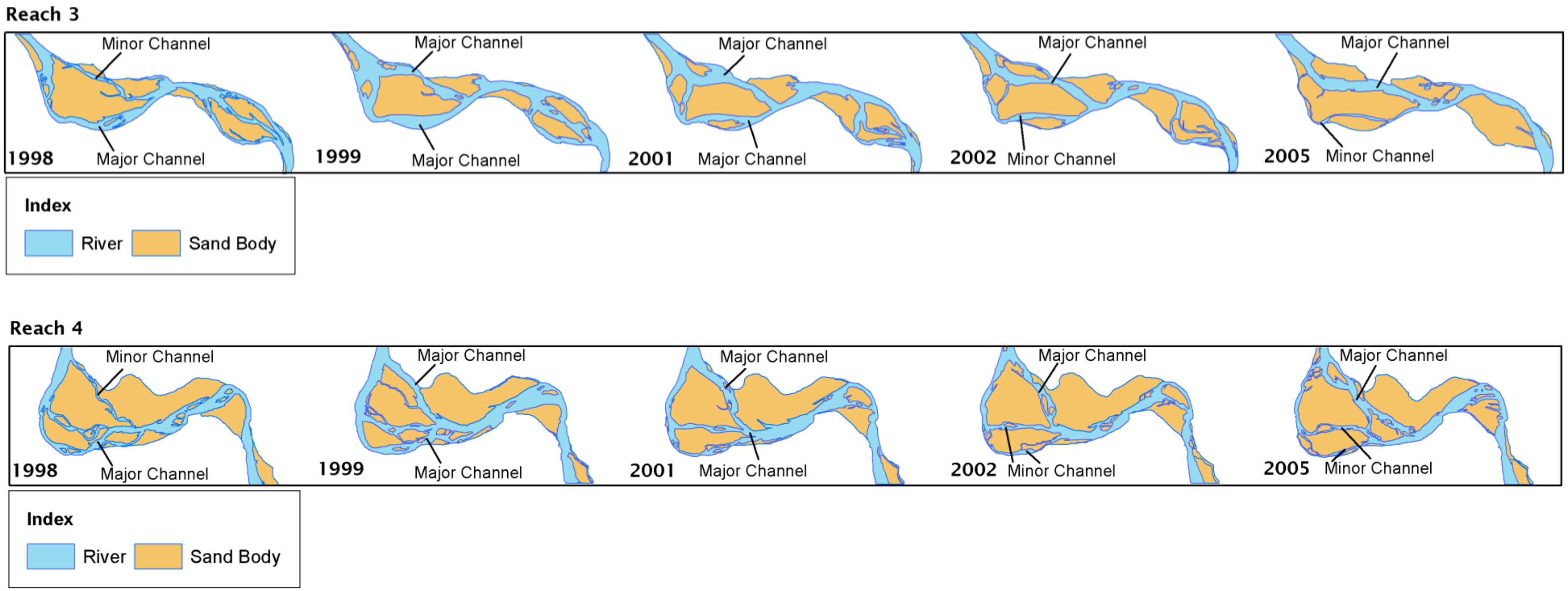


Figure 5-3 Development of chute cut-off in Reach 3 and Reach 4 and change of the chute channel to main channel. Sinuosity is calculated for both the main channel and chute channel from 1992 onwards till 2003 when the chute-channel becomes the main channel and the main channel dies down for Reach 3 and from 1998 onwards till 2005 when the chute-channel becomes the main channel and the main channel dies down for Reach 4. The diagram only shows the period of channel switching but the time period of soft avulsion is calculated from 1972 (first available satellite sensor data) onwards till the time when the chute channel becomes the man channel i.e. 2008.

$$\varepsilon = S\frac{\sqrt{ghB^4}}{Q} \tag{5.4}$$

where *S* is the water surface slope, *g* is acceleration due to gravity, *h* is the channel depth, *B* the channel width and *Q* is the formative water discharge which in the present study was both for the peak (1971-1991) and mean annual discharge. The values of water surface slope, the channel depth and the peak and mean annual discharge were used from available literature sources (Rudra, 2006; Singh *et al.*, 2007, Parua, 2009).

According to Parker (1976) and Dade (2000) if ε <<1 channels are likely to be single thread while if ε >1 then channels are likely to be braided. Combining the mobility number and Parker's stability criterion the style of qualitative channel planform can be predicted (Jerolmack and Mohrig, 2007).

5.3.5 Radius of Curvature

As defined earlier in section 5.1.3 the radius of curvature represents the tightness of a meander bend and can be calculated by drawing a circle around the channel centre line at the meander bend. In individual reaches circles were drawn around the channel centre line at the identified meander bends. The radius of curvature (*r*) was then calculated from the area of the circle based on the formula

$$r = \sqrt{\frac{area}{\pi}} \tag{5.5}$$

In the four reaches that were studied a total of nine bends were identified and amongst the nine bends five bends could be used for calculation of radius of curvature and it was observed that rest of the four bends developed later and was nearly straight at the beginning of the study period of the time series of data (Appendix 8.14 – 8.17). Thus five bends were considered to understand evolution of the four meanders.

5.4 Results

5.4.1 Channel pattern based on potential specific stream power

The potential specific stream powers derived from the hydrological variables related to the Ganga-Padma system were calculated (Appendix 8.4) and plotted based on bar pattern as well as based on sinuosity of channels for each of the sections as seen in Figure 5-4a and Figure 5-4b. The blue line is the discriminator of the upper limit of meandering rivers and the lower limit of highly braided channel and based on the braiding and meandering discriminator of van den Berg (1995). The green line is the lower limit of meandering with chute bars and moderately braided and upper limit of meandering with scroll bars and the discriminate is calculated to be in between the braiding and meandering discriminator of van den Berg (1995) and discriminate function of Makaske *et al.* (2009). The red line is the lower limit of meandering with scroll bars and upper limit of laterally immobile rivers with no bars based on discriminate function of Makaske *et al.* (2009).The light green lines are approximate criteria for beginning of motion and suspension. On plotting the data based on bar pattern the Ganga-Padma system falls within the category of moderately braided and meandering with scrolls and chutes.

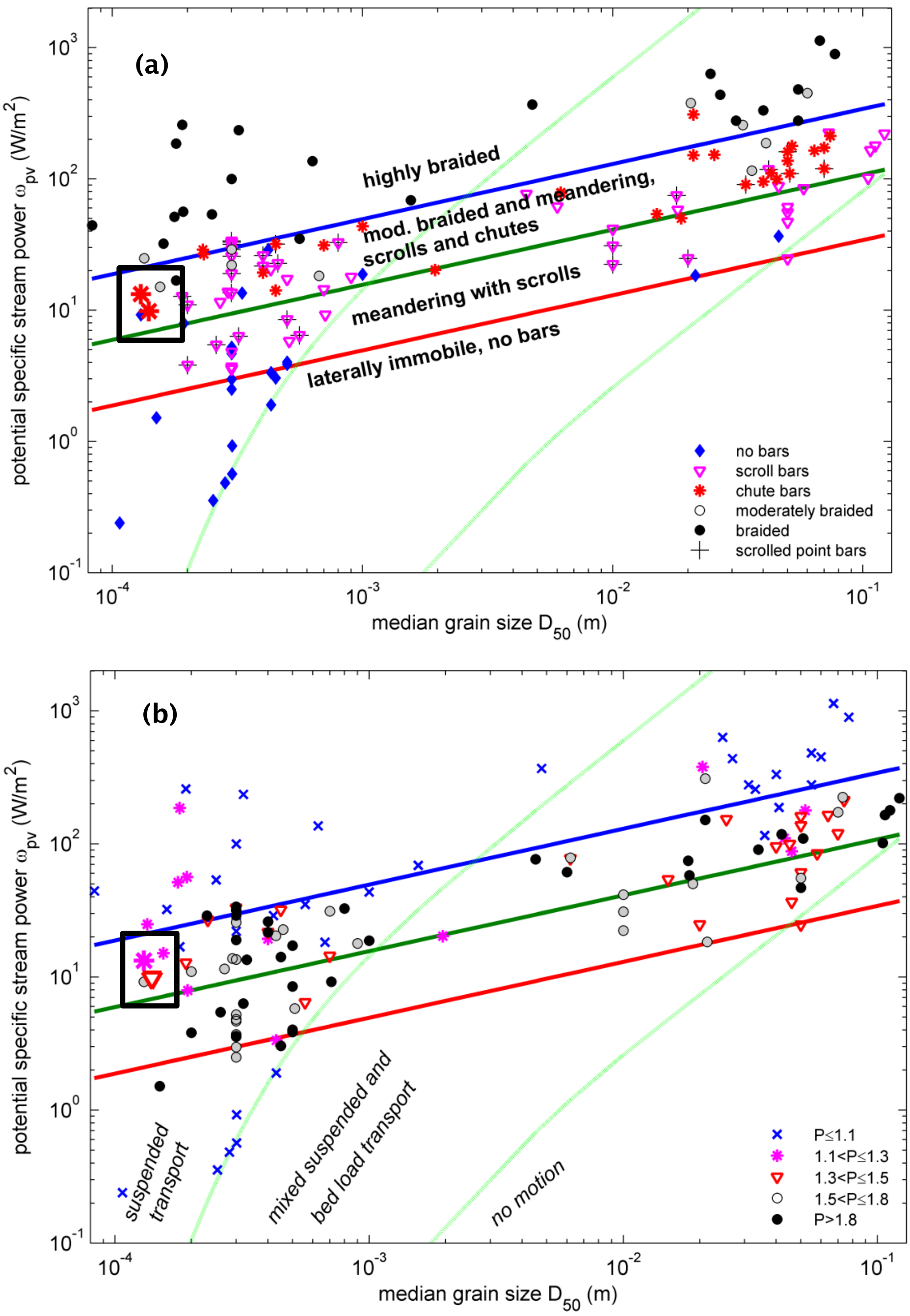


Figure 5-4 Channel pattern of the two sections of the Ganga-Padma system (upstream and downstream of the barrage) marked by larger symbol size within the black square based on (a) bar pattern and (b) sinuosity indicating the river to be moderately braided and meandering with scrolls and chutes.

Similarly when the potential specific stream power is plotted on the basis of sinuosity of the two sections of the Ganga-Padma system they again fall within the category of moderately braided and meandering with scrolls and chutes. Thus based on potential specific stream power and grain size of the sediment the channel pattern of the Ganga-Padma system falls within the moderately braided and meandering pattern.

5.4.2 Channel pattern based on mobility number

The aggradation rate upstream of the Farakka barrage was calculated (Appendix 8.5) based on rise in pond level of the reservoir. A steady increment in bed level was plotted for each year from 1971 onwards till 1991 (Figure 5-5) and it is seen that post 1991 there has been decrease in bed level which can be related to management dredging. A linear function was fitted over the available data of the 20 year period and it is seen that the average increment is about 0.18 m/ year. Based on the aggradation rate upstream of the barrage it can be said that downstream of the barrage as the sinuosity increases, the bend radius also increases and this process should also induce aggradation with a rate not more than that observed upstream of the barrage ~ 0.18m/year.

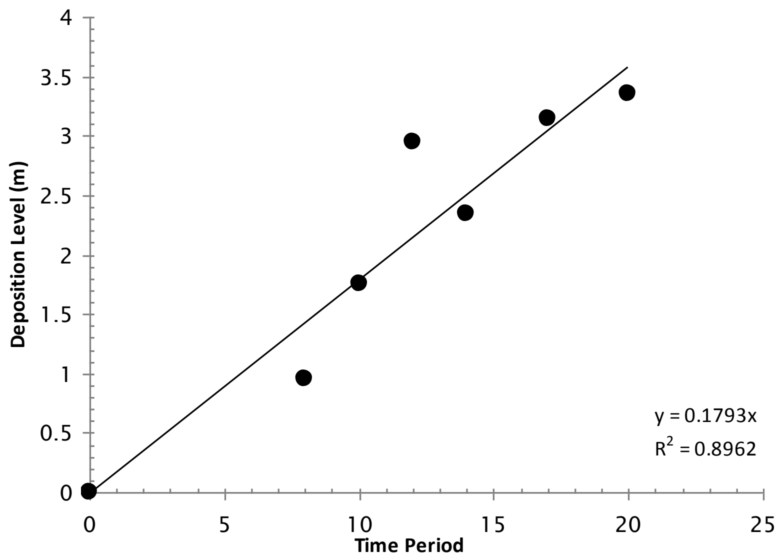


Figure 5-5 Aggradation rate upstream of the barrage over 20 years period (1971 - 1991)

In the present calculation in all the three reaches downstream of the barrage the time period of the maturing of the chute cut-off to a major channel was actually considered as the time scale of soft avulsion i.e. 35 years as seen in Reach 3 and Reach 4 when considered from 1972 onwards which is the beginning of the satellite sensor data time series (Figure 5-3 shows only the period of chute cut-off formation and abandonment of the main channel). The chute cut-off developed in Reach 3 in 1992 while in Reach 4 from 1998. Based on the above time scale of avulsion and time scale of lateral migration the mobility number was calculated (Appendix 8.6 – 8.9) for each of the reaches (Reach 1 – Reach 4). The mobility numbers were plotted for each of the reaches over the time series and compared with the change in sinuosity of each of the reaches. The comparative plots are given in Figure 5-6, Figure 5-7, Figure 5-8 and Figure 5-9. It is seen that except in Reach 3 and Reach 4 the mobility number does not go below the value of 1. When compared with sinuosity it is seen that as the mobility number decreases the sinuosity value increases for Reach 1 and Reach 2 while sinuosity increases with decreasing mobility number for Reach 3 and Reach 4 and then at the end of the time series as mobility number shows an increasing trend the sinuosity shows a decreasing trend.

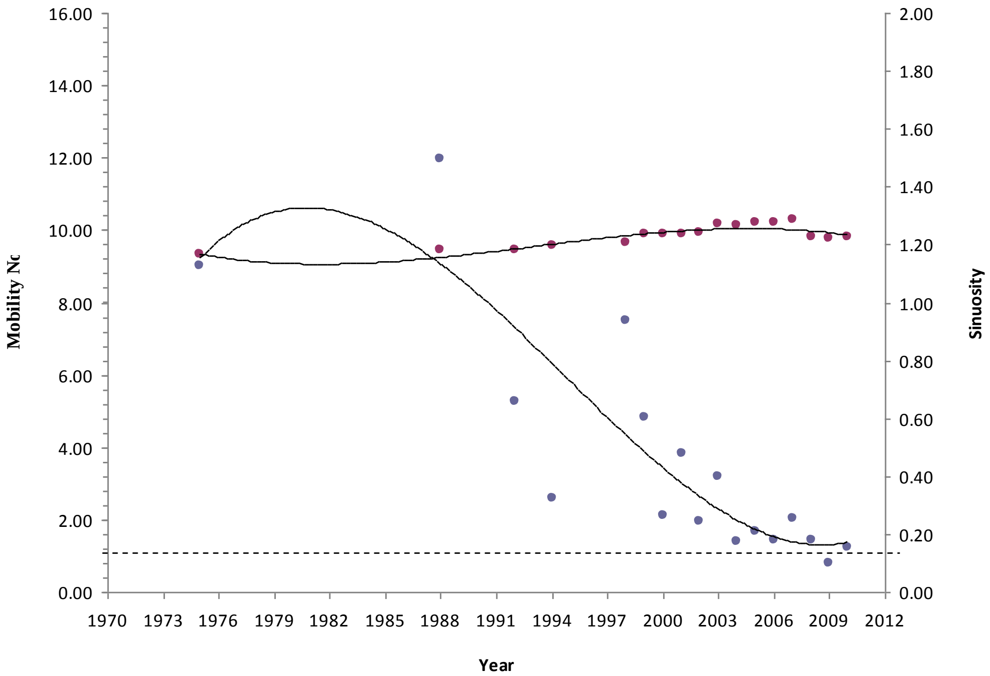


Figure 5-6 Comparative study of mobility number and sinuosity of Reach 1(1972 – 2010). [● Mobility Number;● Sinuosity]

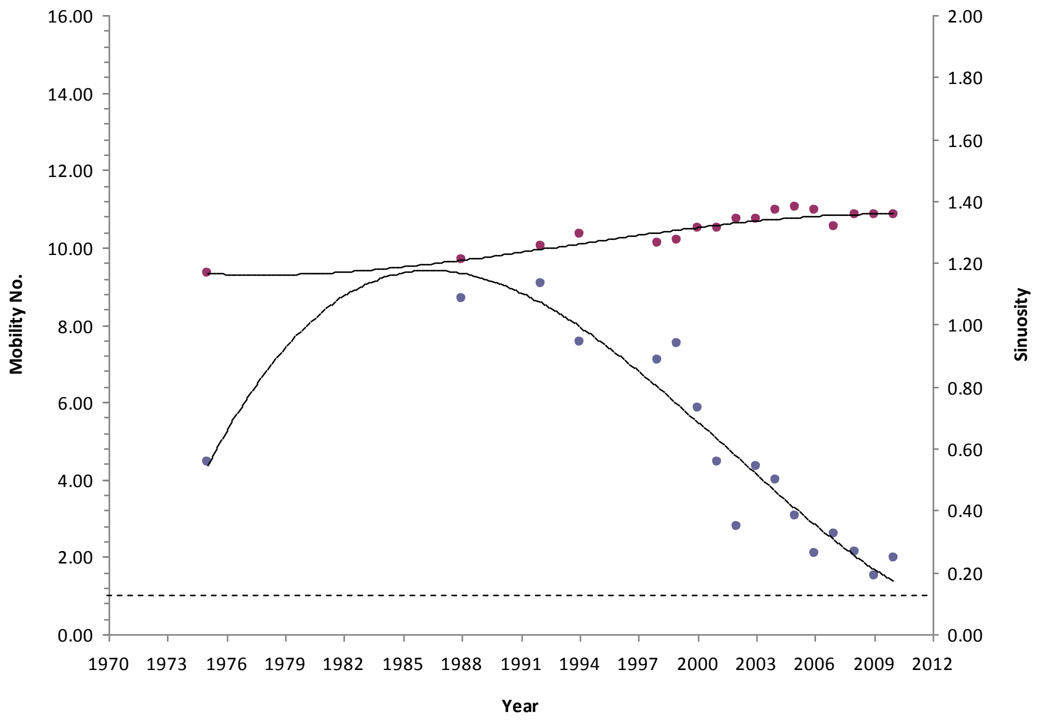


Figure 5-7 Comparative study of mobility number and sinuosity of Reach 2 (1972-2010). [Mobility Number; Sinuosity]

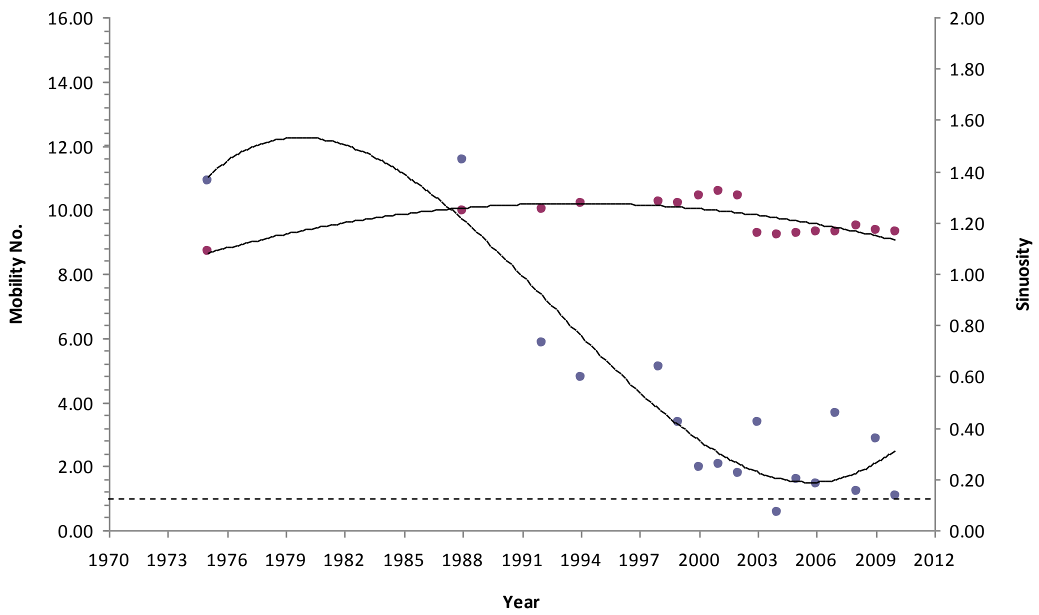


Figure 5-8 Comparative study of mobility number and sinuosity of Reach 3 (1972-2010). [Mobility Number; Sinuosity]

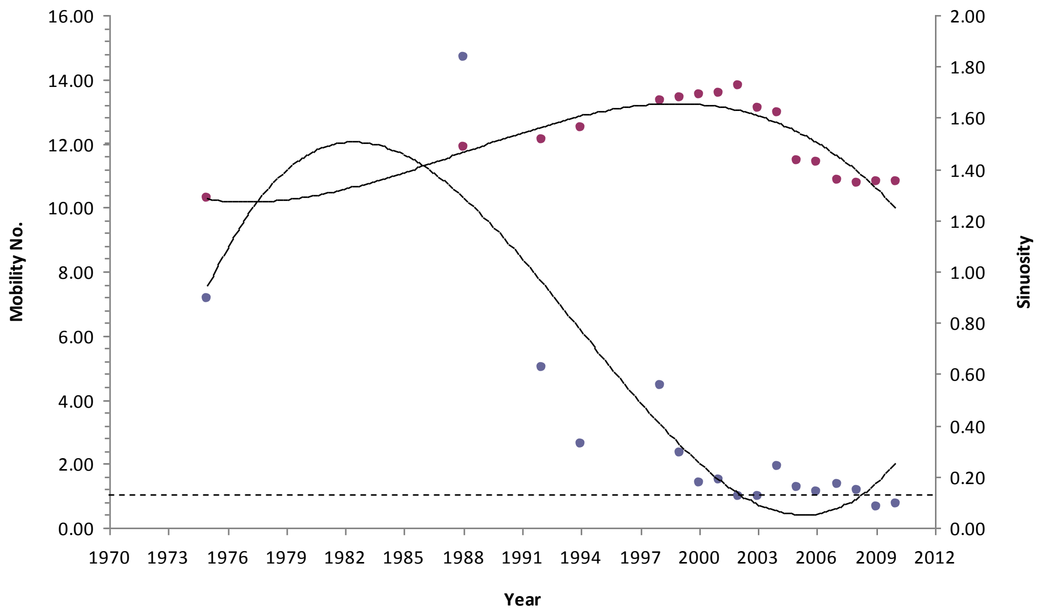


Figure 5-9 Comparative study of mobility number and sinuosity of Reach 4 (1972-2010). [●Mobility Number;● Sinuosity]

5.4.3 Channel pattern based on Parker's criterion

Parker's (1976) criterion predicts whether a river would be braided or a single channel with a sinuous or straight course was also used to determine the channel character of the River Ganga-Padma system. ε was determined (Appendix 8.10 – 8.13) separately based on the average width of each of the reaches, mean peak annual discharge calculated from data available from 1971-1991 as well as mean annual discharge and the channel slope (which was considered as a representative of the energy slope). The channel slope of section 1 (covering Reach 1) was considered as the channel slope for Reach 1 and the channel slope for section 2 (covering Reach 2, Reach 3 and Reach 4) was considered as the channel slope for Reach 2, 3 and 4. The values of the ε and M values of the Ganga –Padma system were plotted in a phase diagram reach-wise as seen in Figure 5-10. The data show the change in the channel pattern over a 38 years period.

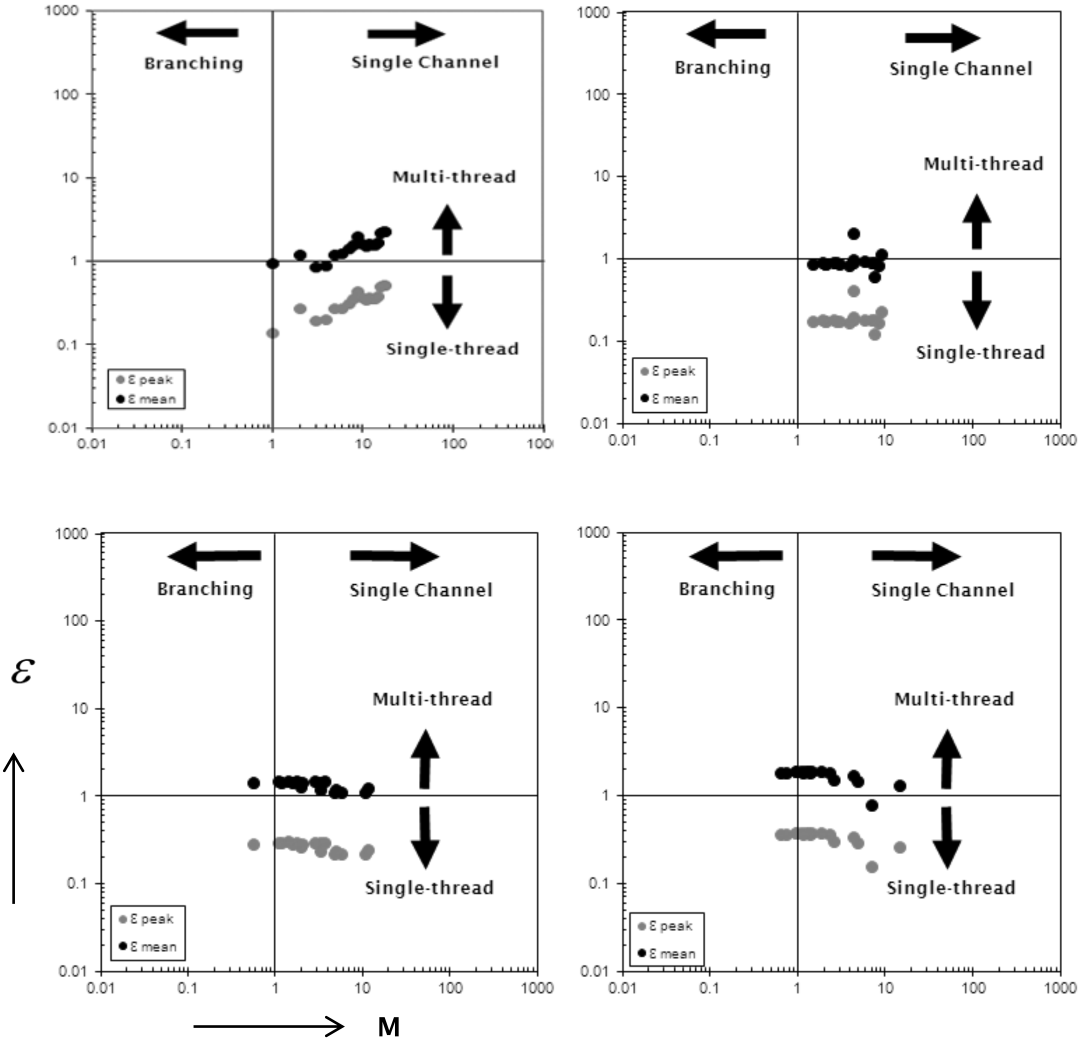


Figure 5-10 Channel pattern of River Ganga -Padma as seen in a phase space of Parker's criterion and mobility number (a) Reach 1 (b) Reach 2 (c) Reach 3 and (d) Reach 4. The values are plotted in logarithmic scale.

5.4.4 Radius of curvature, bend curvature and condition for avulsion

While determining the critical condition for channel cut-off for each bend, it was observed that in all the five bends in the four reaches the radius of curvature decreased through time whereas the channel width (*w*) increased (Table 5.2) except in bend 3. It can also be noted that the values of w/r are consistent between the reaches (maximum of 2.17; s.d. 0.42) and much higher than the value of 0.33 as reported by Begin (1986) for the condition at which river bank retreat through erosion is maximised.

The condition for channel cut-off and a sudden decrease in sinuosity occurred when the radius of curvature fell to between 5000m and 2000m. As discussed earlier to determine the super-elevation at which the outer bend of a meander would breach, the bank full discharge (Q_{bf}) needs to be determined. Bankfull flow (Q_{bf}) for the Ganga-

Padma system in the study reach is uncertain (Rashid & Paul, 1987; Haque, 1998) as bank width varies along its length but it was considered as 56,633 m^3 sec^{-1} (Coleman, 1969). For this discharge condition, for the channel width immediately before cut-off occurs and for the minimum radius of curvature (2000m) the super-elevation (*Δy*) was calculated using the following relation:

$$\Delta y = \frac{CU^2 w}{rg} \tag{5.6}$$

where *C* is a coefficient (0.5) for subcritical flows, *U* is the bulk flow velocity ($U = Q_b/hw$), *w* and h are average values of the channel width and depth at bankfull stage, *g* is the acceleration due to gravity.

Table 5-2 Bendaway radius *w/r* calculated based on radius of curvature (*r*) and average channel width (*w*) of five bends and their corresponding sinuosity (*P*) in the four reaches of the study area

Reach	**Bend No.**	**Year**	***r* (m)**	***w*(m)**	***w/r***	***P***
Reach 1	1	1972	9517.03	2889.75	0.30	1.17
	1	1975	8318.59	4044.00	0.49	1.17
	1	1988	6027.45	3540.40	0.59	1.18
	1	1992	6732.41	3600.80	0.53	1.18
	1	1994	5710.22	4192.80	0.73	1.20
	1	1998	4829.01	4254.00	0.88	1.21
	1	2000	3101.85	4824.60	1.56	1.24
	1	2005	3348.58	4814.20	1.44	1.28
	1	2010	7236.62	5811.80	0.80	1.23
	2	1972	5025.24	2889.75	0.58	1.17
	2	1975	4884.25	4044.00	0.83	1.17
	2	1988	5395.21	3540.40	0.66	1.18
	2	1992	14522.28	3600.80	0.25	1.18
	2	1994	14769.01	4192.80	0.28	1.20
	2	1998	5569.51	4254.00	0.76	1.21
	2	2000	4935.05	4824.60	0.98	1.24
	2	2005	2643.62	4814.20	1.82	1.28
	2	2010	7541.29	5811.80	0.77	1.23

Reach	Bend No.	Year	*r* (m)	*w*(m)	*w/r*	*P*
Reach 2	3	1972	10699.45	6411.25	0.60	1.17
	3	1975	10912.11	6006.20	0.55	1.17
	3	1988	3022.30	3815.00	1.26	1.21
	3	1992	3467.70	4475.20	1.29	1.25
	3	1994	5758.29	3253.40	0.56	1.29
Reach 2	3	1998	4294.85	3930.60	0.92	1.27
	3	2000	5090.20	3988.80	0.78	1.31
	3	2005	4008.53	3873.00	0.97	1.38
	3	2010	3213.19	3963.00	1.23	1.35
Reach 3	4	1972	8111.35	5700.00	0.70	1.09
	4	1975	7904.87	4363.60	0.55	1.09
	4	1988	4040.92	4625.00	1.14	1.24
	4	1992	5191.26	4349.00	0.84	1.25
	4	1994	6902.02	4373.80	0.63	1.27
	4	1998	8140.84	4542.40	0.56	1.28
	4	2000	10028.57	4732.60	0.47	1.31
	4	2005	7550.93	4975.80	0.66	1.16
	4	2010	5368.24	5047.40	0.94	1.17
Reach 4	5	1972	12690.30	3247.00	0.26	1.20
	5	1975	8293.09	3710.00	0.45	1.29
	5	1988	3411.12	4840.00	1.42	1.49
	5	1992	3267.99	5066.60	1.55	1.51
	5	1994	3768.92	5156.20	1.37	1.56
	5	1998	2528.52	5485.40	2.17	1.67
	5	2000	3411.12	5700.40	1.67	1.69
	5	2005	3411.12	5810.80	1.70	1.43
	5	2010	3745.07	5715.00	1.53	1.35

For each of the four reaches the bankfull flow velocity was found to be low (c. < 1m/s) such that inertia is small. Thus super-elevation is no more than 5cm above the water surface elevation at the channel centre line.

5.5 Discussion

The channel pattern prediction study was carried out using three distinctly different methods. The Kleinhans and Van den Berg (2011) method shows that the four sections of the Ganga –Padma river system fall within the same category of moderately braided and meandering with scrolls and chutes. As already mentioned, the input parameters are pattern independent so the results give a clear indication of the expected channel pattern. As observed from the time series satellite sensor data the river is meandering in nature in all the four reaches and in Reach 2, Reach 3 and Reach 4 shows a braiding tendency due to chute cut-offs occurring in these reaches. At the inner bend of the meanders in all the reaches scroll bars are observed and in Reach 3 and Reach 4 chute bars are cut through to form chute cut-offs and the channel evolution progresses. Thus the empirical method predicts the same channel pattern as observed in time series satellite sensor data.

The second method of Jerolmack and Mohrig (2007) used is based on mobility number, sinuosity and the stability criteria of Parker (1976) to distinguish if a channel will be single channel or braided triggered by avulsion. The decrease in mobility number in all the reaches indicates that the river has a tendency to move towards a braided pattern. This result can be interpreted as may be due to the chute cut-offs but both the chute channels as well as the main channel remain active over a period of time such that multiple threads are active in the system. Thus based on the mobility number it can be said that at the start of the time series the river shows a meandering pattern which sweeps across the river corridor eroding its banks, increasing its sinuosity until it reaches a critical value of sinuosity where chute cut-offs occur, sinuosity decreases along the line of the chute cut-offs and the river develops a braided pattern which to some extent concurs with the empirical results discussed in the previous paragraph. It can also be noted that the comparative study of sinuosity with mobility number shows that as the mobility number decreases the sinuosity increases which is again indicative of the meandering river sweeping across the river corridors and then as the mobility number goes to a critical value of one the sinuosity decreases dramatically indicating occurrence of cut-offs and relaxing of meander bends. It is also requires mentioning that though the Jerolmack and Mohrig's (2007) model was mainly intended to predict higher order branching systems (anabranching or more specifically anatomised system) taking into consideration the dynamic processes like avulsion, but in the present research the same modelling concept was used in a smaller scale as Ganga – Padma system attains an anabranching pattern by the process of chute cut-offs or soft avulsion. This enables prediction of the channel pattern evolution of the Ganga –Padma system.

The third method uses Parker's (1976) stability criteria to determine the expected channel pattern. The phase plot of mobility number and Parker's stability criterion generated for each of the reaches shows that the river is in a transitional phase and at peak discharge is single thread as the monsoon flow regime of the Ganga-Padma system usually exceeds bankfull discharge every year. On the other hand at mean annual discharge the river shows a tendency to exhibit a single thread or multi thread planforms; mainly in Reach 1, Reach 3 and Reach 4. Thus based on Parker's criterion the channel pattern of Ganga-Padma system can be classified as a river having mainly a single channel with a tendency to multi thread over the whole studied time series. The Reach 4 partly shows a branching pattern which may be due to the configuration of the system during the study period when the chute cut-off have not died down fully due to localised factors.

In summary, it can thus be said that based on the three different methods of channel pattern prediction over the studied time series, the Ganga-Padma system is mainly a meandering river which migrates laterally along the flood plain and on reaching a critical sinuosity value varying between 1.3 and 1.6 as seen in Table 4.3 (which is similar to observations made by Howard (1997) in Yampa River in Colarado where the maximum sinuosity value was 1.7) is characterised by chute cut-offs leading to a multi-thread pattern. Similar observations were also reported from flume experiments simulating gravel bed rivers where sinuosity increased to a threshold value of 1.19 when chute cut-off occurred though migration rate was very high (Braudrick *et al.,* 2009) and the threshold sinuosity value for chute cut-off to occur was much lower than those reported in natural gravel bed rivers (Hickin and Nanson, 1984; Hooke, 2007). But the above experimental results of Braudrick *et al.* (2009) won't be valid for the Ganga-Padma system as it is not a gravel bed river.

When the radius of curvature is around 3000m in Reach 4, the cut-off generally occurs, but for cut-off to occur the river must flow overbank and avulse by rapid erosion of the levée and floodplain surface. For each of the four reaches the bankfull flow velocity is low ($c <$ 1m/s) as well as the super-elevation at the channel centre line. Thus for these conditions, bankfull flow likely will not induce cut-off, rather sustained overbank flows are required that exceed the levée height considerably. Rapid erosion of the levée on the outside of the bend will occur if the force is sufficient to entrain bank material. Flow resistance in the bendway will reach a maximum as the radius of curvature reaches the minimum value. The skin resistance for a straight channel may be given as:

$$\tau_T = \gamma RS \tag{5.7}$$

where γ is the specific weight of water, R is the hydraulic radius and S is the energy slope. The hydraulic radius in the study reach is ~ 16m with a slope of 6.8×10^{-5} (Coleman, 1969). These data provide an estimate of unit skin resistance of 10.67N.

Determining the addition form resistance induced by bends is complex (e.g. Chang, 1983). However, for illustrative purposes we can utilise the simple procedure of Leopold *et al.* (1960). For maximum values of w/*r*, estimates of the form resistance in the sinuous reaches downstream of the barrage are two orders of magnitude higher than the skin resistance (c. 700N to 1600N). For lesser *w/r* values, form resistance lies between the limits 10N and 1000N. Thus the ability of the Ganga channel to adjust through increasing sinuosity is at a maximum for greater radii of curvature than the minimum and then declines as the bends tighten. In a flume study, Braudick *et al.* (2009) noted similar development of cut-offs at a sinuosity of 1.2, preventing the development of more sinuous channels ($c< 3$), and attributed this to the absence of vegetation stabilizing the channel banks. The lack of vegetation stabilization on the Ganga (floodplains) can be a factor associated with the maximization of flow resistance in the main channel leading to soft-avulsion or chute cut-off at low sinuosity values during high discharges (Howard & Knutson, 1984). However the situation is not so simple, as the development of an avulsive channel relaxes the system. It is seen that over the studied time series both an avulsive channel and the main channel are simultaneously active and there is not usually a simple abandonment of the main channel in favour of the new channel. Edmonds *et al.* (2011) term these avulsions 'soft-avulsions'. The avulsion will divert some discharge and some finer sediment from the main channel but the bedload will mainly continue down the main channel, albeit associated with a reduced discharge. The effects of cut-offs on main channel erosion-sedimentation has been poorly considered in the past (Seminara, 2006), however we might expect deposition to occur in the main channel (below the avulsion point) causing largely a reduction in channel width as the depth of the main thalweg will be less affected as long as the main channel discharge dominates over the avulsive channel discharge. Flow resistance in the main channel downstream of the avulsion point is reduced and as the radius of channel curvature cannot adjust rapidly, *w/r* decreases; which ironically sustains the potential for river bank erosion downstream of the avulsion as the flow is increasingly confined by the channel narrowing through time. Thus it can be said that soft avulsion may assist a meandering channel maintain its meandering habit without reducing the sinuosity too catastrophically.

Thus, it can be summarised that lack of vegetation stabilization on the Ganga-Padma floodplain can be a reason for chute cut-off to occur at low sinuosity value and high discharge. The vegetation on the floodplain is mainly agricultural crops and not deep rooted vegetation cover to hold the soil to resist erosion. The cut-off occurs when the radii of curvature reduces to about 3000m (Table 5-2) and it can be said that chute cut-off is a response of the system to its' increasing inability to adjust further through gradual adjustment of sinuosity but rather channel alignment seeks to reset by erosion of an avulsion channel or cut-off to regain a low sinuosity value.

Another important observation which can be made based on the present study is that the channel pattern as well as the evolution of the river system is to some extent predictable. The Ganga-Padma system is a self-regulating system which resets itself after a time period of around 35 years due to a homeostatic mechanism by means of chute cut-off after reaching a critical sinuosity value. This has a major significance in terms of river basin management as well as future planning of LGP.

5.6 Conclusion

Analysis on the channel pattern of the River Ganga-Padma based on different empirical methods show that the river is a meandering river with a tendency to a multi thread configuration at the end of the time series. The river can be said to be in a transitional phase and this phase can be a part of cycle which was dealt in details in chapter 4. The empirical methods also showed that the river channel pattern can be predicted based on some pattern independent variable like mean annual flood discharge (Q_{af}), median particle size (D_{50}) of the channel bed and valley slope. The other methods used for prediction of channel pattern which was based on mobility number and Parker's stability criterion also predicted a similar channel pattern as the pattern independent empirical method.

The study also shows that the condition for chute cut-off in the Ganga-Padma system is not due to bankfull flow velocity and the super elevation but mainly due to lack of vegetation stabilization on the Ganga-Padma floodplain. This may be the reason for the chute cut-off to occur at low sinuosity value. The cut-off was seen to occur when the radii of curvature goes down to about 3000m and it can be said that due to the inability of the river system to adjust further through gradual adjustment of sinuosity it goes for channel alignment by erosion and chute cut-off to regain a low sinuosity value.

The response of the river system is to some extent predictable as it is a self-regulating system with a reset time period of around 35 years and as a result would enable better management of the river basin. Though it may seem coincidental that the reset time of 35 years is more or less within the data window period of 38 years, but it has been observed that for Reach 3 the river has adjusted itself after chute cut-off within 35 years but for Reach 4 there is a possibility that the adjustment (i.e. the older channel is totally closed down and the chute channel remains the only channel in that reach) make take more time than 38 years. This can only be seen if the data window is extended for a few more years which is practically not feasible.

6 Effect of tectonics and meandering on anabranch evolution following the Ganga – Bhagirathi avulsion

6.1 Introduction

Some fluvial rivers are not single channels, but bifurcate into two or more downstream branches. Such branches characterise anabranching and braided river systems and are ubiquitous in distributive systems such as deltas and alluvial fans (Kleinhans *et al.*, 2012). Bifurcation, although a critical aspect of distributive fluvial systems, is poorly understood and under-investigated (Ashmore, 1982; Federici and Paola, 2003; Kleinhans *et al.*, 2011). Bifurcation can evolve due to avulsion and in deltas, by the process of repeated avulsion; a river may form an anabranching pattern (resulting in multiple bifurcations) in which new channels are formed and older channels remain morphologically active. Avulsion can be defined as the process by which a river partially or fully relocates itself from its present main course to a new course or to an existing secondary course by natural means (Slingerland and Smith, 2004). River avulsion, as studied in small and medium-sized rivers, is partly explained by the water surface gradient advantage of a new channel course over the old course, caused by spatial differences in aggradation and compaction.

In large river systems, the avulsion process remains poorly understood, as gradients are very small and several anabranches can remain active simultaneously with the major branch. In addition to low gradient, high discharge in large rivers may lead to much larger backwater effects than in smaller rivers, which may also lead to older branches remaining active simultaneously. Besides the avulsion process in large rivers, another property which needs to be defined is the avulsion duration. In large rivers, the duration of avulsion (starting from the creation of the bifurcation to complete abandonment of the older channel in favour of the new one) can vary from as low as 28 years for the River Kosi, India to 1400 years for the River Mississippi, USA (Slingerland and Smith, 2004). Ideally, avulsion duration is defined as the time between initiation of a new channel and complete abandonment of the previous channel (Stouthamer and Berendsen, 2001). However if avulsion is by the process of annexation (Slingerland and Smith, 2004) of an existing secondary channel and the older channel is not abandoned after the major discharge shifts to the secondary channel, then it becomes difficult to define the timeline of avulsion as no new channel is created and no old channel is abandoned. Where two channels exist simultaneously the avulsion duration can be defined as the time taken for the original secondary channel to become dominant in discharge conveyance. In the present analysis chapter, this definition is used.

Avulsions can be gradual or abrupt depending on the rate at which a river aggrades over the existing floodplain as well as the bifurcation dynamic of the point of separation of the older and the new channel. The initiation of the bifurcation can be either erosion or deposition though in deltaic region it is by means of crevasse splays which enlarge during over bank flooding. Besides differential aggradation and bifurcation dynamics, tectonic movement is also responsible for avulsion (Smith *et al.*, 1997). In most rivers, however, avulsions are often explained without recourse to tectonic effects (Speight, 1965; Smith and Smith, 1980; Smith, 1983; Wells and Dorr, 1987; Schumann, 1989; Smith *et al.*, 1989; Brizga and Finlayson, 1990; McCarthy *et al.*, 1992; Li and Finlayson, 1993; Richards *et al.*, 1993; Blum, 1994; Törnqvist, 1994),although several studies attribute avulsion to tectonic causes (Coleman, 1969; Mike, 1975; Mc-Dougall, 1989; Blair and McPherson, 1994; Dumont,1994; Harbor *et al.*, 1994). In the Okavango River in Botswana, tectonic movement has been held responsible for major avulsions in the past (Wilson, 1973; Hutchins *et al.*, 1976; Cooke, 1980), although direct evidence is absent. In fact, the resulting bifurcation evolution due to avulsion in some large sedimentary basins can be attributed to tectonics (Schumm *et al.*, 2000).Recently, it has also been observed that other than tectonics, meandering above the bifurcation or the node has an equally large effect on the avulsion process (Kleinhans *et al.*, 2011).

Avulsions and the resulting bifurcations have both negative and positive societal relevance, varying from risk of flooding and drought in the downstream reaches due to sudden avulsion (Li and Finlayson, 1993) to reduced inundation by the sea in delta regions due to decrease in rate of aggradation with reduced rate of sea level rise (Slingerland and Smith, 2004; Kleinhans *et al.,* 2012). Two thirds of the world's population lives in fluvial and deltaic plains, so there is a need to study the causes and effects of avulsion and bifurcation.

One of the most densely populated deltaic regions of the world is the Indo-Gangetic plain. The Himalayan Rivers, including the Ganga and other rivers in the Indo-Gangetic plain, have a highly dynamic environment both in terms of hydrological character and geological activity (Kale 2002; Latrubesse *et al.*, 2005). The River Ganga has changed its position and planform often over the past centuries. The original course of the Ganga in historical times was through the present Bhagirathi-Hooghly system, which flows alongside the city of Kolkata, India which either gradually or suddenly shifted to the present Ganga-Padma System; thus flowing into present-day Bangladesh and joining the River Yamuna (aka River Brahmaputra). Historical evidence and remnant palaeo-channels corroborate the changing pattern of the Ganga river system, but the exact cause of the shifting remains unclear.

As different theories have been proposed in the literature about the cause of the avulsion of the Ganga – Padma system from the previous course to the present, it leaves ample scope for further research. Moreover, because the event occurred about three to four centuries in the past, reconstruction of the historical event requires hydrological or morphodynamic models. An appropriate model needs to be formulated depending on data availability pertaining to the Ganga river system in the deltaic plain to reach a conclusion about the cause(s) and process (es) that led to avulsion.

6.1.1 Theories on the existence of a main flow through the Ganga – Bhagirathi and subsequent avulsion

Some 19th century literature associates the avulsion from the Ganga – Bhagirathi system with a major earthquake in the region in the early 16th century. Captain Sherwill who was assigned in 1857 by the Government of India to ascertain the condition in the Hooghly was of the view that the Ganga previously flowed on the present bed of the Bhagirathi-Hooghly (Parua, 2009). The present course along the Padma was described as of recent origin, formed by the opening out of the left bank of the Ganga near Malda. This was described as the result of a catastrophe which he attributed to the sudden collapse of the left bank, made of loose yellow sand.

Haydene and Pascoe (1910) of the Geological Survey of India were of the view that the conditions prevailing on the Indo-Gangetic plain from early Tertiary time were similar to those existing at present and that there was a gradual subsidence, leading to the accumulation of enormously thick alluvial deposits. This accretion resulted in the change of the Ganga course from the Bhagirathi-Hooghly to the present Ganga-Padma.

In 1919, H. G. Reaks, River Surveyor of Calcutta Port, in his study on the river hydraulics of the Ganga delta region ascertained from the existence of old beds and from the histories of noted towns that the main flow of the Ganga was through the present Bhagirathi-Hooghly system as it was the most natural and direct course to the sea. An old 15th century map of the rivers of Bengal revealed by eminent Indian scientist Prof. Meghnad Saha shows the absence of the south-east flow of the River Padma (Parua, 2009). Prof. Saha also emphasized that all the major settlements of south Bengal were on the banks of the Bhagirathi-Hooghly, as noted by Reaks in 1919.

Based on the above studies it is widely accepted that the main course of the Ganga-Padma system was through the present Bhagirathi-Hooghly system and the river avulsed from the older course to the present after the 16th century. It can also be said that active tectonics could be a reason for the avulsion as indicated by some authors.

6.1.2 Role of tectonics in river avulsion

Tectonics play an important role in shaping Earth surface features. Many observable effects can be due to active tectonics or due to the tectonic framework developed in geologically recent times known as neotectonics. Unfortunately, as measurements of past tectonic activity are largely unavailable it remains difficult to interpret whether observed effects are due to on-going active tectonics or due to geologically recent tectonics (Schumm *et al.,* 2000).

The role of tectonics on river channel morphology varies; ranging from change in channel slope, fluvial process and hydrological characteristics to lateral changes in river planform and avulsion (Ouchi, 1985; Jain and Sinha, 2005). River avulsion due to active tectonics generally occurs as an effect of lateral tilting (Peakall, 1996). Flume experiments have shown that besides lateral tilt, uplift also leads to avulsion, but the effects depend on the rate at which deformation occurs. A slow uplift leads to significant lateral shift in contrast to rapid uplift. Conversely, rapid uplift can lead to an avulsion which is not observed with a slower uplift (Peakall, 1996). It has been argued that although slow uplift and rapid tilt are the most favourable for avulsion, the outcome is also dependent on the type of channel (e.g. a bedload channel with a weak bank would be more vulnerable to avulsion than a suspended load channel with a cohesive bank which instead is likely to adjust by changes in sinuosity upstream) (Schumm *et al.*, 2000).Most of the experiments carried out, or observations made, as discussed above relate to active tectonic deformation which is rapid and measurable.

Active tectonics can have a significant effect on the morphology or hydrology of a river; for example, resulting in temporary or permanent avulsion. Large alluvial rivers may avulse due to faulting and tilting; signalled by earthquakes. Earthquake induced faulting in the River Indus at two locations (apex of two fans) resulted in repeated avulsions (Schumm *et al.*, 2000). Similarly, in the 18th century the River Brahmaputra avulsed 80 km to 100 km to the west due to tilting induced by a major earthquake (Morgan and Mcintire, 1959; Johnson and Alam, 1991). Moreover, major earthquakes may result in failures along river banks and loss of natural levees which, during high discharge, can result in avulsion.

6.1.3 Inter-relationship between avulsion and bifurcation

A bifurcation may evolve during the avulsion process when a river relocates during high discharge to a new or a secondary channel from an existing channel. Bifurcation plays a key role as the morphodynamics of the individual branches downstream of the bifurcation depend on the amount of water being divided into the two branches as well as the sediment fluxes in the two bifurcations. The bifurcation can be stable or unstable based on the time-span during which the two branches co-exist. It has been seen that the balance between a bifurcation being stable or unstable changes over time due to variation in discharge or due to the growth of one bifurcation at the expense of the other (Kleinhans *et al.*, 2011). During the avulsion process the sediment coming from upstream is unlikely to be distributed equally across the two channels downstream of the bifurcation resulting in changes in discharge, slope or cross-section and leading to changes in the carrying capacity of the channels. The change in the carrying capacity results in growth of one of the branches and closure of the other branch due to aggradation, ultimately leading to the completion of the avulsion process.

The initiation and location of an avulsion is governed by the trigger mechanism and the physical characteristics of the location. The trigger mechanism is generally a flood, but can be related to tectonics, logjams and bank failures or bar migration leading to blockage of one of the channels (Jones and Schumm, 1999). However, the location where the avulsion will occur is determined by physical characteristics such as channel geometry, bank stability and topography. Outer meander bends where flow velocities are high and weak areas of channel bank represent the most likely locations of avulsion (Chrzastowski *et al.*, 1994; Smith *et al.*, 1998).

Physics-based numerical modelling of idealized bifurcation configurations has shown an interrelationship between bifurcation stability, avulsion duration and channel patterns (Kleinhans *et al.*, 2008). Model simulations have shown that very few bifurcations close down entirely, especially in large rivers. Instead, they attain a configuration of highly asymmetrical equilibrium, in which the major flow, along with the sediment from the upstream branch, goes through the new branch created as a result of the avulsion or a pre-existing secondary branch and a small percentage (<5%) flows through the older branch (Kleinhans *et al.*, 2008). In small rivers such channels transport no significant sediment load but gradually transform into floodplain through filling with suspended load during high flow stages. In large rivers we hypothesize that such channels may still transport bed sediment and have sufficient velocity to prevent transformation to floodplain.

If free bar dynamics are taken into account in models then it has been observed that bifurcation stability, as well as avulsion duration can be affected severely. Bar dynamics can result in switching of the main flow into either of the two bifurcates (Miori *et al.*, 2006). In the present research, knowledge of the development of bifurcations and the resulting avulsions is based on general historical records of channel change, whereas the details of free bar configuration and the location of perturbations are unknown

(Kleinhans *et al.*, 2008). In this regard, the effect of free bar dynamics has not been considered in this research. However, forced bars due to channel curvature (meandering) have been considered.

The duration over which avulsion takes place is partly dependent on width-depth ratio, the upstream bend radius, gradient advantage of one bifurcate over another and the length of the bifurcates. A varying combination of the above parameters can lead to sharp changes in the duration of the avulsion; although in general the time period of avulsion is directly proportional to the bifurcate length (BollaPittaluga *et al.*, 2003).

The simulation model of Kleinhans *et al.*(2008) showed that most bifurcates which do not close off entirely, but remain active as residual channels, act as passages for large discharges during floods (Makaske *et al.*, 2002) and can reactivate as major channels (Makaske *et al.*, 2002; Stouthamer, 2005). The model also demonstrates that the anastomosing channel patterns are representations of asymmetrical bifurcates where, despite a number of active branches existing simultaneously, the discharge and bed sediment flow are predominantly through one major channel (Makaske *et al.*, 2002; Huang and Nanson, 2007). The major channels are, thus, subjected to morphological modification while the other minor active channels feed washload onto the surrounding floodplains (Makaske *et al.*, 2002).

Bifurcation can lead to network channel patterns where bifurcates attain asymmetrical equilibrium. However, other factors like backwater effects due to tides, meander migration, bank erosion, and bed sediment sorting can also influence bifurcations and, thus, the avulsion threshold as well as the duration of avulsion. In the large rivers of the world, especially tropical rivers, complex anabranching systems are common. The mechanism which produces such multiple channel systems in large rivers are either avulsion-based or accretion-based processes or both (Nanson and Knighton, 1996). Anabranching in the Mississippi delta has been observed to occur due to lateral shift of the existing channel and the capturing of an old palaeo-channel where a part of the flow is diverted due to gradient advantage of the latter (Fisk, 1952). On the other hand, the avulsion of the Ganga-Bhagirathi system to the present Ganga-Padma system has not been explained or well documented in the literature and there has been little research on the evolution of the system compared with other large rivers of the world.

6.1.4 Objective and approach

The present research has two main objectives. The first was to investigate the factors that led to the avulsion of the Ganga–Bhagirathi system to the present Ganga–Padma system and the factors which play an important role in the pacing of the avulsion. The second was to determine why the older channel is still active, leading to an anabranching pattern, contrary to expectations and observations for small and medium rivers where the abandoned channels are seen to close off completely. We used a combination of historical data, satellite sensor data and one-dimensional (1D) modelling to explain the avulsion of the River Ganga from the older course to the new one.

Based on the problem statement as well as the objective and approach of the research we can propose two sets of hypotheses. The first set pertains to (1) the avulsion process while the second set pertains to (2) the resulting channel pattern. Considering (1) a hypothesis can be stated as: (a) for a given gradient advantage and tectonic framework, avulsion from the older channel to the present channel took place due to upstream bend development. An alternate hypothesis can be stated as: (b) for a given gradient advantage and bendway geometry, tectonics forced the avulsion of the older channel to the present channel. Considering (2) a hypothesis can be stated as: (a) multiple channels are stable due to the simple division of flow and sediment between the bifurcates. An alternate hypothesis can be stated as: (b) in such low-gradient systems, back water effects play a key role in moderating the simple division of flow and sediment between the bifurcates.

6.2 Study location

The present study was conducted in the Lower Ganga Plain (LGP), which is a part of the larger Ganga–Brahmaputra–Meghna (GBM) basin, covering parts of India and Bangladesh. The GBM plain is well known for its dynamic character. Due to the general presence of erodible bank material, the rivers in the GBM plain respond to large changes in discharge and sediment load by shifting their course and/or dramatically changing their morphology and bed forms. Evidence of planform changes include abundant ox-bow lakes, scroll bars and abandoned channels throughout the GBM plain (Kale, 2002).

6.2.1 Geological and structural setting of the Bengal basin

The study area (Figure 6-1) is part of the Bengal plain of the Indo-Gangetic alluvial tract (Singh, 1987). The Bengal plain is located at the junction of three tectonic plates – the Indian plate, the Eurasian plate and the Burmese plate. The plate boundaries are convergent; forming the Indian arc and the Burmese arc. The Indian plate is moving at $60 mmyr^{-1}$ in the north-east direction and subducting under the Eurasian plate at $45 mmyr^{-1}$ and at $35 mmyr^{-1}$ under the Burmese plate (Sella *et al.*, 2002; Bilham, 2004). Thus, the study area is traversed by major faults and lineaments. The N-S Malda-Kishangunj fault controls the river Ganga and one of its tributaries; the river

Mahananda (Dasgupta, 1987). The NW-SE stretch of the Ganga-Padma system flowing into Bangladesh is bounded by two prominent sub-surface faults: (a) the curvilinear Gondwana basin margin fault and the Eocene hinge zone. The presence of some other NW-SE / NE-SW or E-W trending faults is also presumed to be related with the above two sub-surface faults (Figure 6-2). The river Ganga in the study area borders the Himalayan fore deep zone in the north and the shelf zone and mid-basinal zone in the south (Ghosh and Majumder, 1990). Studies indicate that the geological structure of the region as well as the existing neotectonism may be responsible for changes in the river course as well as the potential source of major earthquakes (Morgan and McIntire, 1959). According to Morgan and McIntire (1959) changes in the courses of the river Ganga and river Brahmaputra during the last few hundred years can be possibly attributed to faulting and resulting tilting of fault blocks. These changes are likely to have influenced the Ganges to join the Brahmaputra–Meghna system to the southeast, abandoning western distributaries. The subsidence rate of the Gangetic delta has been documented as varying between 0.03 and 0.05 m yr^{-1} (Morgan and McIntire, 1959).

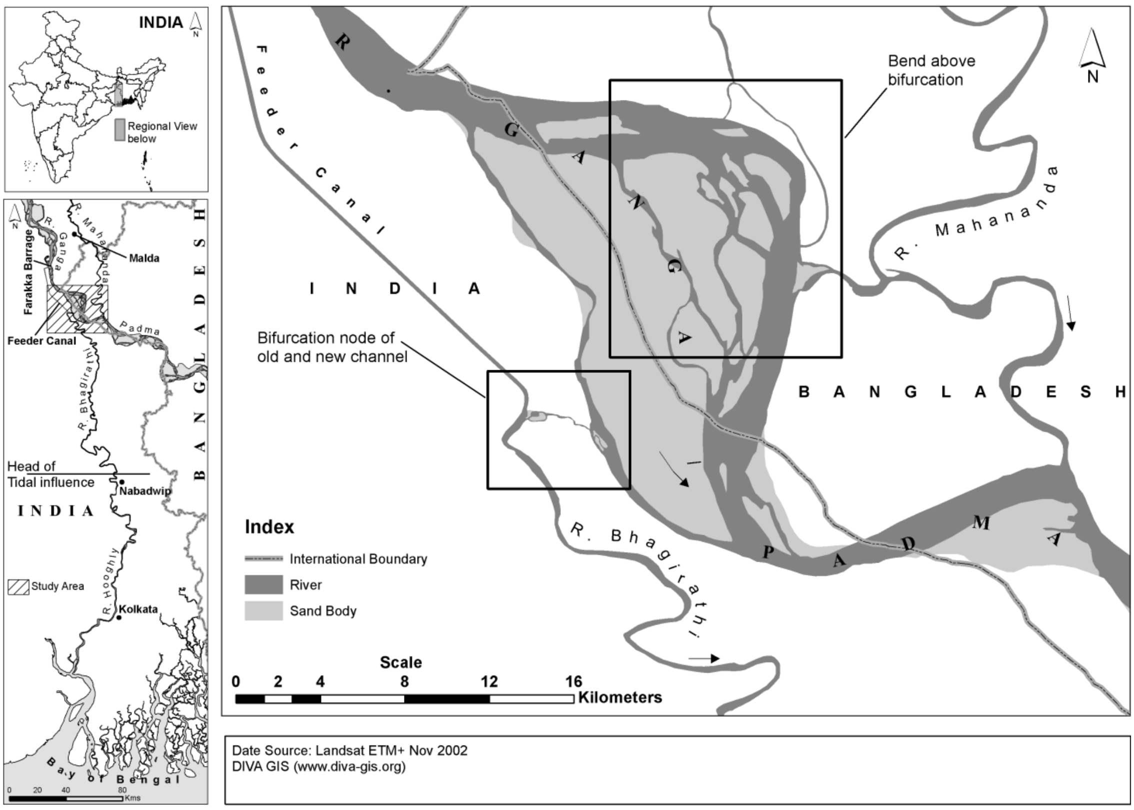


Figure 6-1Location of the study area in the state of West Bengal, India.

6.2.2 Earthquake history of Bengal basin

Major seismic activity in the past has brought about drastic shifts in the courses of the tributaries of the river Ganga as well as the river Brahmaputra. Major seismic activity in

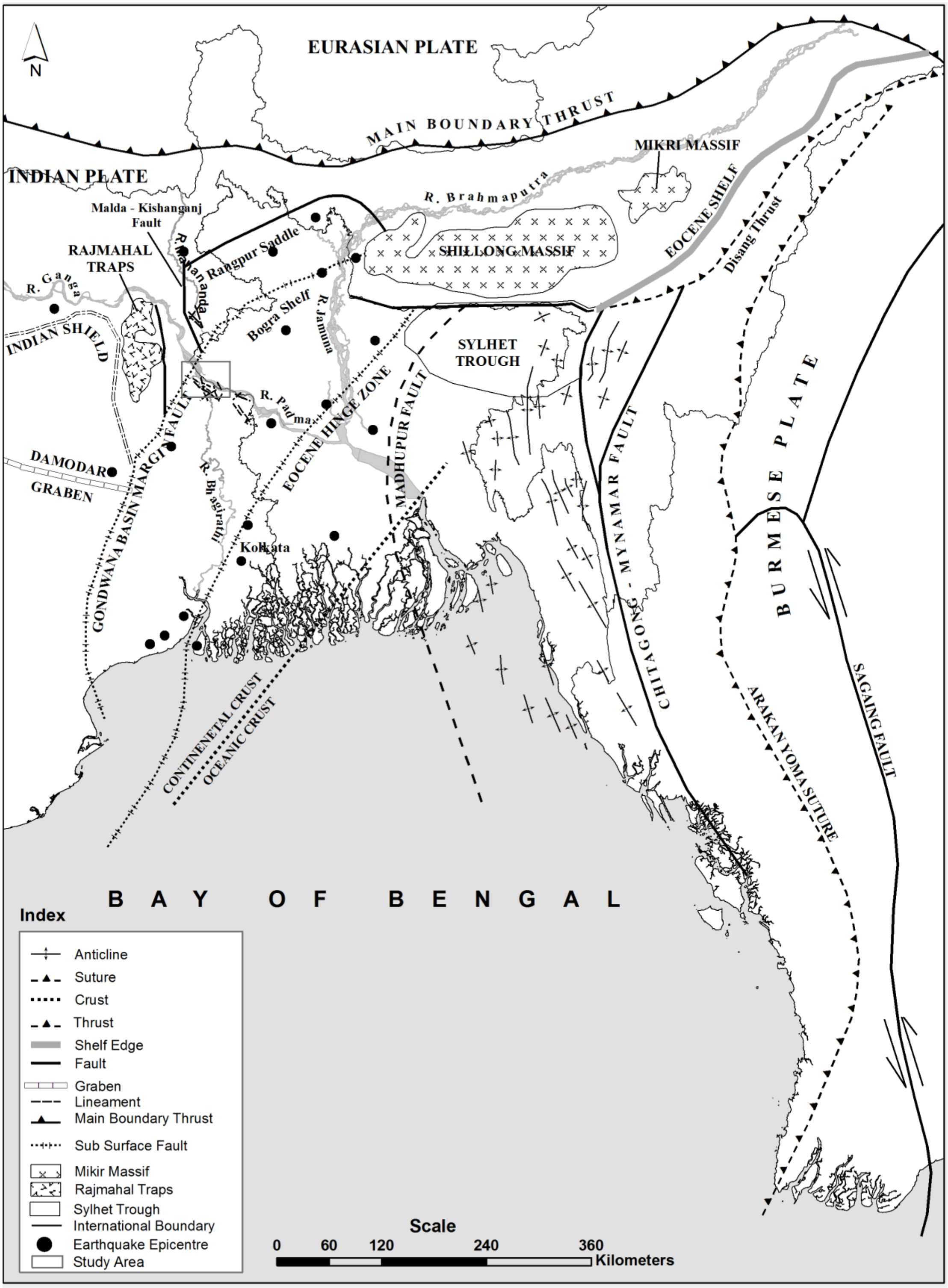


Figure 6-2 Seismotectonic map of the study area traversed by faults and lineaments and some major earthquake locations (modified from Nandy, 1994 and Curiale *et.al,* 2002)

the late 1700s shifted the river Brahmaputra from its former course from east towards west and the river Teesta, a tributary of the river Ganga, also changed its course and is presently a tributary of the river Brahmaputra (Bhattacharya, 1959; Chowdhury and Kamal, 1996).

A study on the earthquake history of the study area and the surrounding region from as early as 1548 (Akhter, 2010) shows the occurrence of earthquakes at regular intervals (Figure 6-3). Past studies (Morgan and Mcintire, 1959) indicated that more structural modifications have taken place in the eastern and northern parts of the Bengal basin than in the southern and western parts. The recorded seismic activities and epicenters of recorded earthquakes in the Bengal basin (Figure 6-2) and the adjacent region are seen to have a similar distribution to that of the location of faults and folds in the Bengal basin (i.e., north of the River Ganga) (Morgan and Mcintire, 1959; Akhter, 2010).

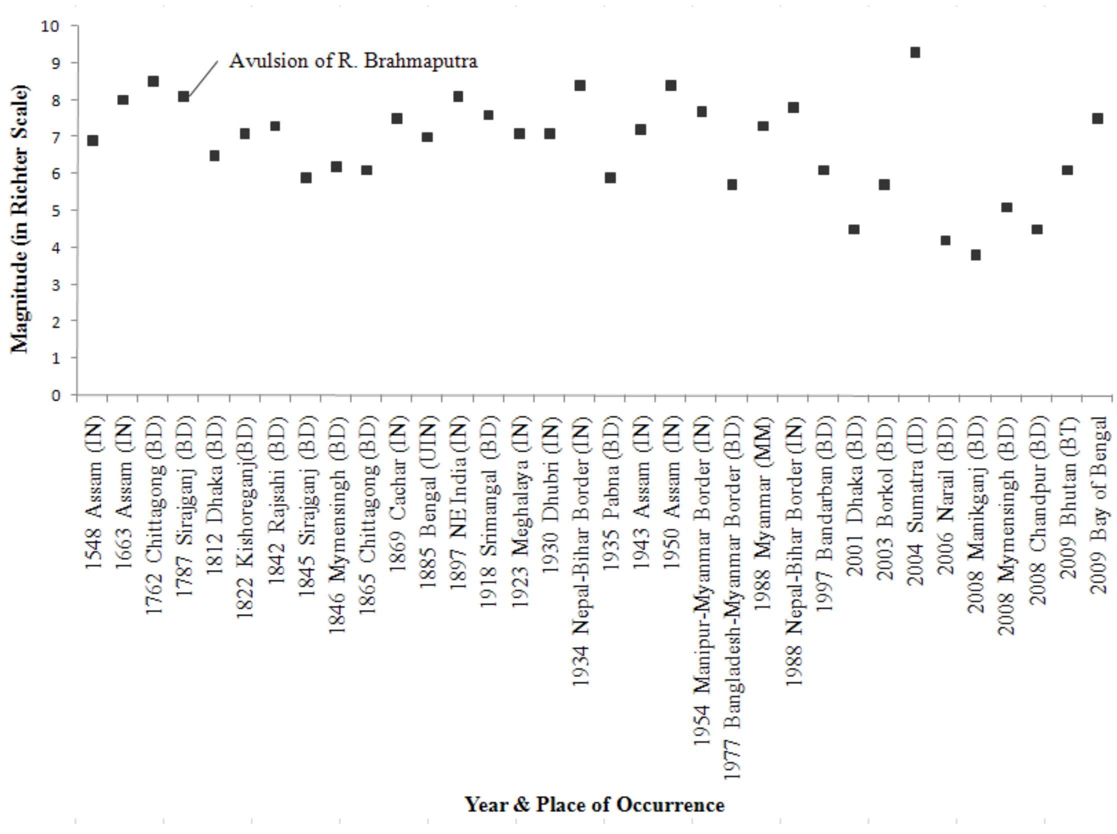


Figure 6-3 Earthquake history of the study area.

The area south of the study area is a deltaic region such that backwater effects due to tides are prominent.

6.2.3 Discharge and sediment character of the River Ganga in the LGP

The River Ganga-Padma presently has an average annual peak discharge of about 62,600 $m^3 sec^{-1}$ at Farakka with the minimum and maximum peak discharge at Farakka varying between 36,760 $m^3 sec^{-1}$and 73,030 $m^3 sec^{-1}$, respectively, from 1975 to 1995 (Parua, 2009). The average annual discharge is about 12,000 $m^3 sec^{-1}$ measured over a period from 1949 – 1973 (GRDC, Germany). On the other hand the peak discharge of the Bhagirathi-Hooghly at the bifurcation location varied from a minimum of 1,315 $m^3 sec^{-1}$ to a maximum of 1,669 $m^3 sec^{-1}$from 1973 to 1985 (Parua, 2009). The suspended load carried by the river Ganga-Padma has been estimated to be 800 million tonnes yr^{-1} (Abbas and Subramaniam, 1984)or 729 million tonnes yr^{-1} (Wasson, 2003) at Farakka. Of the total suspended sediment measured at Farakka about 328 million tonnes yr^{-1} is transported down the Bhagirathi-Hooghly system while 440 million tonnes yr^{-1} (Milliman and Syvitski, 1992) is transported by the Ganga–Padma system into Bangladesh. The sediments constitute very fine sand and silt-clay fractions. Eighty percent of the bed load is transported as graded suspension by the River Ganga (Singh *et al.,* 2007). Median grain size (D_{50}) varies from 0.13 mm to 0.14 mm in the LGP (Singh *et al.*, 2007). The channel gradient varies from 6 cm km^{-1} to 4 cm km^{-1} in the study area (Singh *et al.*, 2007).

6.3 Method

6.3.1 Channel and meander migration from Earth observation data

The time scale of the present study and the model run period was300 hundred years during which change or avulsion cannot be monitored using satellite sensor data. Thus, we had to depend on accounts from historical literature (Rennell and Banks, 1781; Colebrooke, 1803; Hirst, 1915; Reaks, 1919) and some scientific studies (Bhattacharya, 1959; Morgan and Mcintire, 1959, Nandy, 1994; Parua, 2009) to characterize the river behaviour. Landsat MSS, TM and ETM + data were used to determine the meander migration rate upstream of the bifurcation of the Ganga-Bhagirathi and Ganga-Padma systems (Figure 6-4).The channel migration rate was calculated based on an established method of georectification of images (Lillesand *et al.*, 2004) of individual years, extracting bankline by digitization (Heywood *et al.*, 2006), and measuring the migration of the meander apex over the years (Gupta *et al.*, 2012). The meander migration rate calculated over the last 38 years using the Landsat sensor data was used as an input to the model.

Besides estimating the meander migration rate, the Landsat series data were also used to identify the presence of older meander scrolls and palaeo channels (Figure 6-5). The older meander scrolls and palaeo channels are presumed to be indicators of the dynamic nature of the river and its planform change as indicated by Kale (2002) and others.

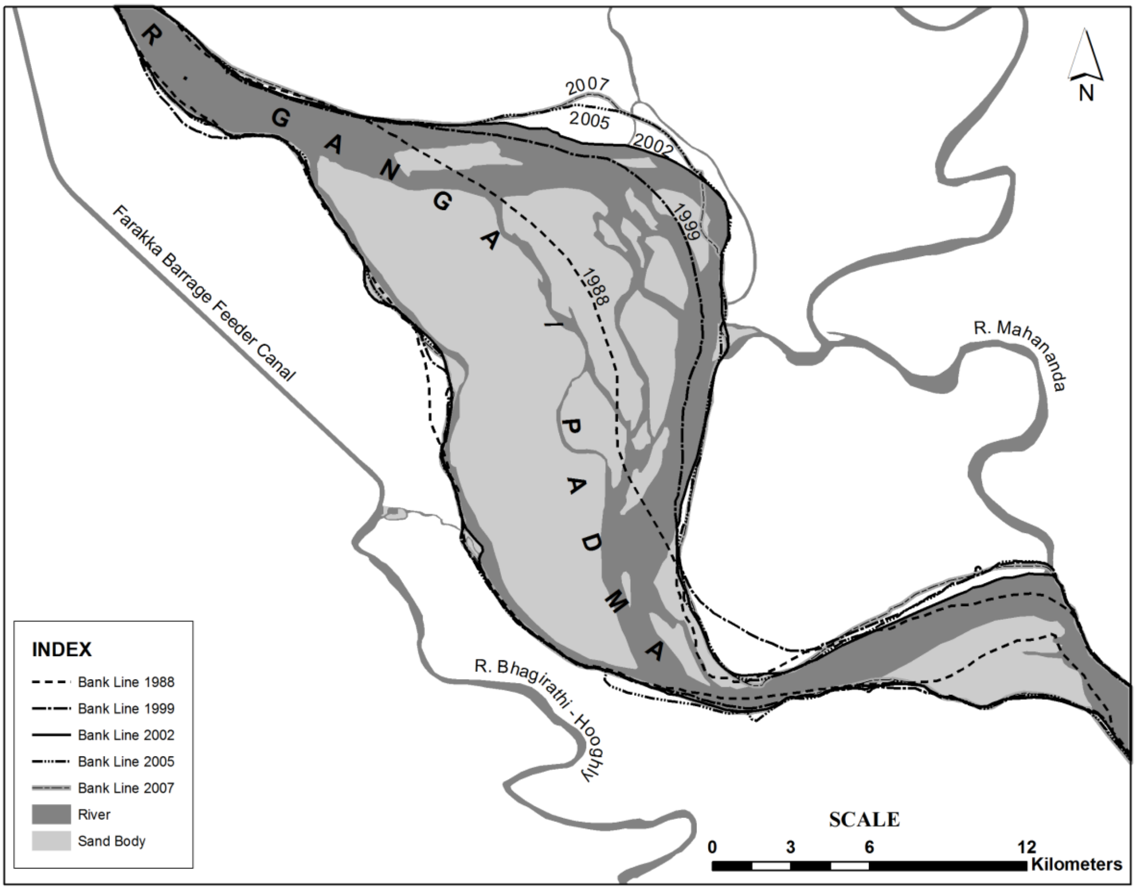


Figure 6-4 Recent meander migration history as extracted from Landsat time series.

6.3.2 Model Approach

6.3.2.1 Model formulation

A morphodynamic model was used to simulate several scenarios to assess the effect of gradient advantage, bends and tectonics on channel evolution. A morphodynamic network model with Y-shaped bifurcations was built (Kleinhans *et al.*, 2008) consisting of two downstream 1D models connected to one upstream branch (Figure 6-6). At the bifurcation, the flow and sediment fluxes were partitioned as proposed by Kleinhans *et al.*(2008, 2012), which includes the effect of migrating meanders at the bifurcation, which steer water and sediment preferentially into one bifurcate depending on the orientation of the bend. The flow in each branch is based on the Bélanger equation (backwater formulation for gradually varied flow) which was formulated as follows:

$$\sin\theta - \cos\theta \frac{\partial d}{\partial x} - \frac{P_w}{A} (a\,V + b\,V^2) + \frac{Q^2}{gA^3}\frac{\partial A}{\partial x} = 0 \qquad (6.1)$$

where θ is the angle between the bed and the horizontal, x is the longitudinal distance positive downstream, *d* is the flow depth measured normal to the invert, *A* is the cross-section area, *Pw* is the wetted perimeter, *Q* is the discharge.

Initially, equal discharge between the branches was specified and the branches were allocated a fixed downstream water level. In each time step, the backwaters on the downstream branches were iterated by varying the discharges until their water levels at the bifurcation were equal. The upstream branch then received a constant flow discharge that can transport the annual sediment budget. Upstream sediment feed in the model was set at capacity.

The sediment partitioning model included a transverse bed slope and a spiral flow parameterization within the bend depending on bend radius. The bend radius can be specified as constant at the bifurcation, or, alternatively, the length, amplitude and period can be specified so that the bend radius is calculated from a sinusoidal meandering river migrating into the bifurcation. The meander migration was represented as a time-varying radius of curvature. The presence of migrating bars was not accounted for in the model, but the forced inner bend bars were considered in the model formulation.

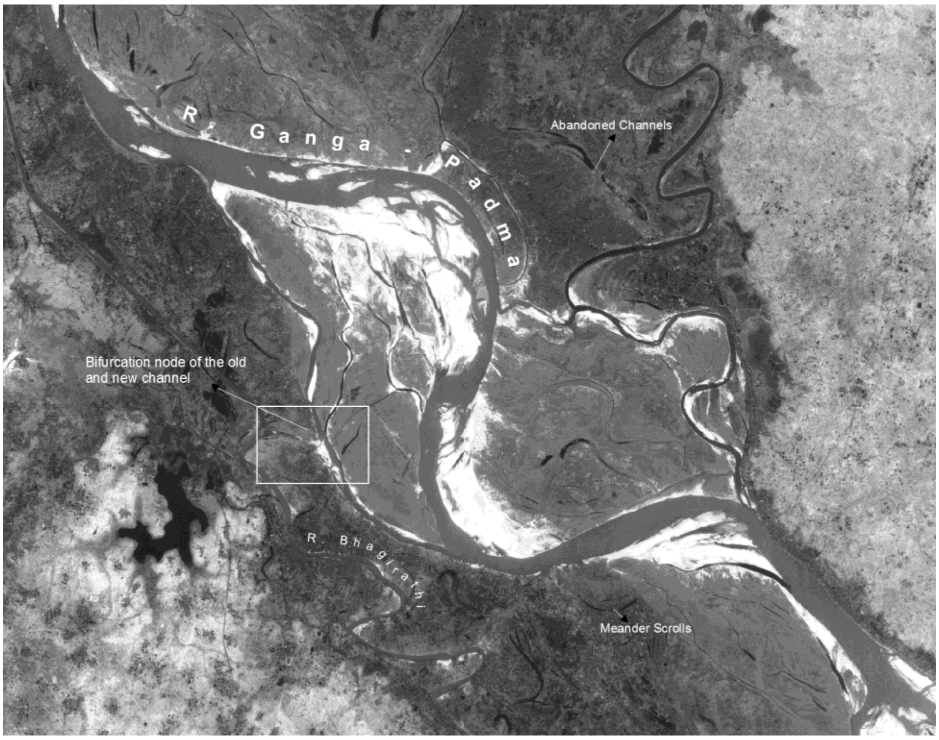


Figure 6-5 Location of the bifurcation of the morphologically active residual (Ganga-Bhagirathi system) and main channel (Ganga-Padma system) as well as older meander scrolls and abandoned channels which indicate the dynamic nature of the river in the past, as seen in Landsat ETM+ data (October-November, 2000).

The morphology in each branch was updated to the flow conditions by application of the Exner sediment conservation law with a sediment transport gradient based on the Engelund-Hansen (1967) predictor for all locations, except for the upstream boundaries of the bifurcates where the bifurcation sub-model was applied. As the branches evolved, the width adjusted to changing flow discharge following a hydraulic geometry relation, whilst conserving the sediment in bed and banks through the Exner equation as given below.

$$\frac{\partial \mathrm{n}}{\partial t} = -\frac{1}{\varepsilon_0}\nabla . q_s \tag{6.2}$$

where change in bed elevation, *n*, over time, t, is equal to one over the grain packing density, ε_0, times the negative divergence of sediment flux, q_s. This procedure allowed the growth and abandonment of branches (Kleinhans *et al.*, 2012). The effects of tectonics was also applied through the Exner equation by addition of a constant lowering or raising of the bed elevations per unit of time in specified reaches of the branches as per equation 6.3 below.

$$\frac{\partial \mathrm{n}}{\partial t} = -\frac{1}{\varepsilon_0}\nabla . q_s + \sigma \tag{6.3}$$

where subsidence term σ is added to the mass balance. With every model time step the bed elevation in specified reaches of specified branches was lowered or raised such that it followed the required rate of subsidence per unit of time, in addition to any bed elevation changes caused by gradients in sediment transport. In other words, we added a time-dependent term to the Exner equation for specified locations (Kleinhans *et al.,* 2008).

Several constants, parameters and coefficients were considered. Constants were: bed sediment size, porosity and density, water density and gravitational acceleration. Coefficients for hydraulic roughness and two calibration coefficients for the nodal point relation were calibrated using the three-dimensional (3D) model in Kleinhans *et al.*, (2008). Coefficients for the channel width prediction and rates of tectonic movement are described later. Numerical parameters were spatial step length, required precision of water level equilibration at bifurcations, and a Courant criterion (0.8) for bed level disturbances that specifies the optimum variable time step for each iteration. A summary of the values of the constants is described in Figure 6-6 along with a plan view of the model.

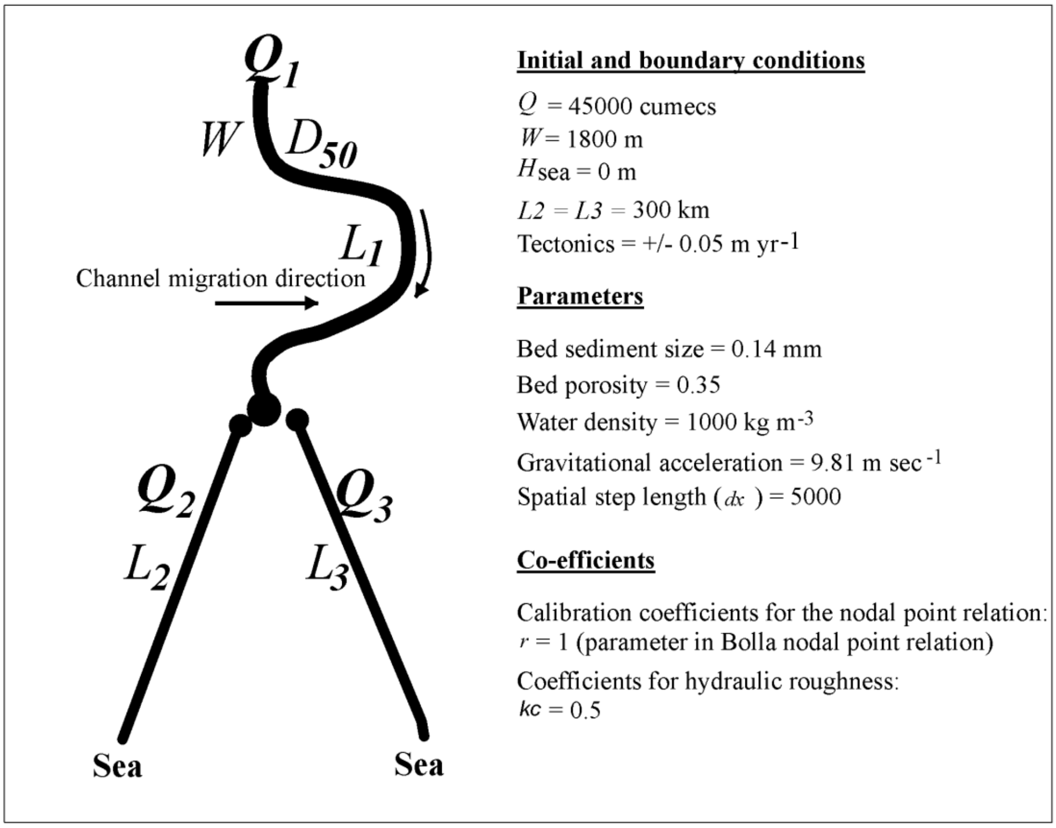


Figure 6-6 Schematic diagram of 1D model setup showing the bifurcation point and the division of discharge into two branches. The initial and boundary conditions, along with constant parameters and coefficients used, are also shown.

Table 6-1 Initial parameter values considered for base case (equal condition) in basic scenario modelling.

Base case (other parameters are zero e.g. gradient advantage, subsidence)			
	Upstream	**Bifurcate 1 (abandoning channel)**	**Bifurcate 2 (growing channel)**
Q (m^3/s)	45000	40000	5000
Length (km)	100	300	300
Gradient	0.00005	0.00005	0.00005
Grain size (mm)	0.14	0.14	0.14
Upstream Width (m)	1800	-	-

6.3.2.2 Initial and boundary conditions for the Ganga and Bhagirathi bifurcation

Several initial and boundary conditions were considered to run the model. Hydrological data for the study area are restricted and, as a result, hydrological data related to the river and sediment characteristics were obtained from various published sources (Mirza, 2004; Singh *et al.*, 2007; Parua, 2009). The initial parameters for the base case within the basic model scenario are given in Table 6-1. Another initial condition of the model is that two channels have already formed due to avulsion (which may have formed due to crevasse splay as discussed in chapter 2) and the model tries to find out the conditions which lead to the initial smaller channel to become dominant and vice versa resulting in a successful avulsion event in a shorter time period.

The upstream boundary condition of the model was that a constant discharge of 45,000 $m^3 sec^{-1}$ was sent downstream. A value in between the peak discharge of around 60,000 $m^3 sec^{-1}$ and the annual average discharge of around 12,000 $m^3 sec^{-1}$ was decided to initialize the model. The model also considers that two channels already exist and the avulsion process has already initiated. The model intends to find out the time period of the smaller channel becoming the dominant one and vice versa. The initial consideration was equal distribution of water in the two bifurcates and the water levels downstream of the two bifurcates were fixed at mean sea level (i.e., H_{sea} = 0 m). The length of the two bifurcates were fixed at 300 km (no gradient advantage) for the base case within the basic model scenario and all other parameters like gradient advantage, subsidence and bend migration were considered to have a value of zero. As the sediment is fine sand the median grain size D_{50} was considered as 0.14 mm. The gradient was considered as 0.05 m km^{-1} and the average water depth was considered as 16 m. The basic model scenario was then extended to include new parameters and modify some existing parameters to understand the avulsion process at the Ganga-Bhagirathi bifurcation. The details of the cases and the parameters added or modified for each case in the basic model scenario are given in Table 6-2. The initial parameters of discharge, upstream length, upstream width and grain size were the same as the base case (equal condition) in all the cases of the basic model scenario. Based on the above initial and boundary conditions the model was run for various scenarios as described in the next section.

Table 6-2 Parameter values of each case in the basic scenario modelling.

	Cases (within basic scenario)	**Parameter**	**Value (m/yr)**	**Parameter**	**Value (m/m)**	**Parameter**	**Value (km/yr)**
B	Gradient advantage	-	-	Gradient	0.00006	-	-
C	Subsidence	Subsidence rate	0.05	-	-	-	-
D	Migrating bend	-	-	-	-	Migration rate	0.483
E	Gradient advantage & subsidence	Subsidence rate	0.05	Gradient	0.00006	-	-
F	Gradient advantage & migrating bend	-	-	Gradient	0.00006	Migration rate	0.483
G	Subsidence & migrating bend	Subsidence rate	0.05	-	-	Migration rate	0.483
H	Subsidence, gradient advantage & migrating bend	Subsidence rate	0.05	Gradient	0.00006	Migration rate	0.483

6.3.3 Base Scenario modelling

The avulsion duration and the probable cause of the avulsion of the Ganga–Bhagirathi system to the present Bhagirathi-Padma system were determined taking into consideration eight cases (Figure 6-7). Initially, a base case (equal condition) (A) was considered in which the water from upstream was divided equally into the two branches, the length of each branch was assumed to be the same and there was no gradient advantage. The model was run for a period of 300 years. The 300 year model run period was chosen based on the fact that in the 15thcentury AD (around 1477 as mentioned in a famous Bengali epic (Parua, 2009)) the River Ganga flowed through the older course (Parua, 2009) and in the late 18thcentury (around 1787 - 1790) the River Brahmaputra changed its course from the east towards the present course in the west (Morgan and Mcintire, 1959; Johnson and Alam, 1991). During this period (late 18thcentury)the River Ganga was already flowing through its new course as surveyed by James Rennell in 1767 (Sarker, 2004). Hirst (1915) also reported that a major earthquake in 1505 AD resulted in the avulsion of the Ganga from the older course to the present course. So the avulsion must have occurred within a 300 year period between the early 16th(1505 AD) and late 18th(1787 AD) centuries (i.e. around 282 years).

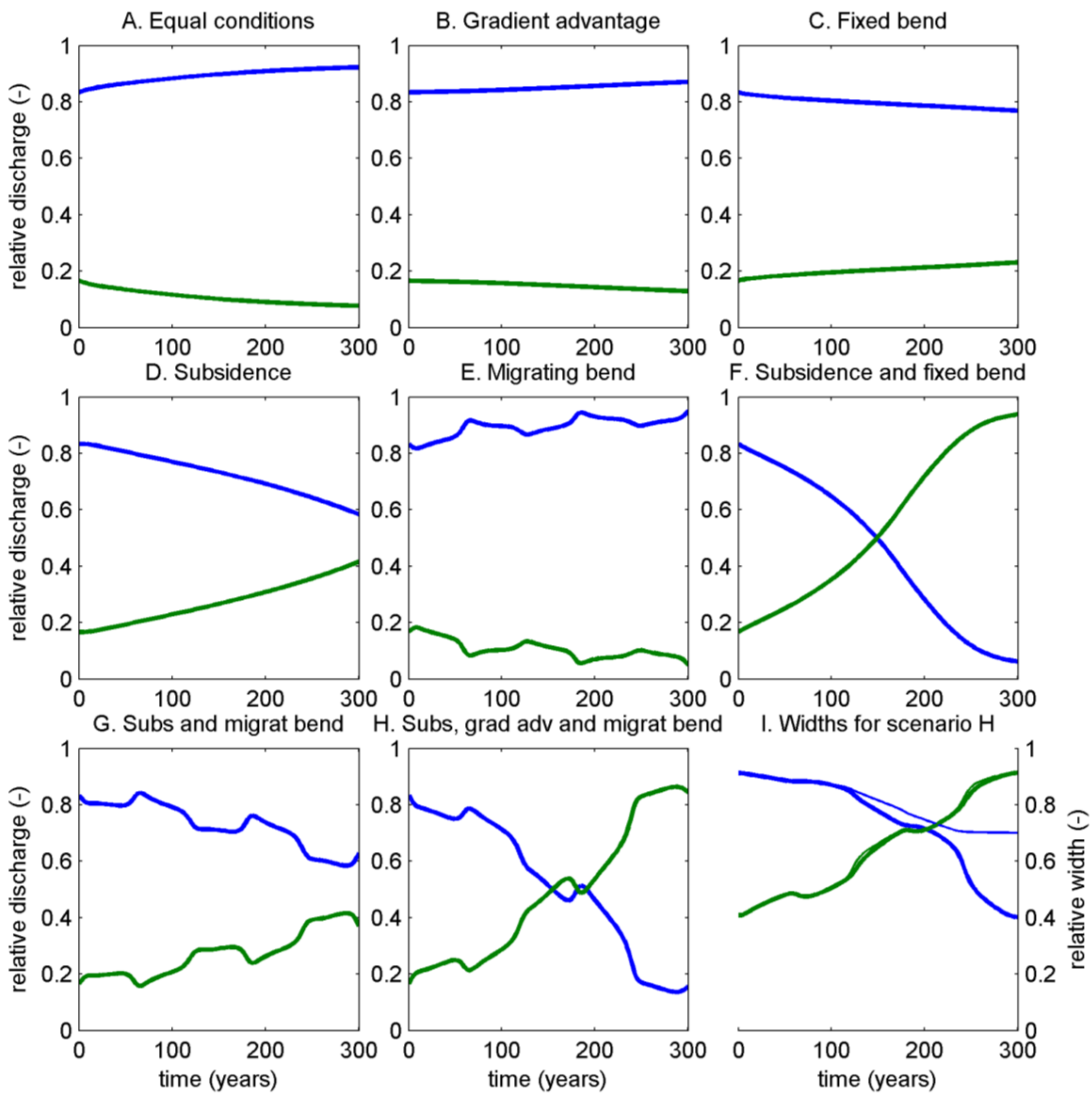


Figure 6-7 Scenarios modelled showing the change of relative discharge of the two bifurcates over the 300 years of model run period. In all scenarios except F and H the major relative discharge flows through the present Ganga-Bhagirathi system (marked in blue) and no avulsion takes place where the Ganga-Bhagirathi system becomes the residual channel and the Ganga-Padma system (marked in green) becomes the dominant one. Only when subsidence is introduced into the model, does the avulsion occur. Scenario I indicates the change in relative width of the two channels and shows that the residual channel is morphologically active even after the avulsion.

Gradient advantage was then introduced into the model (B) with the Ganga-Padma branch having a gradient advantage (250 km) over the major Ganga-Bhagirathi branch (300 km). Tectonics was then introduced into the system by means of subsidence (C) where the Ganga-Padma branch was subsided longitudinally at a uniform rate of 0.05 m yr^{-1} with respect to the Ganga-Bhagirathi branch (Morgan & McIntire, 1957). In the next case (D), we considered a migrating bend based on the Earth observation data available over the last 35 year period. The historical literature for this area dates to the early 19th century (Colebrooke, 1803) and records the planform dynamics of the river system. Presently, we observe from Earth observation data (Figure 6-4) that the river still exhibits planform dynamics. The meander upstream of the bifurcation has a migration rate of about 0.483 km year^{-1} and as no historical migration rate has been recorded and based on the indication that the river has a similar dynamic nature as in the past, we assume that a similar migration rate existed during the avulsion period. In case (E), we take into consideration both gradient advantage and subsidence while in case (F) we combine gradient advantage and a migrating bend. In case (G), we combine subsidence with a migrating bend. Then, a final case (H) is tested where we combine subsidence, migrating bend and gradient advantage. In addition to the above cases, which allow estimation of avulsion duration, we also modelled the change of width of the two branches in case (H).

6.4 Results

6.4.1 Model results

The results of the basic model scenario show that in the base case (equal condition) (A) the relative discharge of the Ganga–Bhagirathi System (plotted in blue) dominates over the Ganga–Padma System (plotted in green) throughout the model run period and the relative discharge even increases for the dominant branch and decreases for the other branch. On introduction of gradient advantage (B) the results indicate that the Ganga–Bhagirathi channel dominates even after the Ganga–Padma system has gradient advantage over the major channel. The model output on introduction of tectonics (C) into the system also shows similar results where the Ganga–Bhagirathi channel dominates over the Ganga–Padma system. On addition of a migrating bend (refer section 6.3.2.1) to the model (D) the results do not show any change from the earlier scenarios except that the relative discharge of the Ganga-Bhagirathi channel increases to a certain extent and then becomes constant and similarly the relative discharge of the Ganga – Padma branch decreases to a certain extent before it becomes constant. On combining both the parameters of gradient advantage and subsidence in (E), we find that the relative discharge of the Ganga-Bhagirathi channel decreases while the relative discharge of Ganga-Padma system increases and the avulsion takes place after 240 years. Next on combining parameters of gradient advantage and migrating bend in (F) no avulsion takes place within the model run period. In G, we observe a similar outcome to that for scenario (F) on combining the parameters of subsidence and migrating bend. When all the parameters of gradient advantage, subsidence and migrating bend are combined in (H) it is seen that the Ganga-Padma branch becomes the dominating branch of the two branches after 240 years.

The model also shows that the width of the Ganga-Padma system downstream of the bifurcation increases considerably to accommodate the excess discharge passing through it while the width of the Bhagirathi-Hooghly system downstream of the bifurcation decreases in (I), but it stabilizes over the time of model run.

6.4.2 Sensitivity analysis

A sensitivity analysis was conducted on the input values to the model to determine the robustness of the 1D model. Several scenarios were tested by changing input parameter values one at a time and observing the effect on the model output. Changes in the parameters: grain size, upstream width and downstream length did not lead to any significant change in model output, whereas changes in the parameters: discharge, gradient and subsidence rate led to changes in the model output. A total of about 100 cases were tested and from them 32 cases were chosen for the sensitivity analysis. Table 6-3 shows the parameters considered and the input values changed for the new scenarios which were tested in the sensitivity analysis.

The normalized avulsion index was calculated as $T_{crossing} / T_{real\text{-}avulsion}$ where $T_{real\text{-}avulsion}$ is around 282 years (discussed in section 6.3.3) and $T_{crossing}$ is the model run time until the relative discharges of the two bifurcates cross (Figure 6-7). In some cases the model had to be run for a period >300 years for the cross over. The model run was restricted to a maximum of 900 years. A hypothetical scenario was also considered in which only dominant suspension load was considered and no bed load transport was considered, and this nullified the effect of transverse bed load. The result of the sensitivity analysis is given in Table 6-4 and is discussed below.

6.5 Discussion

6.5.1 Inference from the modelling scenarios

The different model cases indicated that gradient advantage or a migrating bend at the bifurcation cannot be considered as the causes of a major avulsion in such a short period of time. The inclusion of subsidence in the model in combination with gradient advantage and a migrating bend led to avulsion over a short period of time. The 1D model showed that realistic tectonic subsidence of the new branch may force an avulsion to take place quickly. The tectonic uplift of the old branch or subsidence of the new branch was the more realistic explanation as the other parameters fed into the model did not support an avulsion or a short period. The model also supported the findings of flume experiments that a rapid tilt results in an avulsion (Peakall, 1996). The dominant control of neotectonics on avulsion shown in the modelled output is consistent with the historical record. Hirst (1915) stated that a major earthquake in

1505 AD resulted in the avulsion of the Ganga–Bhagirathi system to the Ganga-Padma system, attributing the changes in the courses of the Bengal Rivers to tectonic activity. Other historical records also have argued that large river systems in the Bengal basin have avulsed due to tectonic activity. The most significant amongst them was the shift of the Brahmaputra River to the west of the city of Dhaka due to a large earthquake in the late 18th century (sometime between 1787 –1790) and shifting of the Teesta River from a tributary of the River Ganga to become a tributary of the River Brahmaputra. During the time of the change in the courses of the River Brahmaputra and River Teesta, the River Ganga had already shifted its course to the present configuration. So the model results, indicating preferred avulsion duration of between 200 and 300 years, are consistent in time-frame with the historical record (c. 282 years duration) and we can infer that the avulsion of the Ganga–Bhagirathi System is less than three centuries old.

6.5.2 Mechanisms controlling avulsion within the Ganga–Bhagirathi system

The process of avulsion modelled in the 1D morphodynamic model considers the various mechanisms which actually lead to an avulsion at any particular location. In reality, gradient advantage and presence of a bend at a bifurcation leads to sediment flux to the closing branch and the closure of the branch depends on the time required to fill the downstream disadvantaged branch, but these controls have been found to dominate mainly in small and medium rivers (Kleinhans *et al.*, 2012). The main focus of the present modelling was to explain the historically apparent shorter period of avulsion of the Ganga–Bhagirathi system to the Ganga-Padma system, that is, to determine the reason for the short avulsion duration. The model results showed that, for this large river, neither gradient advantage nor a migrating bend upstream of the bifurcation leads to an avulsion within centuries. On the other hand, a realistic tectonic uplift of the old branch or subsidence of the new branch may force an avulsion to take place quickly. Thus, the model agrees with the alternate hypotheses that in a bifurcating channel the major flow will pass through the new channel if there is subsidence in addition to gradient advantage and the existence of a bend above the bifurcation.

The sensitivity analysis carried out (Table 6-4) also showed that two cases (gradient advantage and subsidence as well as the combination of subsidence, gradient advantage and migrating bend) actually brings about an avulsion in the system over a shorter period of time with a normalized avulsion index of between 0.5 to 1.0. Although avulsion takes place in the cases of subsidence, and subsidence and migrating bend, within a low discharge scenario, the normalized avulsion index is > 2 indicating a longer time period which does not agree with the historical literature. Even

Table 6-3 The input parameter values considered in different scenarios for sensitivity analysis.

	Other Scenarios							
Parameters	**Peak discharge**		**Low discharge**		**Reduced subsidence**		**Lower Gradient**	
	Bifurcate 1	**Bifurcate 2**	**Bifurcate 1**	**Bifurcate 2**	**Bifurcate 1**	**Bifurcate 2**	**Bifurcate 1**	**Bifurcate 2**
Q (m^3/s)	55000	5000	25000	5000	40000	5000	40000	5000
Gradient	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00004	0.00004
Subsidence (m/year)	-	0.05	-	0.05	-	0.03	-	0.05

Table 6-4 Sensitivity analysis based on normalized avulsion index showing that subsidence has a major role to play in the avulsion of the Ganga – Bhagirathi system to theGanga – Padma system.

Scenarios	**Cases**							
	Equal Condition (Base Case)	**Gradient advantage**	**Subsidence**	**Migrating bend**	**Gradient advantage & subsidence**	**Gradient advantage & migrating bend**	**Subsidence & migrating bend**	**Subsidence, gradient advantage & migrating bend**
Basic	0.00	0.00	0.00	0.00	0.85	0.00	0.00	0.86
Peak Discharge	0.00	0.00	0.00	0.00	0.89	0.00	0.00	0.85
Low Discharge	0.00	0.00	2.27	0.00	0.57	0.00	2.55	0.53
Reduced Subsidence	0.00	0.00	0.00	0.00	1.45	0.00	0.00	1.31
Lower Gradient	0.00	0.00	0.00	0.00	0.62	0.00	0.00	0.78

Normalized avulsion Index

0.5 - 1.0	(yellow)
1.0 - 1.5	(blue)
> 1.5	(red)

when only suspended load was considered in the system and the transverse bed load effect was nullified, the combination of subsidence, gradient advantage and a migrating bend led to an avulsion. Thus, we can say that subsidence has a major role to play in the avulsion of the system although the sensitivity analysis indicates that it has to be in combination with gradient advantage and a migrating upstream meander bend to match the observed dynamics as inferred from the historical literature. Thus, the model outcome agrees with the alternate hypothesis that for a given gradient advantage and bendway geometry, tectonics forced the avulsion of the Ganga - Bhagirathi channel to the present Ganga – Padma channel.

6.5.3 Channel pattern of large rivers

Large fluvial systems of the world generally have a different channel pattern from the medium and small sized rivers and, thus, the terms straight, meandering and braided cannot readily be applied to them (Latrubesse *et al.,* 2005). The large rivers are generally dominated by anabranching channel patterns as observed by Jansen and Nanson (2004) and Latrubesse (1992). The cause of the anabranching channel pattern has been attributed to the fact that the large rivers have very high discharge of > 17000 $m^3 sec^{-1}$and very low gradient of < 0.00007 (Latrubesse, 2008). Although meandering patterns exist in large rivers, the intrinsic characteristics of discharge and a large width/depth ratio leads to formation of an anabranching channel pattern and it remains unclear why this planform style seems to be stable in the case of large rivers.

In respect of the last point above, the 1D model demonstrated that both the old and new branches can remain `open' and morphologically active for a long time leading to a sustained anabranching channel pattern in large rivers. However, this would not be true for small or medium sized rivers (such as the River Rhine) where avulsion would be followed by channel-filling of the older residual branch. The fact that the older branch in large rivers remains morphologically active, especially in the delta region, is due to the huge backwater adaptation length which has been found to be around 300 km for the Ganga–Bhagirathi system. The huge backwater adaptation length keeps the channel morphologically active during ebb tide and the upstream flow during the monsoon season compensates for the silting taking place in the upstream reach unaffected by backwater effect from the tide during the dry season. The considerable back water adaptation length is due to the low gradient of large river systems. Besides the back water adaptation length (which does not have any influence at the bifurcation location in the present study area), the anabranching channel pattern is due to the size of the residual channel as well as due to high sediment mobility at the bifurcation which actually leads to incomplete closure of the residual channel.

During monsoon months the river carries a significant amount of discharge which actually clears temporary plug bars at the mouth of some of the residual channels. Thus, we can agree with the alternative hypotheses on the channel pattern that in such low-gradient systems, back water effects play a key role in moderating the simple division of flow and sediment between the bifurcates resulting in anabranching channel patterns in large alluvial rivers.

6.5.4 Model limitations

As models are approximate representations of the real world, they are inherently inexact. The model limitations actually determine to what extent the model results can be supported. The present study had two families of limitations. One pertains to the initial and boundary conditions that have been considered for the model runs and the other pertains to the physics involved in the 1D model. The initial and boundary conditions defined in the model were generalized. Various scenarios were considered to investigate the plausibility of certain causes of avulsion in nature. Floods may initiate avulsion, but avulsions take a long time relative to individual floods, so the time of flood may not be an important factor other than that it represents the sediment transport regime with the channel-forming discharge. Most importantly, some of the parameters such as the migration rate of the bend just above the bifurcation, which were calculated from Landsat sensor data over a recent period of time, may be different from the actual scenario during the avulsion period. The same is true for the subsidence rate, which is based on a few studies (Morgan and McIntire, 1959) carried out in the Bengal basin, as well as the discharge and other hydrological characters which have been accumulated from various sources (Mirza, 2004; Singh *et al.*, 2007; Parua, 2009). Nevertheless, the sensitivity analysis demonstrates clear model behavioural patterns that are consistent when parameters are varied within physically realistic limits.

The foremost limitation of the model was that it was a one-dimensional model. We considered that there were two branches and their lengths were 300 km each (when we consider the scenarios without gradient advantage) and 300 km and 250 km (in the scenarios with gradient advantage), although this was an approximation of reality. In the 1D model the level of channel closure is reduced in comparison with a 3D model (Kleinhans *et al.*, 2008) where bar formation can be taken into account. Thus, the choice of the 1D model affected the final asymmetry of the bifurcation (Kleinhans *et al.*, 2008). However, the general direction of evolution in the 1D and a 3D model is the same, as are the underlying physics, whereas a full 3D model of this large river is computationally inhibitive. A 2D model could have been another alternative, but a 1D model was chosen over a 2D model to provide a simplified representation of the cause of the avulsion. Moreover, as mentioned earlier in section 6.1.3, past details of bar configuration and the location of perturbation are unknown so it becomes difficult to represent the avulsion process in a 2D model. The model assumed that total bed material transport was partitioned under the effects of flow division and transverse bed slope, but it was perhaps important that suspended bed material transport was relatively less affected by transverse bed slope effects (because it has relatively little contact with that sloping bed) and was affected mainly by spiral flow, and also by spatial acceleration or deceleration at the bifurcation. The model portrayed a simplified process of width adjustment and meandering to model bifurcation and meander migration. Despite the simplifications the results clearly indicate, for understandable reasons, that uplift of one branch effectively adds so much sediment along its entire length that closure is much faster in this river than with any other mechanism known to destabilize bifurcations.

6.6 Conclusion

The one-dimensional model for a bifurcating channel formulated here and tested on the Ganga-Bhagirathi system in India, suggests that subsidence (tectonics) has a major role to play in the avulsion of the system to the present Ganga-Padma system within a short time period (< three centuries), in combination with gradient advantage and a migrating upstream meander bend. The avulsion duration can be considered very fast considering the size of the river both in terms of discharge and the sediment load it carries. The model initially considered the effect of meanders just above the bifurcation and adaptation of channel width to discharge. The model showed that migrating meanders at bifurcations and gradient advantage alone cannot lead to an avulsion within a short period of time from one channel to another in larger rivers, especially in areas where gradient is very low (deltaic regions). Avulsion in larger rivers is possible over a short period of time if active tectonics / neotectonics lead to subsidence of the smaller branch which may then lead to an avulsion from the active branch to a smaller branch.

The modelling suggests that for large rivers a stable bifurcation may persist rather than the older channel atrophying due to aggradation and the newer channel accommodating the total discharge. Historical evidence shows that even after the diversion of the major flow to the new branch, the older branch can be morphologically active. This can be attributed to a large backwater effect as well as mobility of sediments due to flood time flow coming from the upstream forming an anabranching pattern. Evidence of channel switching where the main flow coming back to the Ganga-Bhagirathi channel has not reported in historical literatures. The backwater effect was not in the scope of the model as the bifurcation explored in this research was outside the influence of the tides from the sea. In addition, in large river systems the sediments coming to the older branch cannot fill the residual channel due to flood discharges coming from upstream at a regular interval. Thus, the Ganga-Bhagirathi channel (the residual channel) is still morphologically active (though during the dry season it is fed by the artificial feeder canal from the Farakka barrage) leading to stabilization of the bifurcation with an asymmetrical flow and sediment division. The results indicate that the anabranching nature of many of the world's largest rivers stems from the large backwater effect on the bifurcation evolution compared to smaller rivers.

7 Conclusion

Time-series satellite sensor data freely available from Landsat archives provided by USGS from mid-2008 in association with archival data from the Indian remote sensing satellite programme was one of the main inputs to the present research. The availability of these data have opened up a new avenue for fluvial geomorphologists to study the large tropical river systems of the world. As multi-senor, multi-platform data were used it required standardisation of the dataset for a meaningful inter-annual comparison. The information extracted from the time-series data supported by limited hydrological information from the existing literature was used to infer the morphological processes occurring in the Ganga-Padma river system which has resulted in a reconstruction of the planform dynamics of the system from historical times to the present. The present research showed that earth observation data can be used very effectively supported by limited ground data and historical evidence to understand the evolution of large rivers in tropical countries. The present study was able to understand the basic evolutionary mechanism of the Ganga-Padma system and throw light on some misconceptions of the planform behaviour of the system enabling better management of the river system. The study also established the possible causes of the avulsion of the Hooghly-Bhagirathi system to the Ganga-Padma system. Though there are limitations in this study but the research showed that behaviour of large river systems like Ganga-Padma can be analysed by the applied methodologies. Based on the objectives presented in the scientific chapters in the thesis the following specific conclusions were reached.

7.1 Specific conclusion

The specific conclusions have been summarised based on the individual scientific chapters presented in the thesis:

7.1.1 Chapter 3

As tropical river systems have a large size and have a huge extent, ground data availability for these river systems are limited. The availability of sensor data from the Landsat archives from mid-2008 provides an effective source of data to study the morphodynamics of these large river systems in tropical regions. The availability of sequential archival data has opened a new avenue for fluvial geomorphologists to study the large river systems of the world. In the present research on the Ganga-Padma system, as the area is outside the North American continent, gaps existed in the data availability from the Landsat archives and as a result such gap were compensated by data from other archives (e.g. Indian Remote Sensing programme) to create continuity in the time-series.

As data from multi-platforms and multi-sensors were used, issues related to georectification and varying spatial resolution were required to be addressed. A methodology was formulated to convert all available sensor data to a uniform spatial resolution for meaningful comparison. The river planform data were extracted manually which was a time-intensive process, but as the area is a low lying alluvial plain automatic extraction of wetted area and non-wetted area of the river resulted in classification errors due to mixed pixels and similarities in the reflectance of the sand in the point bars and sand splays in the riparian zone.

The Landsat archive was used to characterise the dynamic behaviour of the Ganga-Padma system and sequential data revealed a cyclic process (morphological evolution) occurring within the system. This behaviour was observed for the first time as very few studies have been carried out earlier using time-series data in the study area. The river exhibited a self-organising behaviour in which it periodically reaches a critical value of sinuosity at which point one or more chute cut-offs are triggered. It is notable that this periodically repeating pattern is fixed locally by hard points in the geology, and by the Farakka Barrage, such that it is likely that this pattern will persist, at least in the short-term. This information has increased understanding of the behaviour of the Ganga-Padma system in particular and mega-rivers more generally. It also has implications for local planners and decision-makers. Specifically, local concerns over the potential threat of lateral migration of the river Ganga and consequent erosion and loss of productive land are unlikely to be realised. Instead, a periodic repeating pattern in which the river is constrained to reworking old material has been demonstrated.

7.1.2 Chapter 4

Analysis of the river over a 38 year period, along with historical records and information from the literature representing earlier periods, suggests that the river has changed its planform periodically. Such changes can be placed in the context of non-linear dynamical theory and self-organising criticality (SOC) though non availability of long term data makes it difficult to have evidence of SOC. The periodical change can be better explained as threshold response of a complex geomorphic system. Although the data analysed up to 2010 show that the river is moving towards a straight course, especially in Reaches 3 and 4, it will meander again and erode its banks over the next few decades. It will also likely be influenced by the amount of discharge during the peak flow period in each year, although a lack of discharge data meant that the effect of inter-annual variation in discharge on morphodynamics could not be analysed here.

The meander evolution also follows the principle of bend theory of Ikeda *et al.*, 1981 based on bend sinuosity and bar pattern and relating it to observations made by Hooke (1975).

Natural hard points (e.g., the Barind formation) and artificial embankments influenced the migration of the river along one bank to a greater extent rather than the other. Moreover, the hard points and embankments along the river's course act as constraints to lateral migration such that the river is locked into a long-term periodic pattern of evolution in a dynamic equilibrium system. This has important implications for planners who may fear lateral migration and consequent loss of agricultural land. It means that the evolution of the river is constrained and largely predictable.

The Farakka barrage itself does not appear to be responsible for the system's dynamic behaviour, since the river already had a periodic dynamic behaviour as documented in the literature (Colebroke, 1801; Parua, 2009). Nevertheless, management of the barrage has had some local influence on river evolution. The closure of the left channel just downstream of the barrage location due to the release of water through some selected gates led to a scenario of upstream forcing in the planform evolution of meandering rivers. This may have led to increased erosion downstream of the barrage. Operational management of the barrage may need a critical review with a view to better management outcomes on the Ganga-Padma system.

7.1.3 Chapter 5

Analysis on the channel pattern of the River Ganga-Padma based on different empirical methods showed that the river is a laterally active meandering river with a tendency towards a multi-thread configuration or anabranching pattern (see the third channel pattern in Figure 2.1) at the end of the time-series. The river can be said to be in a transitional phase and this phase can be a part of the cycle. Effect of active tectonics on this transitional phase cannot be established due to lack of recent field data. The empirical methods also showed that the river channel pattern can be predicted based on some pattern independent variables like mean annual flood discharge (Q_{af}), median particle size (D_{50}) of the channel bed and valley slope. The other methods used for prediction of channel pattern (based on mobility number and Parker's stability criterion) also showed a similar channel pattern as the pattern independent empirical method.

The study showed that the conditions for chute cut-offs in the Ganga-Padma system are not due to bankfull flow velocity and the super elevation, but mainly due to lack of vegetation stabilisation on the Ganga-Padma floodplain. The floodplain is mainly covered by agricultural activity (based on field data) with total absence of stable vegetation like forest with tress having deep roots to hold the soil. Thus it can be said that the vegetation characteristics of the area lead to lack of stabilisation. The occurrence of the cut-off may be due to the inability of the river system to adjust further through gradual adjustment of sinuosity. Rather the river system aligns its channels by means of erosion and chute cut-offs to regain a low sinuosity value.

The response of the river system is to some extent predictable as it is a self-regulating system with a reset time period of around 35 years and as a result would enable better management of the river basin.

7.1.4 Chapter 6

According to historical literature it is an established fact that the main course of the Ganga-Padma system was through the present Ganga-Bhagirathi system and due to a major avulsion the course shifted from the older one to the present. Limited information exists about the exact cause of this change although the historical literature suggests that the avulsion is due to a sudden collapse of the bank triggered by high discharge. Some literature suggests tectonic causes for this change as was observed in other major rivers of the region (e.g. River Teesta and River Brahmaputra) (Morgan and Mcintire, 1959; Parua, 2009).

The one-dimensional model for a bifurcating channel formulated here and tested on the Ganga-Bhagirathi system in India, suggests that subsidence (tectonics) has a major role to play in the avulsion of the system to the present Ganga-Padma system within a short time period (< three centuries), in combination with gradient advantage and a migrating upstream meander bend. The avulsion duration can be considered moderate considering the size of the river both in terms of discharge and the sediment load it carries. The model initially considered the effect of meanders just above the bifurcation and adaptation of channel width to discharge. The model showed that migrating meanders at bifurcations and gradient advantage alone cannot lead to an avulsion within a short period of time from one channel to another in larger rivers, especially in areas where gradient is very low (deltaic regions). Avulsion in larger rivers is only possible over a short time period if active tectonics / neotectonics lead to subsidence of the smaller branch which may then lead to an avulsion from the active branch to a smaller branch.

The modelling also suggested that for large rivers a stable bifurcation may persist rather than the older channel dying down due to aggradation and the newer channel accommodating the total discharge. This is due an efficient energy partitioning where a river, without adjusting channel slope increases the number of the channels and decreases the width (Huang and Nanson, 2007). This mechanism enables an unstable river to gain stability leading to an anabranching channel pattern. The model also showed that even after the diversion of the major flow to the new branch, the older branch can be morphologically active and the reason being a large backwater effect as well as the mobility of sediments forming an anabranching pattern.

It was also concluded that, in large river systems the sediments coming to the older branch cannot fill up the residual channel due to flood time discharge coming from the upstream direction at an annual interval. Thus, the Ganga-Bhagirathi channel (the residual channel) is still morphologically active leading to stabilization of the bifurcation with an asymmetrical flow and sediment division.

7.2 Limitation of the research

The first and foremost limitation of the research was the gap in the available time-series of satellite sensor data especially the 13 years gap from 1975 to 1988. Generalisation of the dynamic behaviour of the river had to be accepted in interpreting the meander evolution. Some further insights would have been possible if the data gaps could have been filled up.

To understand morphological evolution of a large river system, the primary requirement is availability of detailed discharge data, sediment regimes, bed material size, channel geometry and rainfall data in the catchment of the river under consideration. As the studied reach of the Ganga-Padma system is trans-boundary, so detailed hydrological and morphological data of the river were restricted and, thus, unavailable. The restricted data availability had an effect on the outcomes of the interpretation of the morphological evolution of the system as well as the explanation of the criticality of the meander evolution, cut-off occurrences and conditions for avulsion.

In the modelling approach limitations existed in the initial and boundary conditions that were considered for the model runs as well as with the physics involved in the 1D model. As discussed in the previous paragraph, data availability was limited so the initial and boundary conditions of the model were generalized. Moreover, as the modelling was carried out for an event in the historical past, so information on the conditions prevailing during that time were unavailable and as a result assumptions were made based on present conditions of the river system. Information on bar dynamics was also unavailable, so 2D modelling could not be carried out and as a result there was a reduction in the level of channel closure affecting the final asymmetry of the bifurcation. Past details of bar configuration and the location of perturbations were also unknown which restricted the representation of the avulsion process in a 2D model. The model, thus, portrayed a very simplified process of width adjustment and meandering to model bifurcation and avulsion.

7.3 Scope for future research

The present research showed that the planform dynamics of a mega-river like the Ganga-Padma system can be studied based on time-series satellite sensor data. The morphological changes can be interpreted from various river metrics extracted from the satellite sensor data supported by limited hydrological information from existing literature and other sources. A simple modelling approach with limited data can also throw some light on the morphological changes that have occurred in the system.

Based on the findings, the present research has enormous scope for further investigation. In future, this research can be carried forward in the following directions:

7.3.1 Detailed morphological interpretation of the dynamics of the system (Process Modelling)

Availability of detailed discharge data, sediment regimes, bed material size, channel geometry and rainfall data would enable greater understanding of the morphological evolution of the Ganga-Padma system and can be compared and validated with existing meander models which have been developed (Bagnold, 1960; Howard, 1992). These models have been validated in temperate rivers by Hickin and Nanson (1975, 1984) as explained in Chapter 5. There have been limited studies on tropical rivers where geomorphological characteristics have been studied (Speight, 1965; Salo et al., 1986; Rutherford and Bishop, 1996; Gilvear *et al.*, 2000; Meshkova and Carling, 2011), thus, providing an enhanced scope for further investigation and testing of these models.

Detailed hydrological data of the study area along with availability of satellite sensor data at annual intervals would enable interpretation of the morphological changes in the river using a more robust methodology. This will enable greater understanding of the criticality in the meander behaviour, the threshold of cut-off occurrences and the condition of avulsion in the system at the local scale in large river systems of tropical regions.

Established 2D and 3D models can also be tested with detailed datasets and these will enable interpretation of the behaviour of the Ganga-Padma mega-river both in the past and the present. This will facilitate better forecasting of the morphological changes that may take place in the system and their periodicity as has been observed in the present study.

Quaternary geological investigations in the Ganga-floodplain would also enable to create a longer record of fluvial dynamics of the system though extensive field work (coring and carbon dating). As the river is transboundary, extensive international collaboration between scientific communities needs to be developed to carry out such investigative studies.

Scope also exists for research on the effect of climate change on the morphodynamics of the Ganga. Studies on effect of sea level rise have shown that 11% of Bangladesh will be inundated in the next century (Mohal *et al.,* 2006) leading to salinity intrusion, storm surge and drainage congestion. The effect of these phenomenon on the morphodynamics of the Ganga-Padma system will also be interesting to investigate.

7.3.2 Forecasting the dynamics of the system for decision support and planning (Geostatistical modelling)

Forecasting an event is carried out to reduce the uncertainty of the future. Forecasting generally diminishes the uncertainty and does not eliminate it. Predictive models have been a great success in principal hydrological variants like precipitation, temperature and runoff with advances in the knowledge base, but for events like natural hazards the predictive models have not been very successful so far. Predicting fluvial systems especially alluvial rivers is more challenging as the freely migrating systems exhibit strikingly complex planform as well as variation in planimetric dimension from one pattern to another (Furbish, 1991) e.g. as seen in figure 2.1 laterally active meandering river or a braided river can both give rise to wandering pattens. Deterministic methods are usually unsuitable in predicting the exact nature and location of channel migration and the resulting erosion. Thus, an alternative method is required to provide an enhanced predicting capability. It needs to predict the land pixels which are likely to be eroded and converted to water pixels. Probabilistic analysis may provide a tool to overcome this problem. A number of studies has been carried out to predict thresholds of channel pattern and their instability (Bledsoe and Watson, 2001; Young *et al.*, 2001), to predict channel morphology using simple regression based on factors like valley slope, annual discharge and median grain size (Schweizer *et al.*, under publication), to perform spatial autoregressive modelling of meander evolution(Furbish, 1991), and to estimate lateral migration rate utilizing multiple stepwise regression analysis to find a relation between rates of movement and flow parameters (Richard, 2001).A limited number of studies have been carried out on forecasting future planform location of a channel. Some prominent studies have been carried out on spatial assessment of channel instability using a probabilistic approach (Graf, 1984) as well as mapping the probability of river bank erosion in a GIS framework (Winterbottom and Gilvear, 2000).The aspect which needs attention in terms of the present research is the simulation of flow so that a realistic channel pattern for the future can be generated. Several studies have been carried out using stochastic methods for aquifer characterisation (de Marsily *et al.*, 2005; de Vries *et al.*, 2008; Mariethoz, 2009).

Variogram-based geostatistics is unable to produce accurate models of fluid flow as it is unable to capture mathematically the complexity of curvilinear features such as channels and cross beddings. Thus, to reproduce a curvilinear feature multiple point correlations or multiple point geostatistics (MPG) would be required. Multiple point geostatistics relies on the concept of training images. The training images contain multiple point information so expected patterns can be observed even before carrying out any geostatistical simulation (Journel and Zhang, 2006; Mariethoz, 2009).The training image construction is bounded by the principles of stationarity and ergodicity.

Simulating a pattern based on a training image requires a geostatistical algorithm which will generate a pattern from the training image taking into consideration the constraints of the real world scenario. This can be achieved by the *snesim* algorithm or the single normal equation simulation (Strebelle, 2000, 2001).The idea behind the algorithm is that each grid cell property is simulated along a random path and the simulation of future cells is restricted by the cells simulated earlier in the process as well as field data. Spatial statistics are retrieved from each training image and stored in a frequency tree (de Vries *et al.*, 2008). The algorithm allows defining training images at multiple scales. The large scale training images take care of large scale variability of the channel while the smaller scale training images take care of local channel features.

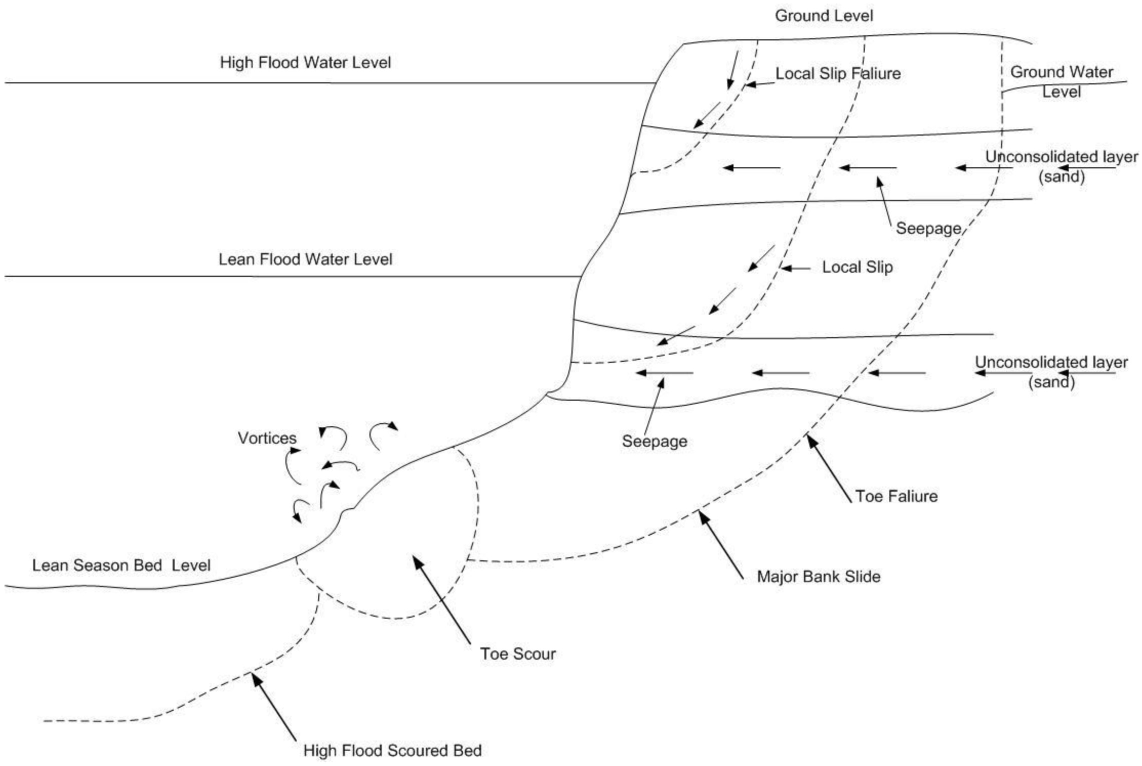
As natural systems generally lack stationarity, MPG has been extended to non-stationary distributions of features. The method divides the training image into different areas. The statistics of each area are stored in a frequency tree and several training images are used to obtain representative statistics of each area. During the simulation process the probability distribution of the feature (facies in case of reservoir study) is calculated by assigning a weight to the probabilities from the frequency tree. By doing so the computational constraint of storing and processing a lot of images generated by stochastic object based simulation is taken care of (de Vries *et al.*, 2008).

Thus geostatistical modelling using MPG approach is a promising technique to forecast the planform dynamics of the Ganga-Padma system based on past locations of the planform as derived from the time series satellite sensor data. The forecasted planform dynamics of the river system can be coupled with risk maps of the region to produce vulnerability maps which can lead to development of a decision support system for the benefit of planners and decision makers towards better management of the river system and formulate a framework for disaster preparedness and mitigation planning.

The author wishes to conclude the thesis by saying that understanding morphological evolution of a mega river like the Ganga –Padma system incorporates a lot of issues besides the planform change by the process of meander migration and transition of channel pattern. The above research is a starting point for a more detailed study. The research generates sufficient scope for future development considering the various limitations of data availability and restricted scope of this work.

8 Appendix

8.1 Schematic sketch of the process of bank erosion along the Ganga-Padma river system



8.2 Gauging station – Data Summary

Station	**Farakka**
River	**Ganga**
Country	**India**
Observation Period:	**1949 - 1973**
Latitude (dec deg):	**24.83 N**
Longitude (dec deg):	**87.92 E**
Annual Discharge: (m3/s):	**12105.4**
Height above MSL	**21.9 m**

8.3 Monthly average discharge data of Ganga-Padma system at Farakka from 1949-1973 in m3/sec (GRDC, Globenz, Germany)

Year / Month	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959
01	3249.00	3238.00	2919.00	2309.00	2304.00	2798.00	2807.00	3460.00	4224.00	2449.00	2978.00
02	3058.00	2892.00	2589.00	1685.00	1946.00	2410.00	2668.00	2829.00	3508.00	2154.00	3062.00
03	2516.00	2365.00	2091.00	1411.00	1564.00	2607.00	2008.00	2235.00	2641.00	1849.00	2342.00
04	2105.00	2039.00	1850.00	1294.00	1228.00	1985.00	1499.00	1937.00	2176.00	1652.00	1866.00
05	2981.00	1977.00	1957.00	1627.00	1359.00	1937.00	1705.00	2807.00	1922.00	1954.00	1864.00
06	5883.00	6665.00	4491.00	3936.00	2942.00	5696.00	3891.00	10199.00	2484.00	2423.00	3980.00
07	17810.00	26673.00	21305.00	24815.00	24569.00	23134.00	33922.00	23482.00	17856.00	14350.00	14250.00
08	43997.00	51340.00	31333.00	40802.00	49411.00	62694.00	61363.00	47602.00	39765.00	53410.00	43717.00
09	40283.00	36951.00	30134.00	33333.00	36982.00	41424.00	52121.00	43415.00	37021.00	39848.00	32093.00
10	18745.00	11591.00	10768.00	11953.00	15014.00	20759.00	29764.00	27375.00	9705.00	26097.00	21400.00
11	9773.00	5457.00	4580.00	5820.00	5966.00	6991.00	9754.00	10719.00	4473.00	7733.00	7424.00
12	4480.00	3659.00	3268.00	3761.00	3717.00	3887.00	5106.00	5399.00	3042.00	4224.00	3924.00

Contd….

Year / Month	1960	1965	1966	1967	1968	1969	1970	1971	1972	1973
01	2667.00	3087.00	2726.00	2394.00	3051.00	2265.00	2564.00	2408.00	3181.00	2289.00
02	2119.00	2431.00	2341.00	2083.00	2360.00	1773.00	2145.00	1962.00	2697.00	2086.00
03	1962.00	2124.00	1972.00	1509.00	1843.00	1491.00	1999.00	1782.00	2387.00	1605.00
04	1693.00	2122.00	1403.00	1494.00	1608.00	1472.00	1754.00	1969.00	2032.00	1594.00
05	1535.00	2915.00	1429.00	1636.00	1576.00	1710.00	1950.00	2594.00	2032.00	2207.00
06	3188.00	3492.00	2762.00	3232.00	4232.00	4112.00	4948.00	1181.00	3834.00	7032.00
07	19448.00	12090.00	14690.00	18950.00	23437.00	17004.00	22358.00	33815.00	14047.00	18657.00
08	40943.00	27790.00	35570.00	34340.00	37104.00	46262.00	34186.00	65072.00	19042.00	37886.00
09	39015.00	27810.00	26270.00	45930.00	19331.00	35098.00	38992.00	49568.00	24693.00	44573.00
10	23856.00	10160.00	7131.00	15280.00	15874.00	17855.00	16894.00	17490.00	10686.00	31053.00
11	7917.00	6153.00	3831.00	4990.00	5483.00	6636.00	5668.00	9401.00	4786.00	10015.00
12	4468.00	3591.00	3070.00	3863.00	3363.00	3977.00	3463.00	5365.00	3371.00	4677.00

8.4 Calculation of potential specific stream power of Ganga-Padma system

Location	Q_{af}	W_r	h_a	D_{50}	S	S_V	P	ω_{pv}
Farakka, West Bengal, India	59960.00	2200	20	0.00013	0.00006	0.00005	1.21	13.26
Hardinge Bridge, Rajsahi, Bangladesh	54966.00	1600	15	0.00014	0.00004	0.00003	1.37	9.84

Where Q_{af} = Mean annual flood (m^3/sec)
D_{50} = median grain size of river bed (mm)
W_r = reference width of channel (m)
h_a = actual measured water depth (m)
S_V= valley slope cm/cm
P = sinuosity; S = channel gradient cm/cm
ω_{pv} = potential specific stream power

8.5 Aggradation in River Ganga upstream of Farakka Barrage

Year	Approx. max. discharge (10^3 m^3/s)	Approx. max. water level (m)	Increase in height (m) (Original pond level : 21.95 m)
1971	-	0	0
1979	42.80	22.90	0.95
1981	57.00	23.7	1.75
1983	60.50	24.90	2.95
1985	57.30	24.30	2.35
1988	68.00	25.10	3.15
1991	69.70	25.30	3.35

8.6 Calculation of Mobility number for Reach 1

Year	Ref. date	Width (*w*)	v_c	T_c	T_a	Mobility No. (*M*)
72-75	1975	4044.00	1043.80	3.874305	35	9.03
75-88	1988	3540.40	1212.80	2.919195	35	11.99
88-92	1992	3600.80	540.40	6.663212	35	5.25
92-94	1994	4192.80	311.00	13.48167	35	2.60
94-98	1998	4254.00	909.60	4.676781	35	7.48
98-99	1999	4558.00	627.60	7.262588	35	4.82
99-00	2000	4824.60	291.80	16.53393	35	2.12
00-01	2001	5392.00	591.00	9.123519	35	3.84
01-02	2002	4919.60	276.33	17.80335	35	1.97
02-03	2003	4716.40	432.33	10.90926	35	3.21
03-04	2004	4882.00	194.00	25.16495	35	1.39
04-05	2005	4814.20	232.33	20.72139	35	1.69
05-06	2006	4827.20	195.67	24.67011	35	1.42
06-07	2007	4942.60	285.67	17.30178	35	2.02
07-08	2008	5691.20	236.00	24.11525	35	1.45
08-09	2009	5755.80	129.80	44.34361	35	0.79
09-10	2010	5811.80	208.20	27.91451	35	1.25

8.7 Calculation of Mobility number for Reach 2

Year	Ref. date	Width (*w*)	v_c	T_c	T_a	Mobility No. (*M*)
72-75	1975	6006.20	767.25	7.83	35.00	4.47
75-88	1988	3815.00	944.25	4.04	35.00	8.66
88-92	1992	4475.20	1158.00	3.86	35.00	9.06
92-94	1994	3253.40	701.25	4.64	35.00	7.54
94-98	1998	3930.60	796.50	4.93	35.00	7.09
98-99	1999	3937.40	846.50	4.65	35.00	7.52
99-00	2000	3988.80	666.25	5.99	35.00	5.85
00-01	2001	4140.00	529.25	7.82	35.00	4.47
00-02	2002	3908.60	313.25	12.48	35.00	2.81
02-03	2003	3938.80	489.75	8.04	35.00	4.35
03-04	2004	3780.80	432.25	8.75	35.00	4.00
04-05	2005	3873.00	337.00	11.49	35.00	3.05
05-06	2006	3852.20	231.75	16.62	35.00	2.11
06-07	2007	3927.80	291.00	13.50	35.00	2.59
07-08	2008	3872.60	235.20	16.47	35.00	2.13
08-09	2009	3863.80	165.60	23.33	35.00	1.50
09-10	2010	3963.00	222.00	17.85	35.00	1.96

8.8 Calculation of Mobility number for Reach 3

Year	Ref. date	Width (*w*)	v_c	T_c	T_a	Mobility No. (*M*)
72-75	1975	4363.60	1357.50	3.21	35.00	10.89
75-88	1988	4625.00	1528.75	3.03	35.00	11.57
88-92	1992	4349.00	726.75	5.98	35.00	5.85
92-94	1994	4373.80	596.25	7.34	35.00	4.77
94-98	1998	4542.40	661.25	6.87	35.00	5.10
98-99	1999	4504.00	431.00	10.45	35.00	3.35
99-00	2000	4732.60	265.50	17.83	35.00	1.96
00-01	2001	4969.20	290.00	17.14	35.00	2.04
00-02	2002	5058.60	260.00	19.46	35.00	1.80
02-03	2003	5004.60	482.50	10.37	35.00	3.37

Contd…

Year	Ref. date	Width (w)	v_c	T_c	T_a	Mobility No. (M)
03-04	2004	4953.80	80.00	61.92	35.00	0.57
04-05	2005	4975.80	223.00	22.31	35.00	1.57
05-06	2006	5089.80	208.75	24.38	35.00	1.44
06-07	2007	5084.80	533.25	9.54	35.00	3.67
07-08	2008	5012.60	171.00	29.31	35.00	1.19
08-09	2009	5051.60	412.00	12.26	35.00	2.85
09-10	2010	5047.40	157.40	32.07	35.00	1.09

8.9 Calculation of Mobility number for Reach 4

Year	Ref. date	Width (w)	v_c	T_c	T_a	Mobility No. (M)
72-75	1975	3710.00	758.75	4.89	35.00	7.16
75-88	1988	4840.00	1556.50	2.38	35.00	14.68
88-92	1992	5066.60	689.75	7.02	35.00	4.99
92-94	1994	5156.20	378.25	13.39	35.00	2.61
94-98	1998	5485.40	652.00	7.91	35.00	4.43
98-99	1999	5692.60	364.75	15.04	35.00	2.33
99-00	2000	5700.40	229.00	24.86	35.00	1.41
00-01	2001	5775.40	242.25	23.53	35.00	1.49
00-02	2002	5779.80	161.25	35.84	35.00	0.98
02-03	2003	5777.40	162.75	35.50	35.00	0.99
03-04	2004	5819.20	315.50	18.44	35.00	1.90
04-05	2005	5810.80	211.25	27.51	35.00	1.27
05-06	2006	5826.80	186.50	31.24	35.00	1.12
06-07	2007	5776.00	227.25	25.42	35.00	1.38
07-08	2008	5689.80	188.80	30.14	35.00	1.16
08-09	2009	5739.20	106.60	53.84	35.00	0.65
09-10	2010	5715.00	122.40	46.69	35.00	0.75

8.10 Calculation of Parker's criterion ($\mathcal{E}$) for Reach 1

Year	Slope (*S*)	*g*	Depth (*h*)	Width (*w*)	*w*^4	Q_{peak}	Q_{mean}	$\mathcal{E}_{peak}$	$\mathcal{E}_{mean}$
1972	0.00006	9.81	21.95	2889.75	69733439972856.9	53620.83	12105.40	0.14	0.95
1975	0.00006	9.81	21.95	4044.00	267451222692096.0	53620.83	12105.40	0.27	1.19
1988	0.00006	9.81	18.80	3540.40	157111989573642.0	53620.83	12105.40	0.19	0.84
1992	0.00006	9.81	18.60	3600.80	168110948973773.0	53620.83	12105.40	0.20	0.87
1994	0.00006	9.81	18.60	4192.80	309041346077721.0	53620.83	12105.40	0.27	1.18
1998	0.00006	9.81	18.50	4254.00	327483891338256.0	53620.83	12105.40	0.27	1.21
1999	0.00006	9.81	18.50	4558.00	431615749332496.0	53620.83	12105.40	0.31	1.39
2000	0.00006	9.81	18.50	4824.60	541807796313790.0	53620.83	12105.40	0.35	1.55
2001	0.00006	9.81	18.50	5392.00	845277938384896.0	53620.83	12105.40	0.44	1.94
2002	0.00006	9.81	18.50	4919.60	585759271416085.0	53620.83	12105.40	0.36	1.62
2003	0.00006	9.81	19.12	4716.40	494814619756487.0	53620.83	12105.40	0.34	1.51
2004	0.00006	9.81	19.12	4882.00	568055933237776.0	53620.83	12105.40	0.37	1.62
2005	0.00006	9.81	18.95	4814.20	537151155329388.0	53620.83	12105.40	0.35	1.57
2006	0.00006	9.81	18.95	4827.20	542976672003005.0	53620.83	12105.40	0.36	1.57
2007	0.00006	9.81	18.95	4942.60	596790442470964.0	53620.83	12105.40	0.37	1.65
2008	0.00006	9.81	18.95	5691.20	1049096387022040.0	53620.83	12105.40	0.49	2.19
2009	0.00006	9.81	18.95	5755.80	1097546121573710.0	53620.83	12105.40	0.51	2.24
2010	0.00006	9.81	18.95	5811.80	1140887028739330.0	53620.83	12105.40	0.52	2.28

8.11 Calculation of Parker's criterion ($\mathcal{E}$) for Reach 2

Year	Slope (*S*)	*g*	Depth (*h*)	Width (*w*)	w^4	Q_{peak}	Q_{mean}	$\mathcal{E}_{peak}$	$\mathcal{E}_{mean}$
1972	0.00005	9.81	16.00	6411.25	1689549220466020.00	54966.00	11000.00	0.47	2.34
1975	0.00005	9.81	16.00	6006.20	1301365108761350.00	54966.00	11000.00	0.41	2.05
1988	0.00005	9.81	16.00	3815.00	211825465350625.00	54966.00	11000.00	0.17	0.83
1992	0.00005	9.81	16.00	4475.20	401097353184418.00	54966.00	11000.00	0.23	1.14
1994	0.00005	9.81	16.00	3253.40	112034001876086.00	54966.00	11000.00	0.12	0.60
1998	0.00005	9.81	16.00	3930.60	238690645671180.00	54966.00	11000.00	0.18	0.88
1999	0.00005	9.81	16.00	3937.40	240346691286664.00	54966.00	11000.00	0.18	0.88
2000	0.00005	9.81	16.00	3988.80	253144819776887.00	54966.00	11000.00	0.18	0.91
2001	0.00005	9.81	16.00	4140.00	293765888160000.00	54966.00	11000.00	0.20	0.98
2002	0.00005	9.81	16.00	3908.60	233391433117544.00	54966.00	11000.00	0.17	0.87
2003	0.00005	9.81	16.00	3938.80	240688708733473.00	54966.00	11000.00	0.18	0.88
2004	0.00005	9.81	16.00	3780.80	204331261921598.00	54966.00	11000.00	0.16	0.81
2005	0.00005	9.81	16.00	3873.00	225003870016641.00	54966.00	11000.00	0.17	0.85
2006	0.00005	9.81	16.00	3852.20	220209123159403.00	54966.00	11000.00	0.17	0.85
2007	0.00005	9.81	16.00	3927.80	238011237940933.00	54966.00	11000.00	0.18	0.88
2008	0.00005	9.81	16.00	3872.60	224910931616386.00	54966.00	11000.00	0.17	0.85
2009	0.00005	9.81	16.00	3863.80	222873561239976.00	54966.00	11000.00	0.17	0.85
2010	0.00005	9.81	16.00	3963.00	246658615426161.00	54966.00	11000.00	0.18	0.89

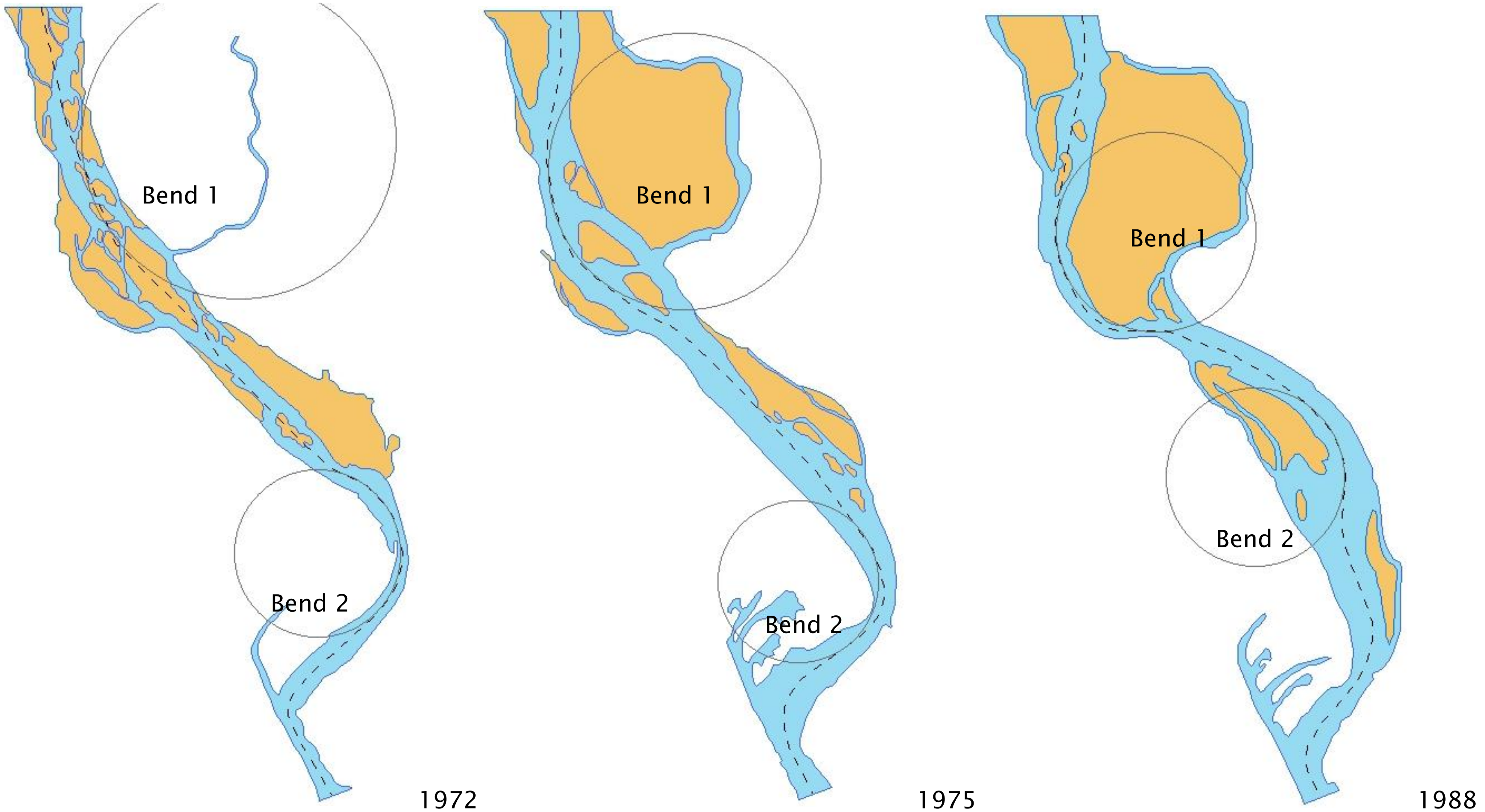
8.12 Calculation of Parker's criterion ($\mathcal{E}$) for Reach 3

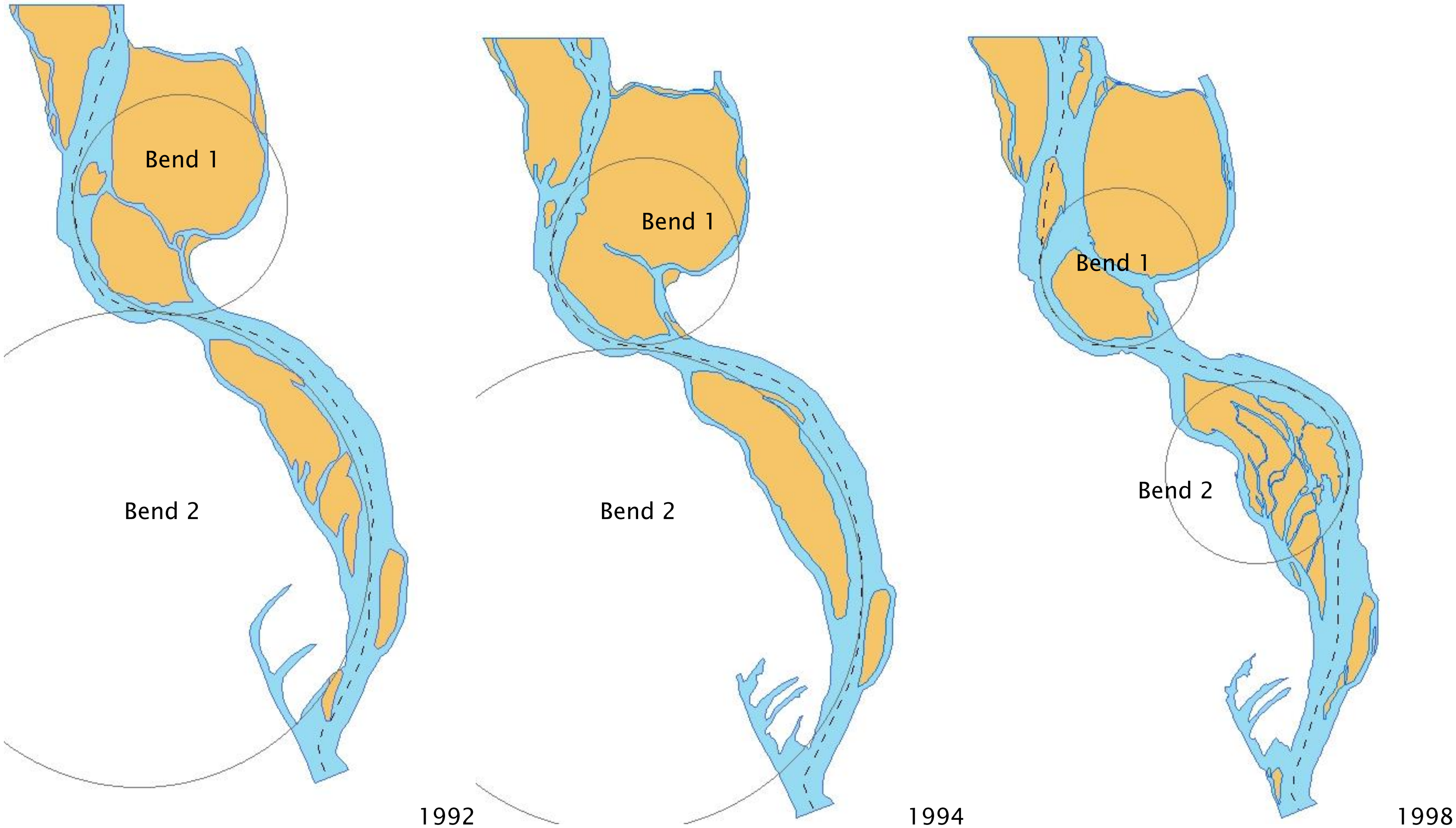
Year	Slope (*S*)	*g*	Depth (*h*)	Width (*w*)	*w*^4	Q_{peak}	Q_{mean}	$\mathcal{E}_{peak}$	$\mathcal{E}_{mean}$
1972	0.00005	9.81	16.00	5700.00	1055600100000000.00	54966.00	11000.00	0.37	1.85
1975	0.00005	9.81	16.00	4363.60	362559869886745.00	54966.00	11000.00	0.22	1.08
1988	0.00005	9.81	16.00	4625.00	457558837890625.00	54966.00	11000.00	0.24	1.22
1992	0.00005	9.81	16.00	4349.00	357731868267601.00	54966.00	11000.00	0.22	1.08
1994	0.00005	9.81	16.00	4373.80	365961737610387.00	54966.00	11000.00	0.22	1.09
1998	0.00005	9.81	16.00	4542.40	425737103122373.00	54966.00	11000.00	0.24	1.18
1999	0.00005	9.81	16.00	4504.00	411522445152256.00	54966.00	11000.00	0.23	1.16
2000	0.00005	9.81	16.00	4732.60	501648129884208.00	54966.00	11000.00	0.26	1.28
2001	0.00005	9.81	16.00	4969.20	609741712537678.00	54966.00	11000.00	0.28	1.41
2002	0.00005	9.81	16.00	5058.60	654819130393201.00	54966.00	11000.00	0.29	1.46
2003	0.00005	9.81	16.00	5004.60	627303175947168.00	54966.00	11000.00	0.29	1.43
2004	0.00005	9.81	16.00	4953.80	602218198333274.00	54966.00	11000.00	0.28	1.40
2005	0.00005	9.81	16.00	4975.80	612987562893214.00	54966.00	11000.00	0.28	1.41
2006	0.00005	9.81	16.00	5089.80	671124154044581.00	54966.00	11000.00	0.30	1.48
2007	0.00005	9.81	16.00	5084.80	668490903714896.00	54966.00	11000.00	0.29	1.47
2008	0.00005	9.81	16.00	5012.60	631323854032725.00	54966.00	11000.00	0.29	1.43
2009	0.00005	9.81	16.00	5051.60	651202138851146.00	54966.00	11000.00	0.29	1.45
2010	0.00005	9.81	16.00	5047.40	649039148976410.00	54966.00	11000.00	0.29	1.45

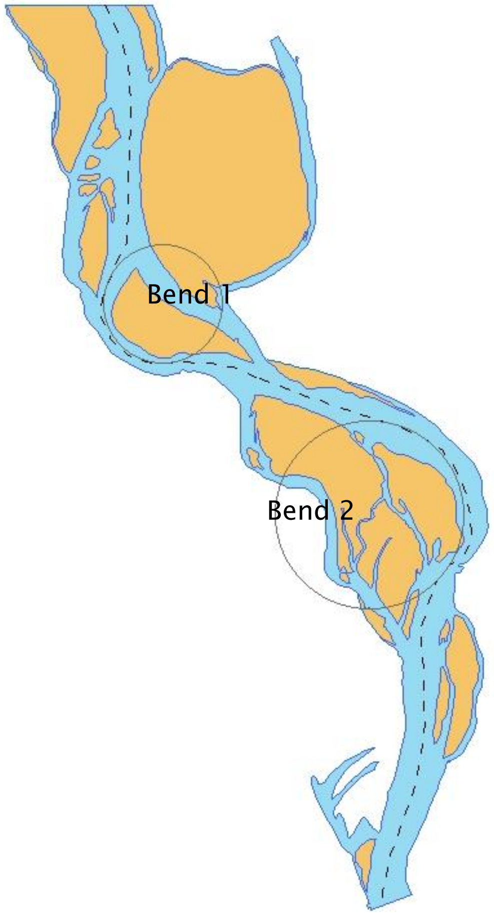
8.13 Calculation of Parker's criterion (ℰ)for Reach 4

Year	Slope (*S*)	*g*	Depth (*h*)	Width (*w*)	*w*^4	Q_{peak}	Q_{mean}	$\mathcal{E}_{peak}$	$\mathcal{E}_{mean}$
1972	0.00005	9.81	15.00	3247.00	111155038774081.00	54966.00	11000.00	0.12	0.58
1975	0.00005	9.81	15.00	3710.00	189450448810000.00	54966.00	11000.00	0.15	0.76
1988	0.00005	9.81	15.00	4840.00	548758735360000.00	54966.00	11000.00	0.26	1.29
1992	0.00005	9.81	15.00	5066.60	658971261840113.00	54966.00	11000.00	0.28	1.42
1994	0.00005	9.81	15.00	5156.20	706836582010434.00	54966.00	11000.00	0.29	1.47
1998	0.00005	9.81	15.00	5485.40	905384820118445.00	54966.00	11000.00	0.33	1.66
1999	0.00005	9.81	15.00	5692.60	1050129052878290.00	54966.00	11000.00	0.36	1.79
2000	0.00005	9.81	15.00	5700.40	1055896439991860.00	54966.00	11000.00	0.36	1.79
2001	0.00005	9.81	15.00	5775.40	1112572379683700.00	54966.00	11000.00	0.37	1.84
2002	0.00005	9.81	15.00	5779.80	1115966718136230.00	54966.00	11000.00	0.37	1.84
2003	0.00005	9.81	15.00	5777.40	1114114299457590.00	54966.00	11000.00	0.37	1.84
2004	0.00005	9.81	15.00	5819.20	1146708772240500.00	54966.00	11000.00	0.37	1.87
2005	0.00005	9.81	15.00	5810.80	1140102010256520.00	54966.00	11000.00	0.37	1.86
2006	0.00005	9.81	15.00	5826.80	1152711023050370.00	54966.00	11000.00	0.37	1.87
2007	0.00005	9.81	15.00	5776.00	1113034787454980.00	54966.00	11000.00	0.37	1.84
2008	0.00005	9.81	15.00	5689.80	1048064482972880.00	54966.00	11000.00	0.36	1.79
2009	0.00005	9.81	15.00	5739.20	1084939290750230.00	54966.00	11000.00	0.36	1.82
2010	0.00005	9.81	15.00	5715.00	1066755618500620.00	54966.00	11000.00	0.36	1.80

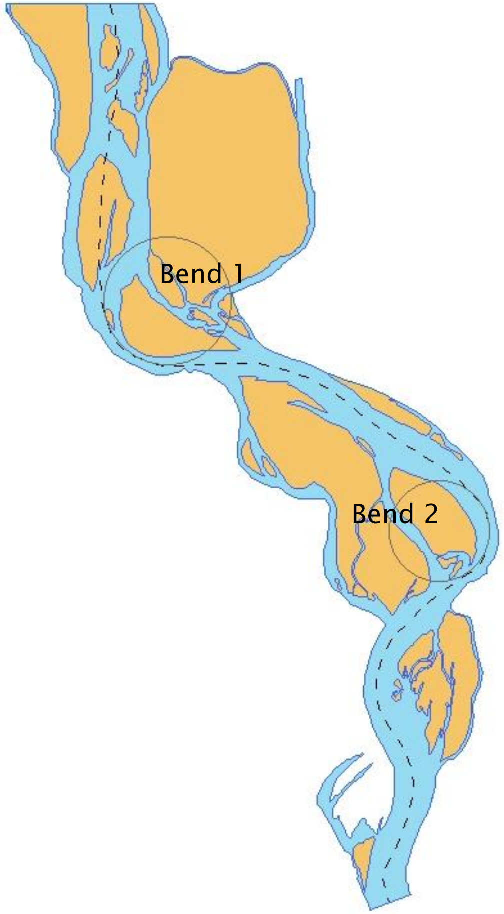
8.14 Radius of curvature calculation for Reach 1



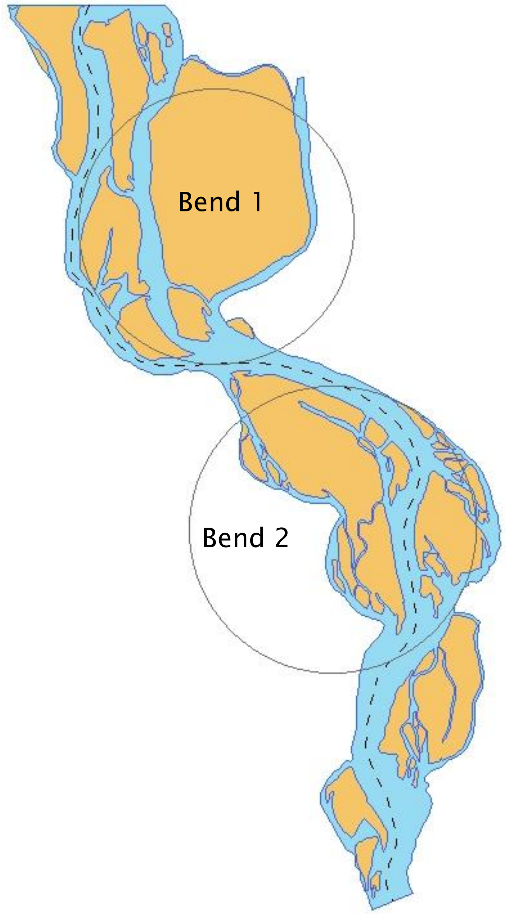

Bend 1
Bend 2
1992
Bend 1
Bend 2
1994
Bend 1
Bend 2
1998



2000

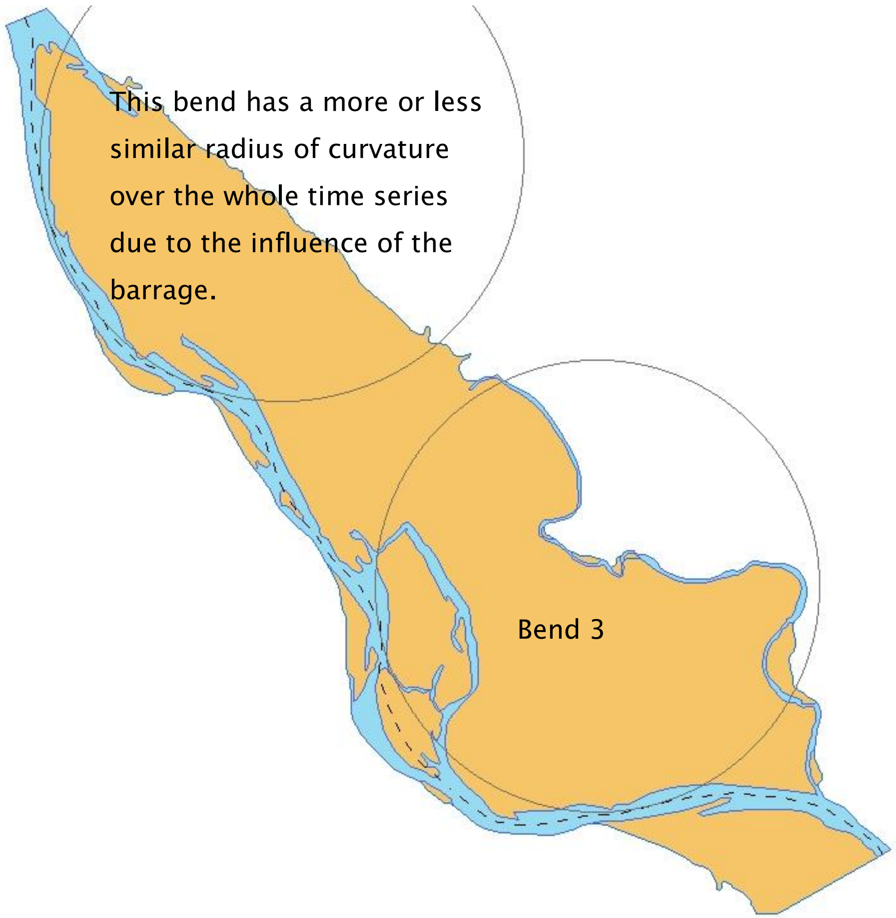


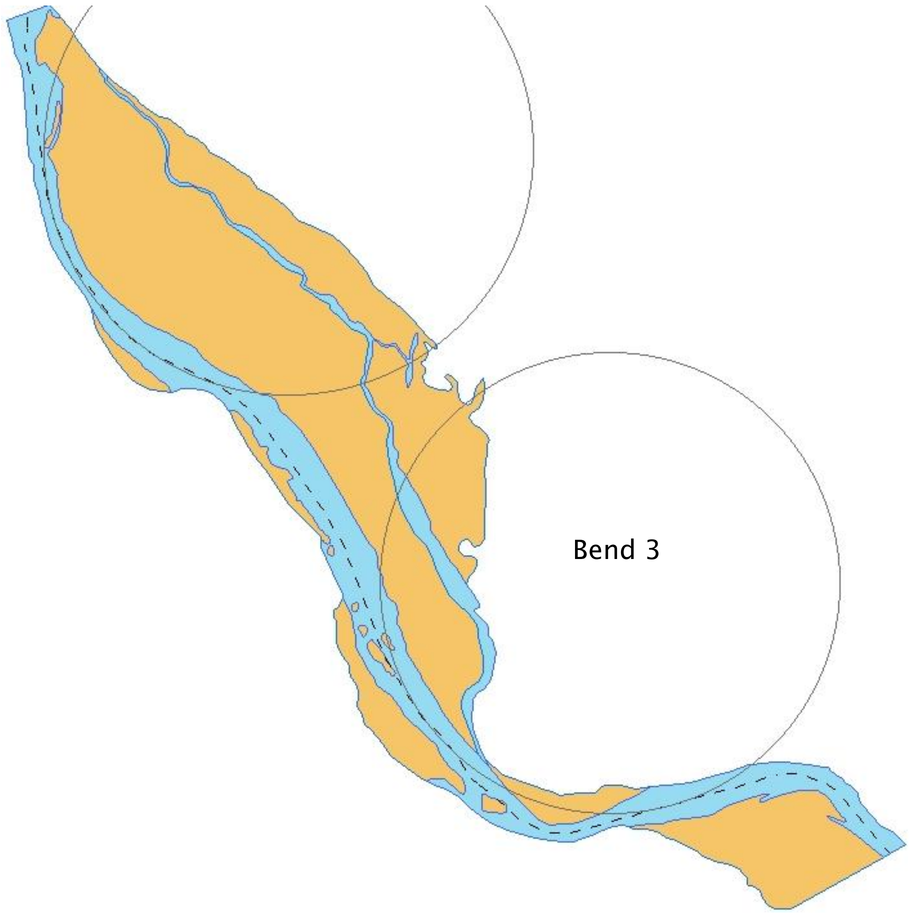
2005



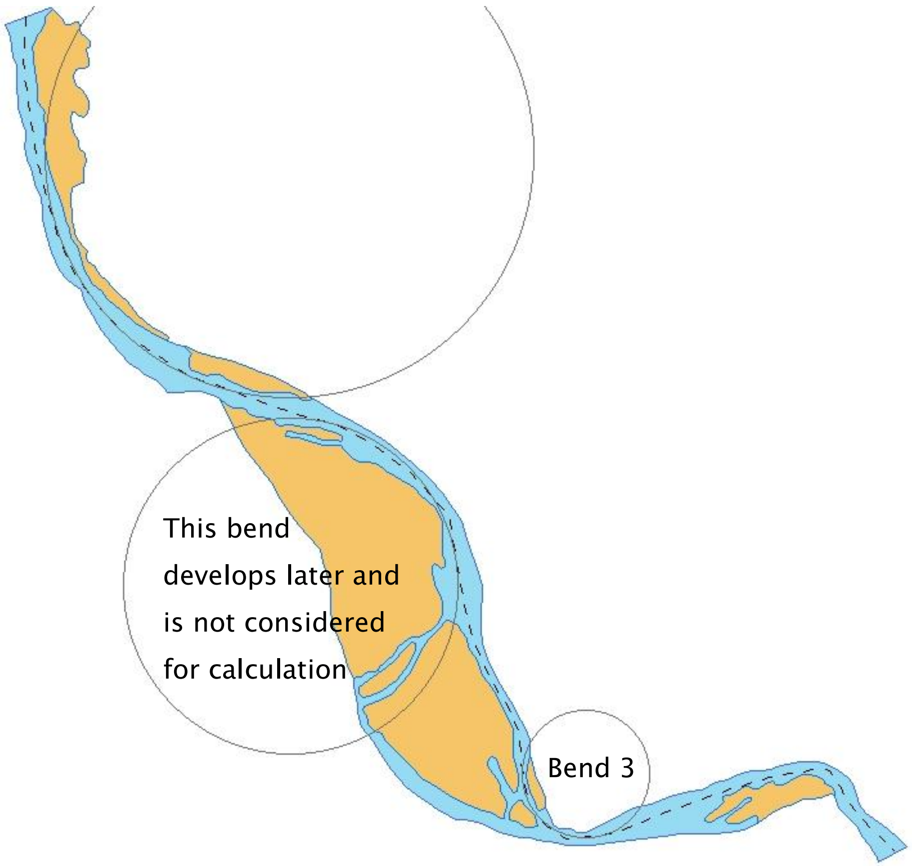
2010

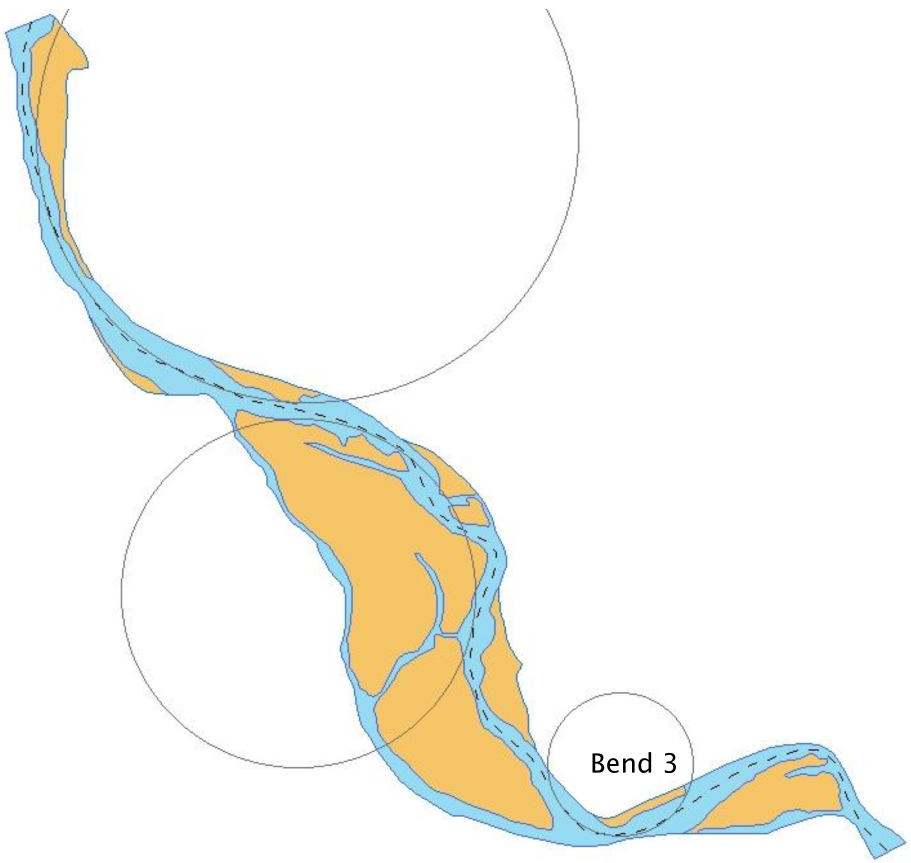
8.15 Radius of curvature calculation for Reach 2



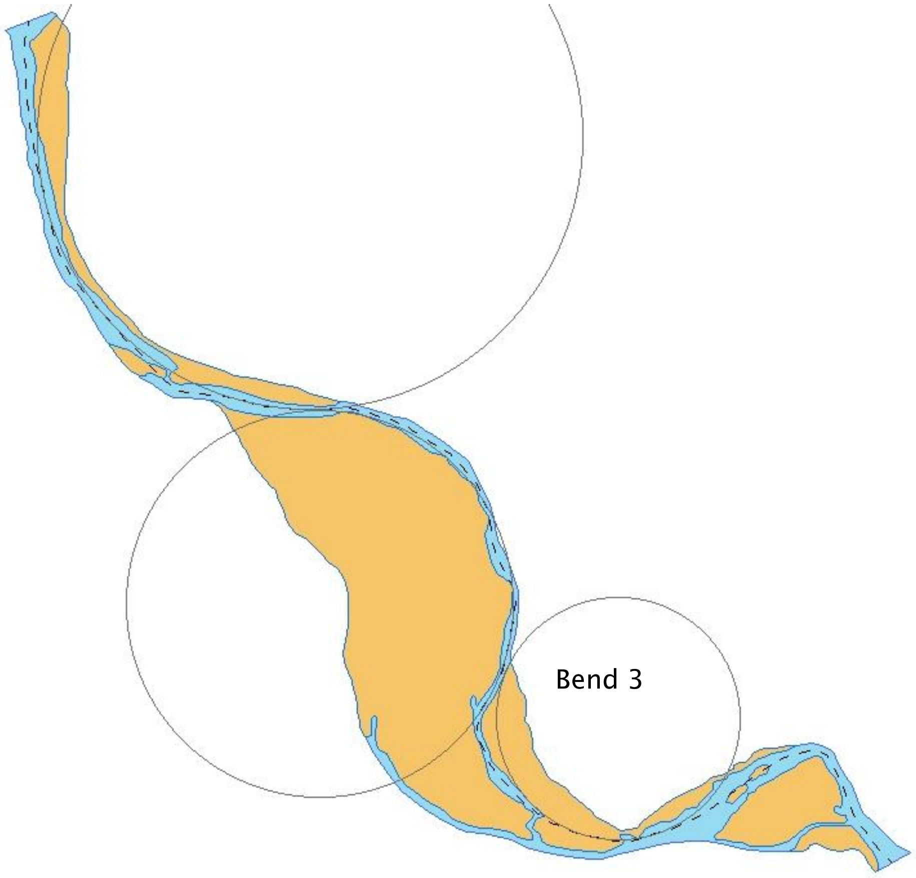


1972 1975

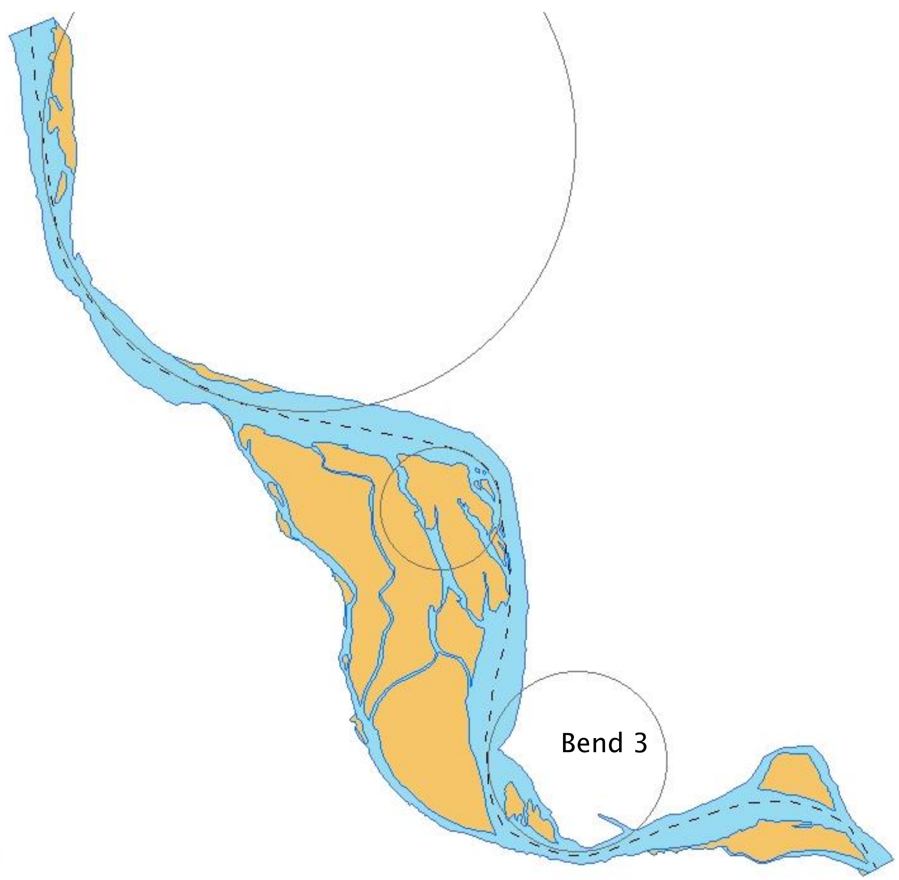




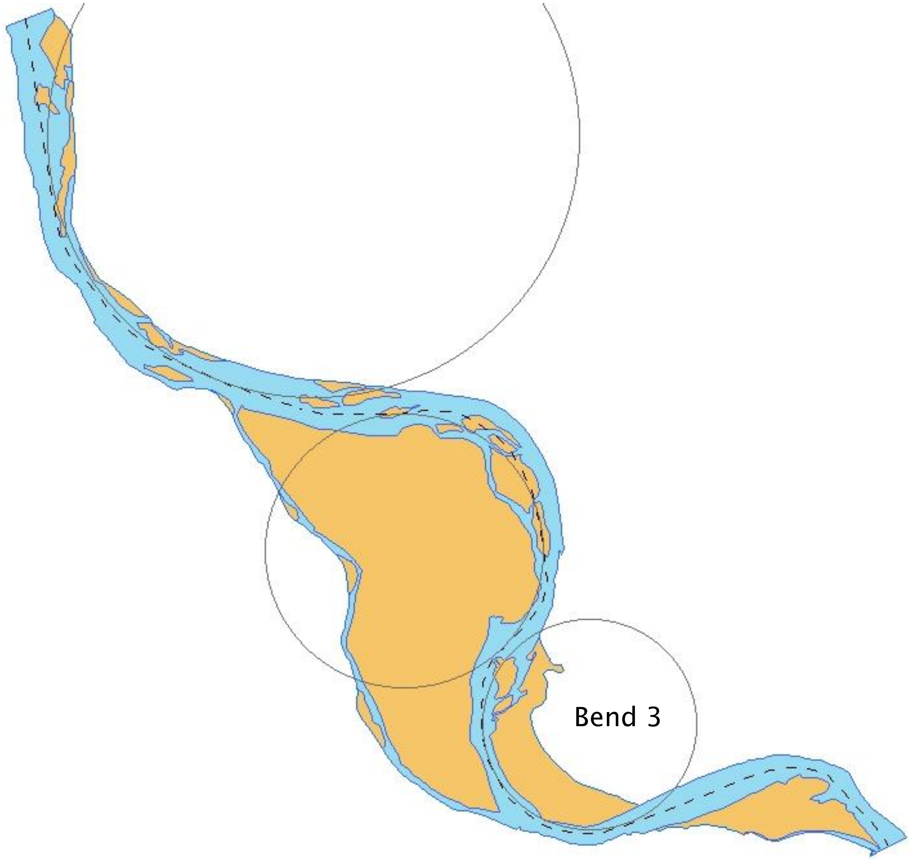
1988 1992



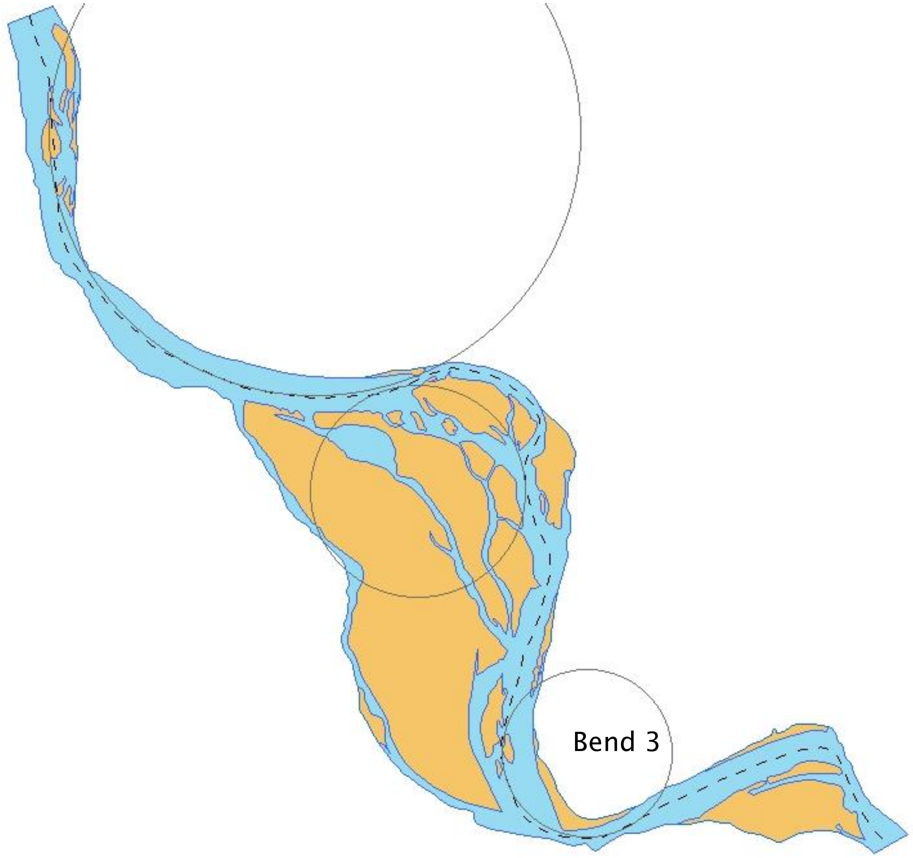
1994



1998



2000



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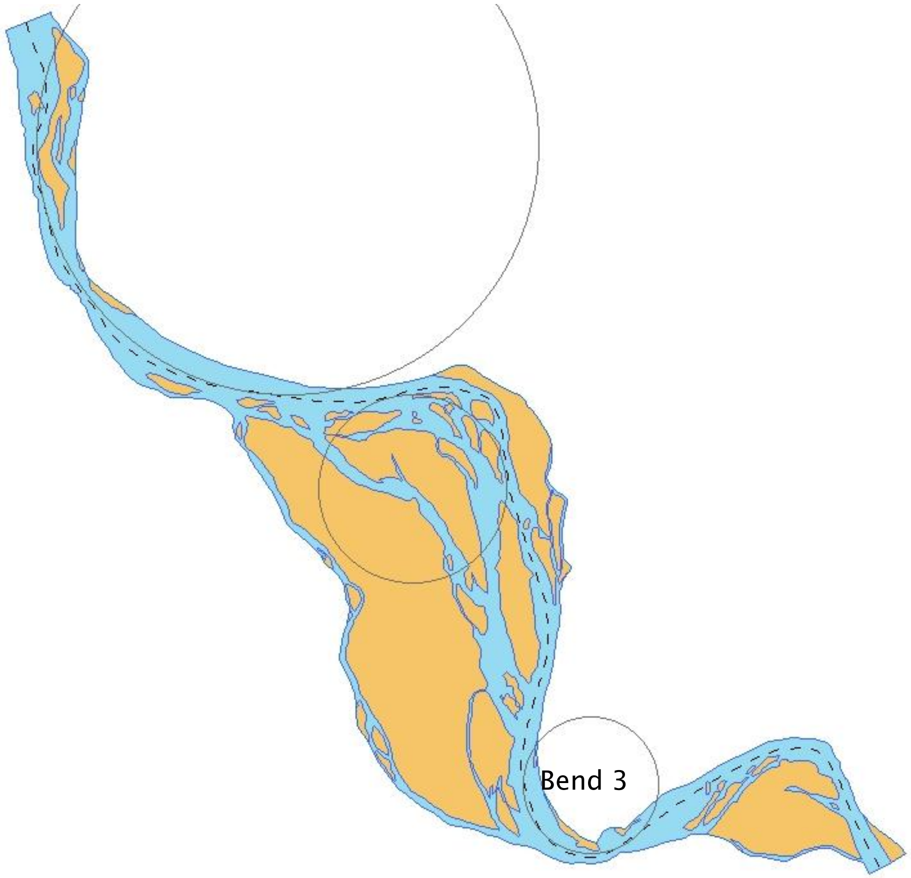
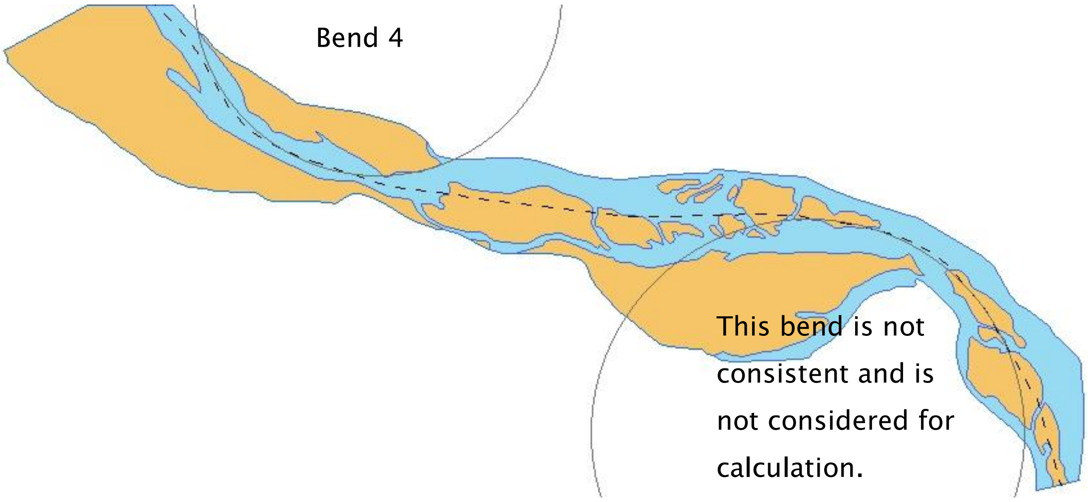


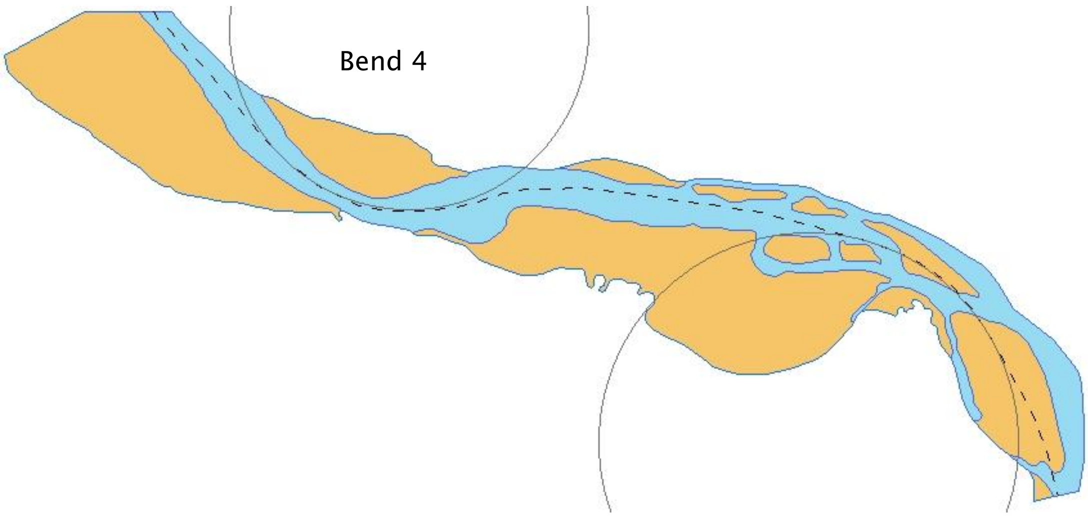
2010

8.16 Radius of curvature calculation for Reach 3

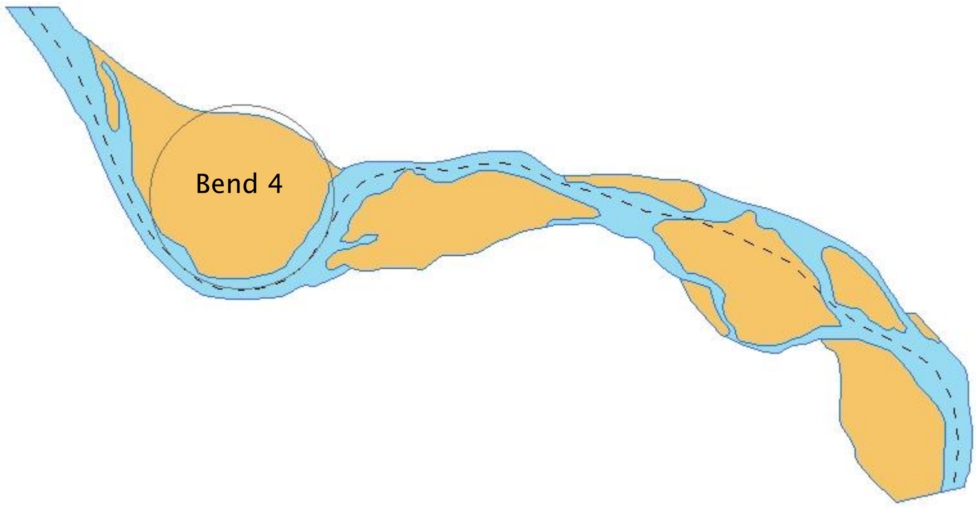
1972



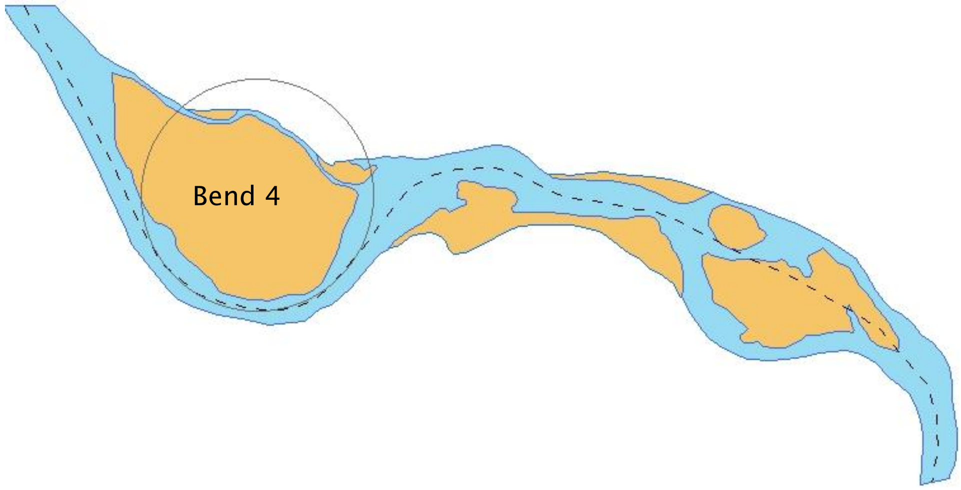
1975



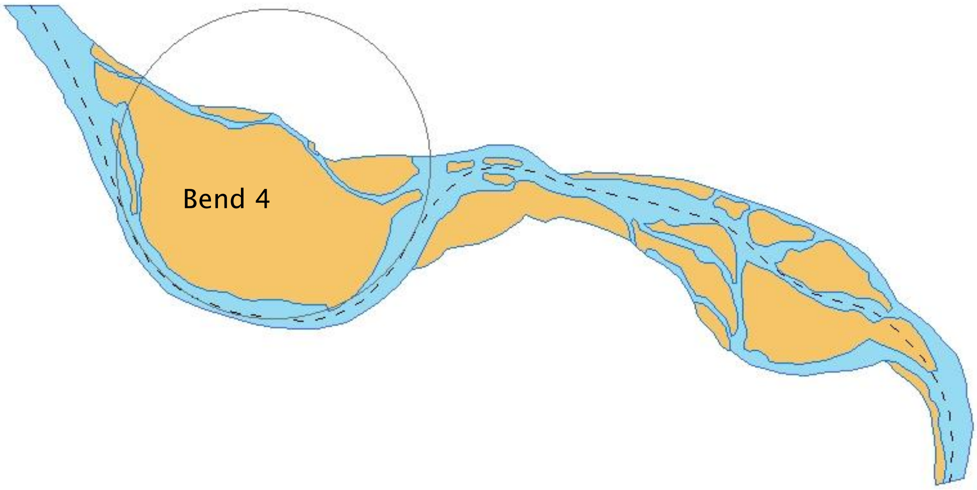
1988



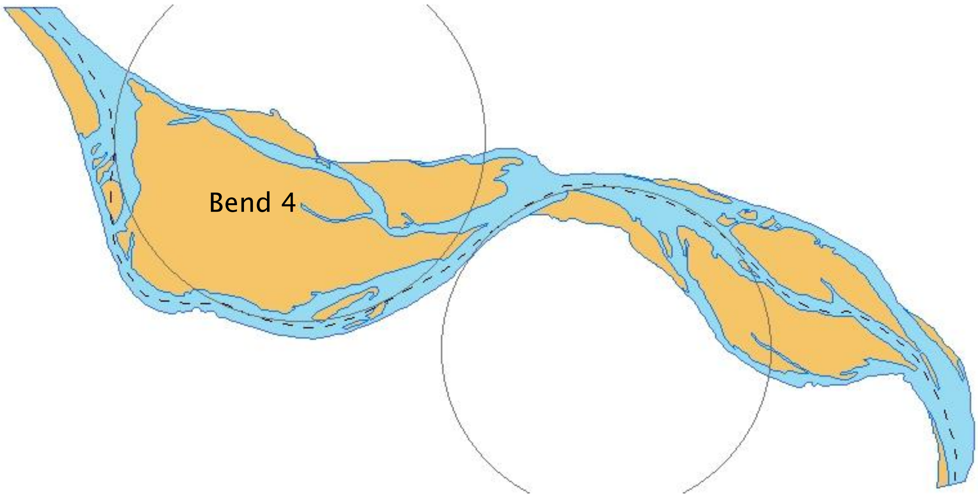
1992



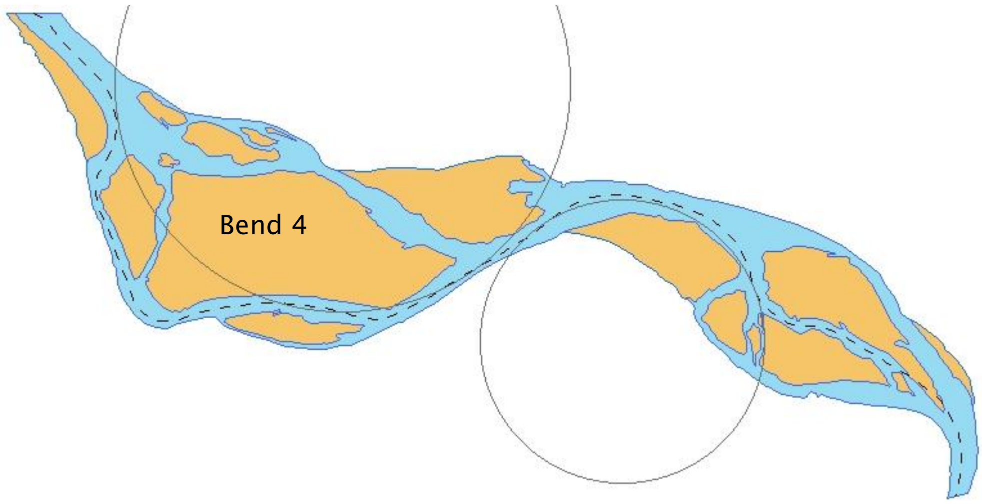
1994



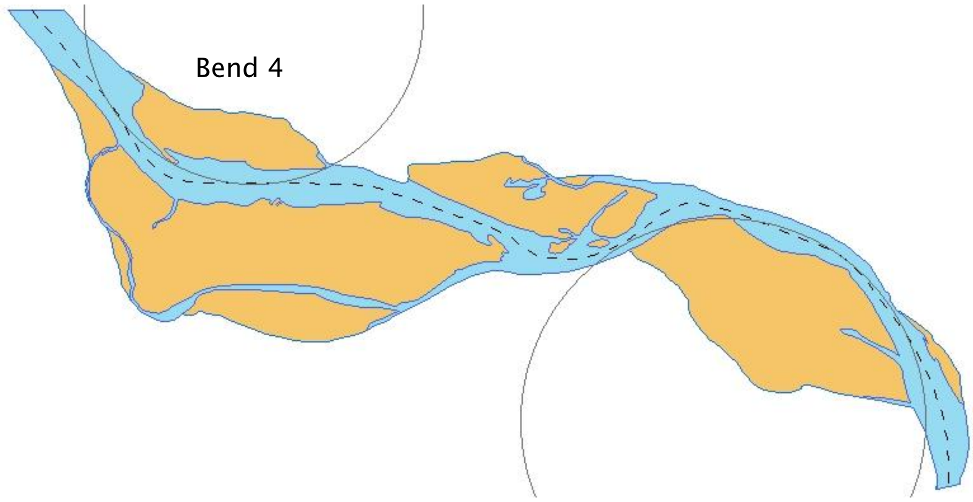
1998



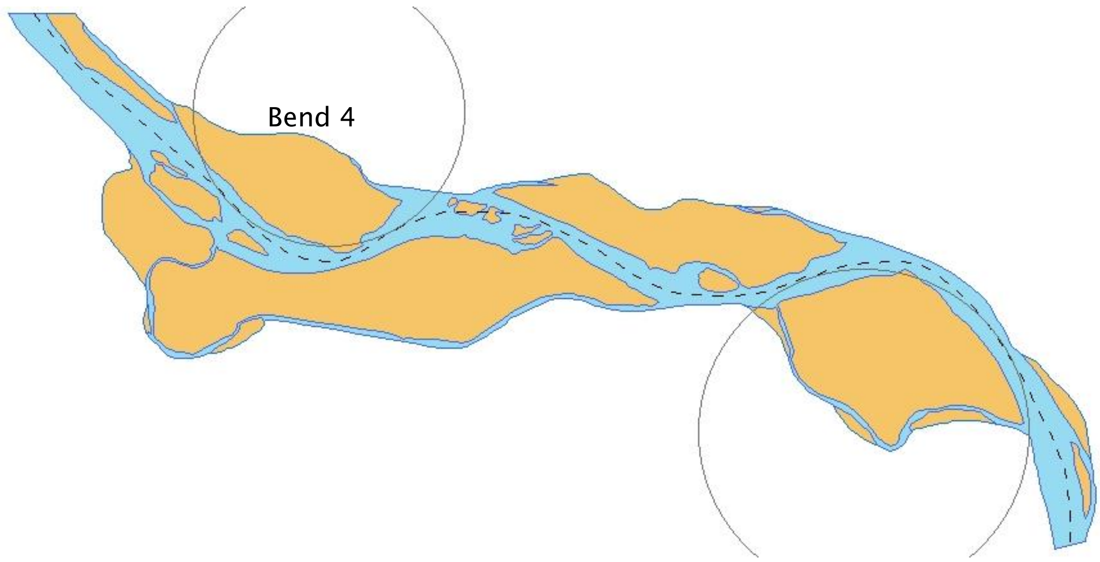
2000



2005

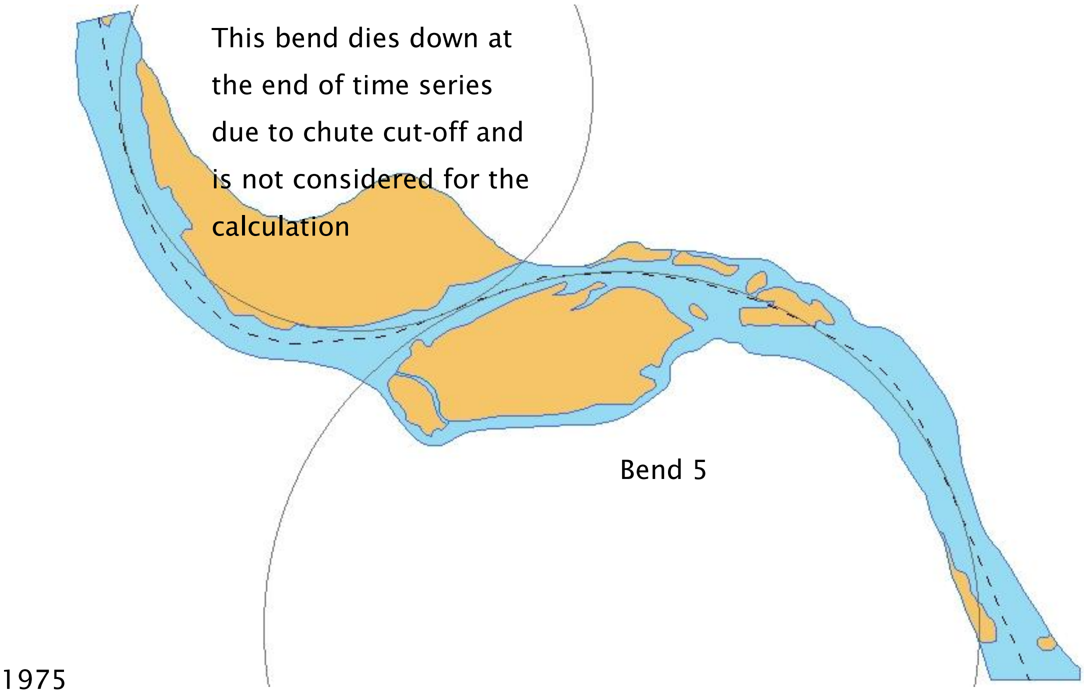


2010

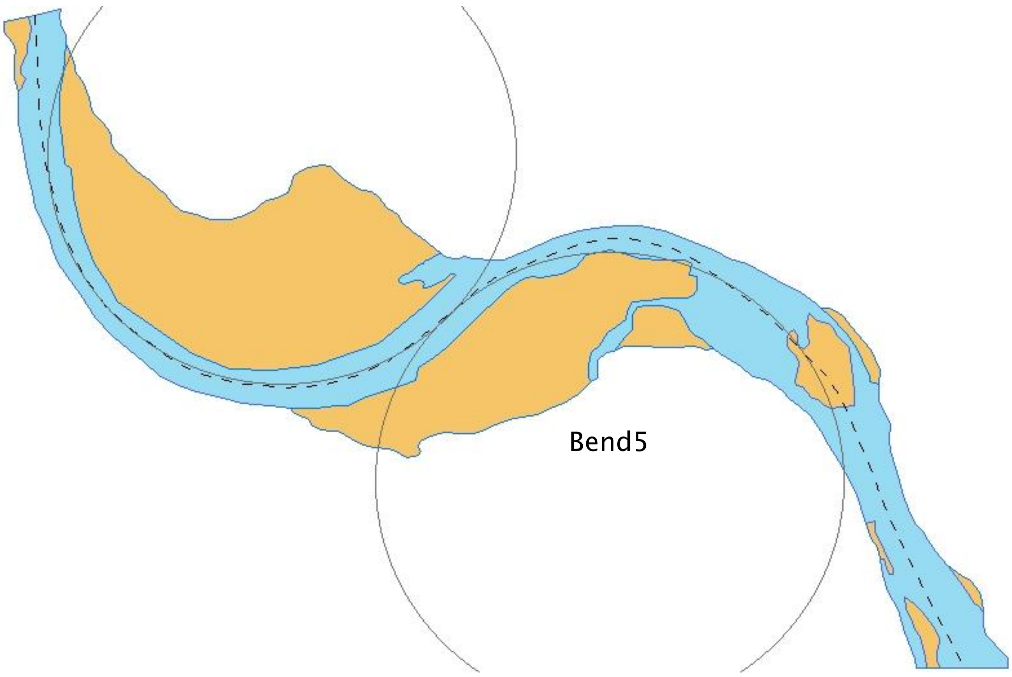


8.17 Radius of curvature calculation for Reach 4

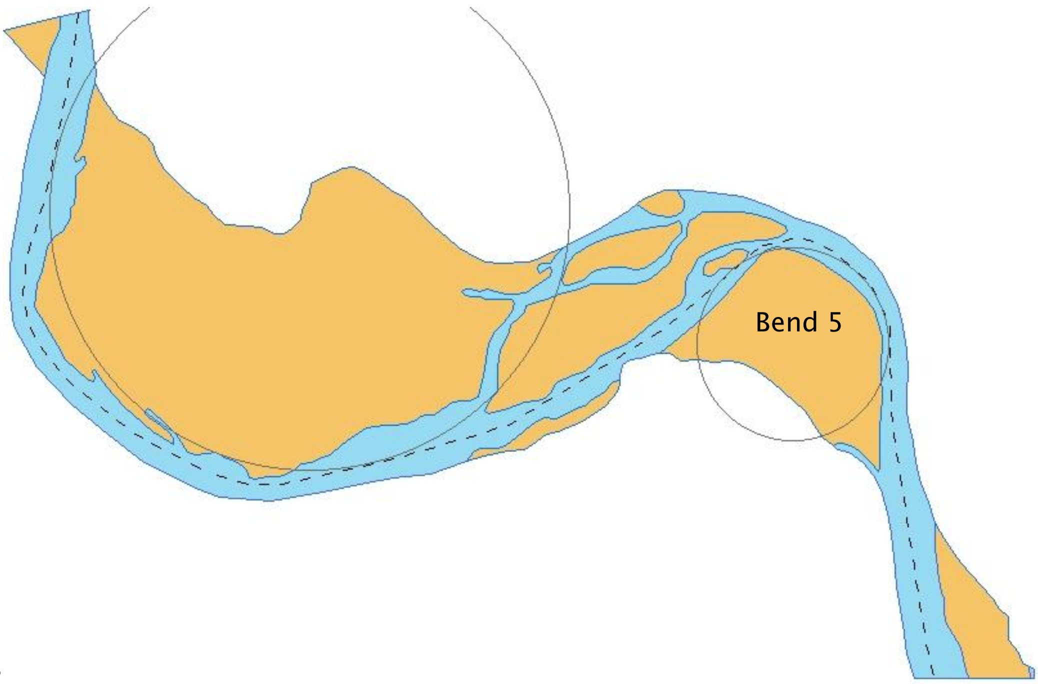
1972



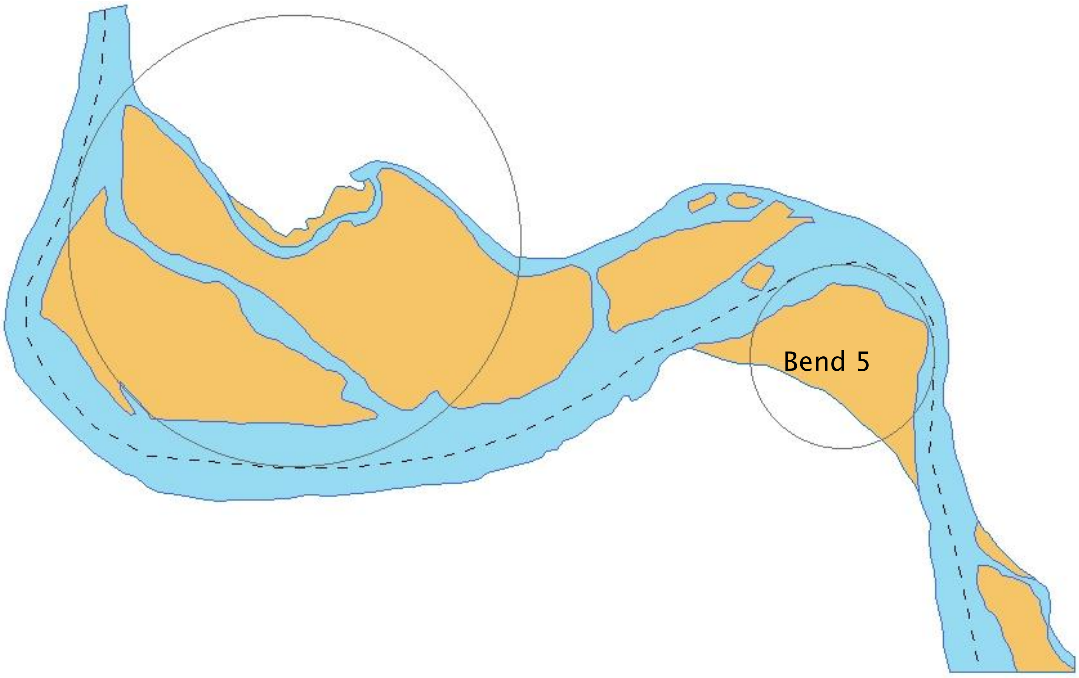
1975



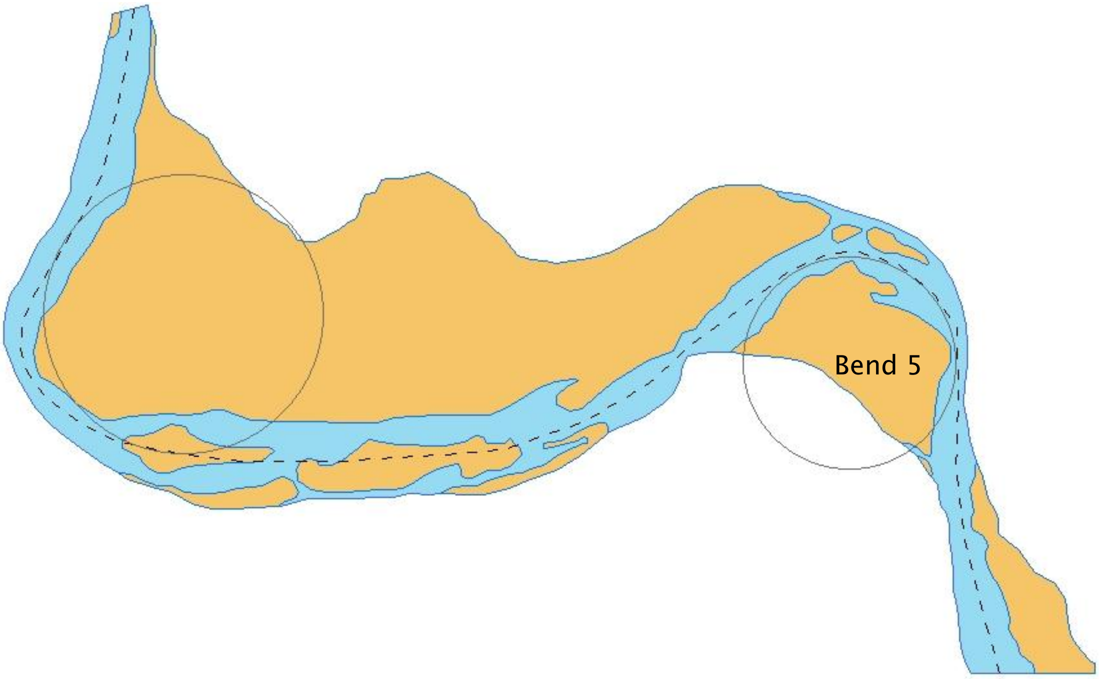
1988



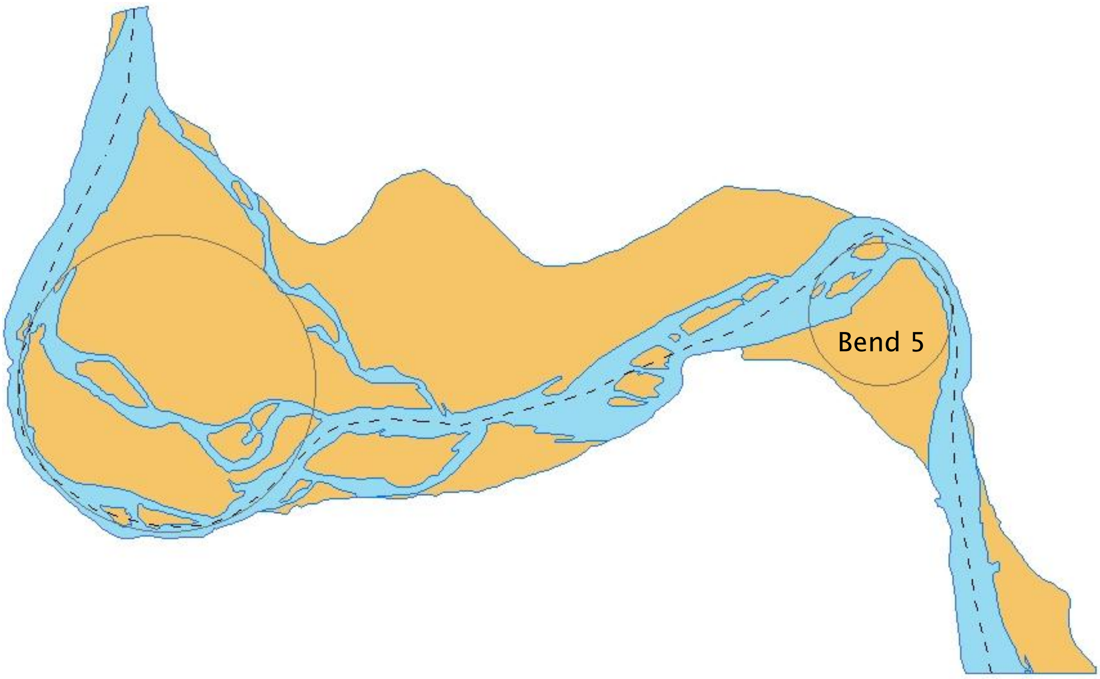
1992



1994



1998



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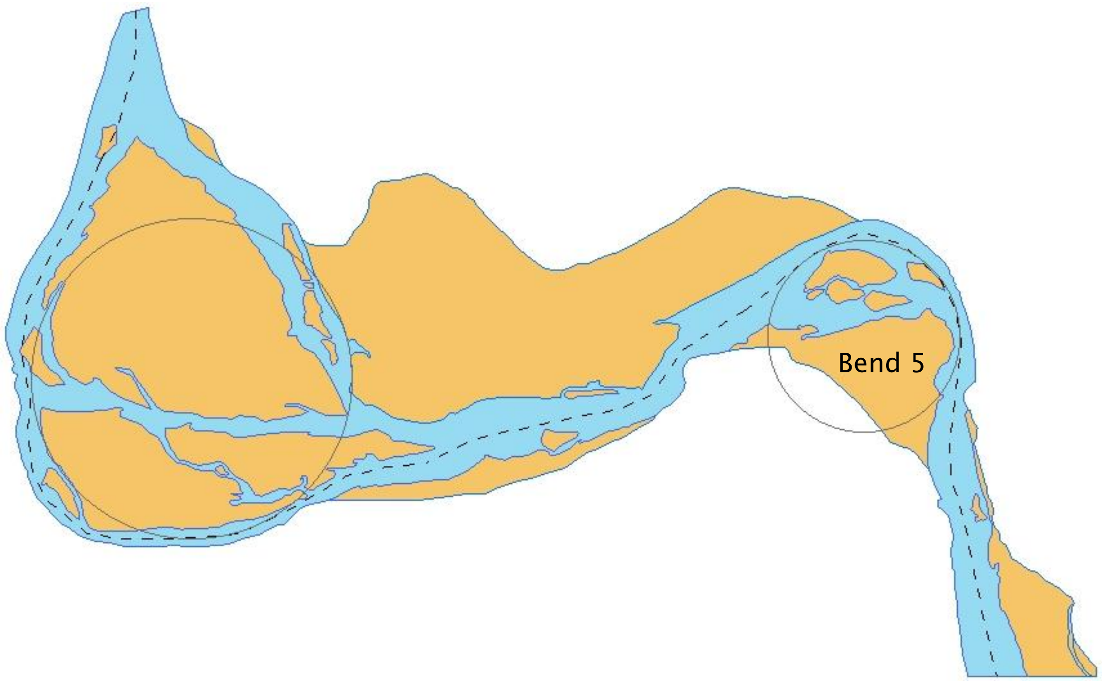

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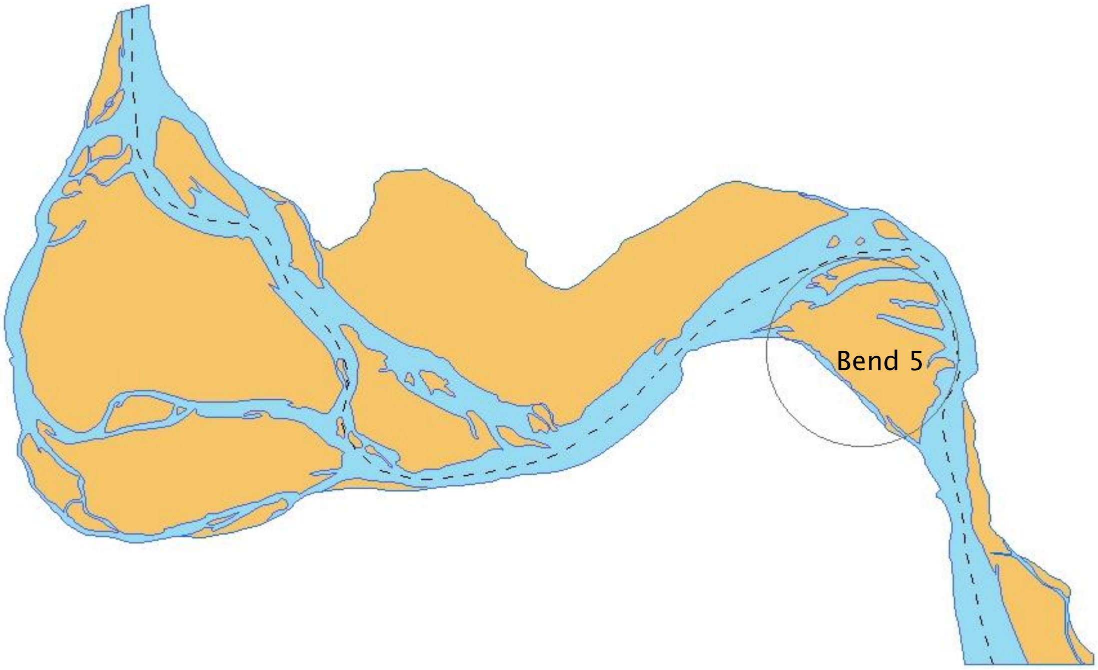

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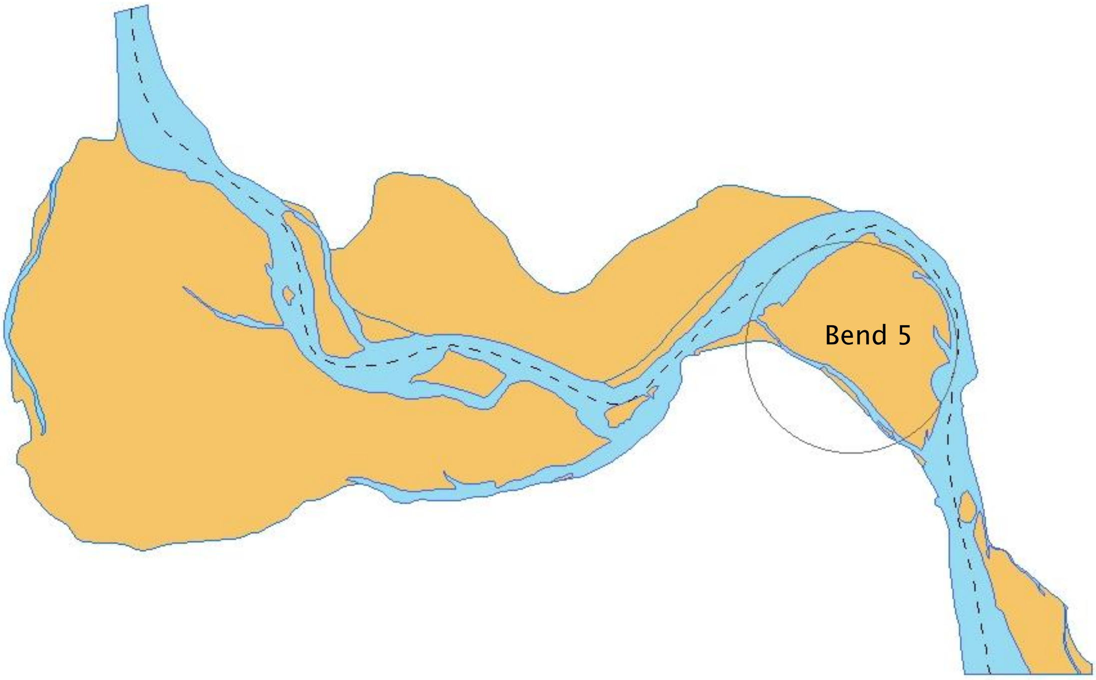

9 References

ASCE Task Force on Bed Forms in Alluvial Channels. 1966. Nomenclature for bed forms in alluvial channels. American Society of Civil Engineers, Proceedings, *Journal of the Hydraulics Division* **92**: 51–64.

Abbado D, Slingerland R, Smith N. 2005. Origin of anastomosis in the upper Columbia River, British Columbia, Canada. *Special Publication of the International Association of Sedimentologists* No. 35, pp. 3–15.

Abbas N, Subramanian V. 1984. Erosion and sediment transport in the GangesRiver basin. *Indian Journal of Hydrology* **69**: 173-182.

Abul-Ata AA. 1980. After the Aswan. Mazingira.

Ackers P. 1982.*Meandering Channels and the influence of bed material*. Gravel Bed Rivers, Wiley, Chichester: 389–393.

Ahmad M. 1961. Effects of barrages on the regime of rivers of the Indus Basin. 9th Congress, Int. Assoc. Hydraul. Res. Dubrovnik, Yugoslavia.

Akhter SH. 2010. Earthquakes of Dhaka, Environment of capital Dhaka- - Plants Wildlife Gardens Parks Air Water and Earthquake. Dhaka Celebration Series. Asiatic Society of Bangladesh: Dhaka, Bangladesh; 401-426.

Alabyan A, Chalov R. 1998. Types of river channel patterns and their natural controls. *Earth Surface Processes Landforms* **23**: 467–474. DOI: 10.1002/(SICI)1096-9837(199805)23:5<467::AID-ESP861>3.0.CO;2-T.

Alvarez A. 2005. Channel planform dynamics of an alluvial river. PhD Thesis, Texas A&M University, USA.

AshmoreP.1991. Channel morphology and bed load pulses in braided, gravel bed streams. *Geografiska Annaler: Series A, Physical Geography* **73**: 37–52.

Ashmore PE. 1982. Laboratory modelling of gravel braided-stream morphology. E*arth Surface Processes Landforms* **7**: 201-225. DOI: 10.1002/esp.3290070301.

Atkinson PM, 1997. Selecting the spatial resolution of airborne MSS imagery for small-scale agricultural mapping. *International Journal of Remote Sensing* **18**: 1903-1917.DOI: 10.1080/014311697217927.

Atkinson PM, Tate NJ. 2000. Spatial Scale Problems and Geostatistical Solutions: A Review, *Professional Geographers* **52(4)**: 607-623. DOI: 10.1111/0033-0124.00250.

Bagnold RA. 1960. Some aspects of river meanders. US Geological Survey, Professional Paper 282-E.

Bak P. 1996. *How Nature Works*. Springer-Verlag: New York.

Bak P, Chen K. 1991. Sel-organized criticality. *Scientific American* **264**: 46-53.

Bak P, Tang C. 1989. Earthquakes as a self-organized critical phenomenon. *Journal of Geophysical Research* **94**: 635-637. DOI: 10.1029/JB094iB11p15635.

Baker V.1978. Adjustment of fluvial systems to climate and source terrain in tropical and subtropical environments. In *Fluvial Sedimentology*, Miall AD (ed). Memoir-Canadian Society of Petroleum Geologists **5:** 211 – 230.

Baki ABM, Gan TY. 2012. Riverbank migration and island dynamics of the braided Jamuna River of the Ganges-Brahmaputra basin using multi-temporal Landsat images. *Quaternary International* **263**; 148-161. DOI:10.1016/j.quaint.2012.03.016

Bartholdy J, Billi P. 2002. Morphodynamics of a pseudo meandering gravel bar reach. *Geomorphology* **42**: 293–310. DOI: 10.1016/S0169-555X(01)00092-7.

Begin ZB. 1986. Curvature ratio and rate of river bend migration-update. *Journal of Hydraulic Engineering* **112**: 904 - 908. DOI: 10.1061/(ASCE)0733-9429(1986)112:10(904).

Bhattacharya KD. 1959.*Bangla Desher Nad – Nadi O Parikalpana*, 2nd Ed. (in Bengali). Bodhoday Library: Calcutta.

Braudick CA, Dietrich WE, Leverich GT, Sklar, LS. 2009. Experimental evidence for the conditions necessary to sustain meandering in coarse bedded rivers. *Proc. Natl. Acad . Sci. USA* **106**: 16936-16941.

Brichieri-Colombi S, Bradnock RW. 2003. Geopolitics, water and development in South Asia: cooperative development in the Ganges-Brahmaputra delta. *The Geographical Journal* **169**: 43-64. DOI: 10.1111/1475-4959.t01-1-00002.

Biedenharn DS, Combs PG, Hill GJ, Pinkard CF, Pinkston CB. 1989.Relationship between channel migration and radius of curvature on the Red River. In *Sediment Transport*

Modelling: Proceedings of the International Symposium, American Society of Civil Engineers: New York; 536 - 541.

Bilham R. 2004. Earthquakes in India and the Himalaya: tectonics, geodesy and history. *Annals of Geophysics* **47**: 839-858.

Blacknell C. 1982. Morphology and surface sedimentary features of point bars in Welsh gravel-bed rivers. *Geological Magazine* **119**: 181–192.

Blair TC, McPherson JG. 1994. Historical adjustments by Walker River to lake-level fall over a tectonically tilted half-graben floor, Walker Lake Basin, Nevada. *Sedimentary Geology* **92**: 7-16. DOI: 10.1016/0037-0738(94)00058-1.

Bledsoe BP, Watson CC. 2001. Logistic analysis of channel pattern thresholds: meandering, braiding, and incising. *Geomorphology* **38**: 281-300. DOI: 10.1016/S0169-555X(00)00099-4.

Blondeaux P, Seminara G. 1985. A unified bar-bend theory of river meanders. *Journal of Fluid Mechanics* **157**: 449-470.

Blum MD. 1994. Genesis and architecture of incised valley fill sequences: a Late Quaternary example from the Colorado River, Gulf Coastal Plain of Texas. In: *Siliciclastic Sequence Stratigraphy: Recent Developments and Applications*, Weimer P, Posamentier HW (eds). *Am. Assoc. Petrol. Geol. Mem.*; 259-283.

Bolla Pittaluga M, Repetto R, Tubino M. 2003. Channel bifurcation in braided rivers: equilibrium configurations and stability. *Water Resources Research* **39**:1046. DOI: 10.1029/2001WR001112.

Boruah S, Gilvear D, Hunter P, Sharma N. 2008. Quantifying channel planform and physical habitat dynamics on a large braided river using satellite data—the Brahmaputra, India. *River Research and Applications* **24:** 650-660. DOI: 10.1002/rra.1132.

Braga G, Gervasoni S. 1989. Evolution of the Po River: An example of the application of historic maps. In *Historical change of large alluvial rivers: Western Europe*, Petts GE, Möller H, Roux AL (eds).Wiley: Chichester; 113–126.

Brice JC. 1974. Evolution of meander loops. *Bulletin of the Geological Society of America* **85**: 581–6. DOI: 10.1130/0016-7606(1974)85<581:EOML>2.0.CO;2.

Brice JC. 1984. Planform properties of meandering streams. In *River Meandering*, Elliot CM (ed).American Society of Civil Engineers; New York;1 - 15.

Bridge JS. 2003.*Rivers and Floodplains: Form, Process, and Sedimentary Record*. Blackwell Science: Oxford.

Bridge JS. 1993. The interaction between channel geometry, water flow, sediment transport and deposition in braided rivers. In *Braided Rivers*, Best JL, Bristow CS (eds). Geol. Soc. Spec. Publ. **75**: 13-71.

Bridge JS. 1985. Paleochannel patterns inferred from alluvial deposits: a critical evaluation. *Journal of Sedimentary Petrology* **55**: 579–589.

Bridge J, Smith N, Trent F, Gavel S, Bernstein P. 1988. Sedimentology and morphology of a low-sinuosity river: Calamus River, Nebraska Sand Hills. *Sedimentology* **33**: 851–870. DOI: 10.1111/j.1365-3091.1986.tb00987.x.

Brierley G, Hickin E. 1991. Floodplain development based on selective preservation of sediments, Squamish River, British Columbia. *Geomorphology* **4**: 381–391. DOI: 10.1016/0169-555X(92)90033-K.

Brizga SO, Finlayson BL. 1990. Channel avulsion and river metamorphosis: The case of the Thomson River, Victoria, Australia. *Earth Surface Processes and Landforms* **15**: 391-404. DOI: 10.1002/esp.3290150503.

Brook GA, Luft E. 1987. Channel pattern changes along the lower Oconee River, Georgia, 1805-1949. *Physical Geography* **8**: 191-209.

Callander RA. 1969. Instability and river channels. *Journal of Fluid Mechanics* **36**: 365-480.DOI: 10.1017/S0022112069001765.

Campbell J. 2002.*Introduction to Remote Sensing*, Guilford Press: New York.

Camporeale C, Perona P, Porporato A, Ridolfi, L. 2005. On the long-term behavior of meandering rivers. *Water Resources Research* **41**: W12403.DOI: 10.1029/2005WR004109.

Carling PA. 1999. Subaqueous gravel dunes. *Journal of Sedimentary Research* **69**: 534-545.

CarsonMA. 1984. The meandering-braided threshold. *Journal of Hydrology* **73**: 315-334. DOI: 10.1016/0022-1694(84)90006-4.

Chakrabarti P. 1998. Changing Courses of Ganga, Ganga-Padma River System, West Bengal, India – RS Data Usages in User Orientation. *River Behaviour and Control* **25**: 19-28.

Chakrabarti P, Nag S, Mitra AP. 2001. Changing drainage pattern of the Ganga-Bhagirathi systems in historic times: A study based on remote sensing technology. *Indian Journal of Geology* **73**: 34-51.

Chang HH. 1988. *Fluvial Processes in River Engineering*. Krieger Publishing: Malabar, FL.

Chang HH. 1983. Energy expenditure in curved open channels. *Journal of Hydraulic Engineering* **109**: 1012-1022. DOI: 10.1061/(ASCE)0733-9429(1983)109:7(1012).

Chattopadhyay SS. 2003. Ravaged by a river.*Frontline*, **20:** September 27 - October 10, 2003, Chennai, India.

Chitale SV. 1977. Ever-changing rivers. *Irrigation and Power Journal* **34**: 69–77.

Chowdhury GI, Kamal MMd. 1996. Tracking in chars of Ganga Valley. *GIS Asia Pacific* (Dec.): 37-39.

Chrzastowski MJ, Killey MM, Bauer RA, DuMontelle PB, Erdmann AL. 1994. The Great Flood of 1993. *Ill. State Geol. Surv. Spec. Rep. 2.*

Church M, Rood K. 1983.Catalogue of alluvial river channel regime data. Tech. rep., Dep. of Geography, Univ. of British Columbia: Vancouver.

Church M, Jones D. 1982. Channel bars in gravel-bed rivers. Gravel-bed Rivers, Wiley and Sons: 291–338.

Coldwell AE. 1947. Effects of Sediment on Design and Operation of Dams and Reservoirs. Proc. of 1st Fed. Inter Agency Sediment. Conf.: 142-157.

Colebrooke RH. 1803. On the course of the Ganges, through Bengal. *Asiatic Researches* **7**:1-31.

Coleman JM. 1969. Brahmaputra River: Channel processes and sedimentation. *Sedimentary Geology* **3**: 129-239. DOI: 10.1016/0037-0738(69)90010-4.

Collins BD, Montgomery DR, Sheikh AJ. 2003. Reconstructing the historical riverine landscape of the Puget Lowland. In *Restoration of Puget Sound Rivers*, Montgomery DR, Bolton SM, Boothand DB Wall L (eds). University of Washington Press: Seattle; 79–128.

Cooke HJ. 1980. Landform Evolution in the Context of Climatic Change and Neo-Tectonism in the Middle Kalahari of North-Central Botswana. *Transactions of the Institute of British Geographers* **5**: 80-99.

Cracknell AP. 1999. Remote sensing techniques in estuaries and coastal zones an update. International Journal of Remote Sensing 20: 485-496. DOI:10.1080/014311699213280.

Curiale JA, Covington GH, ShamsuddinAHM, Morelos JA, Shamsuddin AKM. 2002. Origin of Petroleum in Bangladesh. *AAPG Bulletin* **86**: 625-652.

Dade WB. 2000. Grain size, sediment transport and alluvial channel pattern.*Geomorphology* **35**: 119–126.DOI: 10.1016/S0169– 555X(00)00030–1.

Daniel JF. 1971. Channel movement of meandering Indiana streams. U.S. Geological Survey Professional Paper 732-A . U.S. Geological Survey: Reston, VA.

Dasgupta S, Mukhopadhyay M, Nandy DR. 1987. Active transverse features in the central portion of the Himalaya. *Tectonophysics* **136**: 255-264. DOI: 10.1016/0040-1951(87)90028-X.

de Marsily G, Delay F, Gonçalvès J, Renard P, Teles V, Violette S. 2005. Dealing with spatial heterogeneity. *Hydrogeology Journal* **13**: 161-183. DOI: 10.1007/s10040-004-0432-3.

de Vries L, Carrera J, Falivene O, Gratacós O, Slooten L. 2009. Application of Multiple Point Geostatistics to Non-stationary Images. *Mathematical Geosciences* **41**: 29-42.DOI: 10.1007/s11004-008-9188-y.

Desloges JR, Church M. 1989. Wandering gravel-bed rivers. *The Canadian Geographer* **33**: 360–364.

Dietrich WE, Smith JD, Dunne T. 1983. Boundary shear stress, sediment transport and bed morphology in a sand-bedded river meander during high and low flow. In *River Meandering*. American Society of Civil Engineers: New York.

Downward SR, Gurnell AM, Brookes A. 1994. Variability in Stream Erosion and Sediment Transport. In *Variability in Stream Erosion and Sediment Transport*, Olive LJ, Loughran RJ, Kesby JA (eds). IAHS: Canberra; 449-456.

Dumont JF. 1994. Neotectonics and rivers of the Amazon headwaters. In: *The Variablilty of Large Alluvial Rivers*, Schumm SA, Winkley BR (eds). A.S.C.E. Press: New York; 103-113.

Eaton BC, Church M, Millar RG. 2004. Rational regime model of alluvial channel morphology and response. *Earth Surface Processes Landforms* **29**: 511–529. DOI: 10.1002/esp.1062.

Eaton BC, Millar RG, Davidson S.2010. Channel patterns: Braided, anabranching, and single-thread. *Geomorphology* **120**: 353-364.

Edmonds DA, Paola C, Hoyal DCJD, Sheets, BA. 2011. Quantitative metrics that describe river deltas and their channel networks. *Journal of Geophysical Research* **116**: F04022. DOI: 10.1029/2010JF001955.

Edwards P, Kollman J, Gurnell A, Tockner K, Ward J. 1999. A conceptual model of vegetation dynamics on gravel bars of a large Alpine river. *Wetlands Ecology and Management* **7**: 141–153. DOI: 10.1023/A:1008411311774.

Engelund FA, Hansen E. 1967. Monograph on sediment transport in alluvial streams. Teknisk forlag: Copenhagen.

Evans JE, Huxley JM, Vincent RK. 2007. Upstream channel changes following dam construction and removal using a GIS/remote sensing approach. *Journal of the American Water Resources Association* **43**: 683-697. DOI: 10.1111/j.1752-1688.2007.00055.x.

Federici B, Paola C. 2003. Dynamics of channel bifurcations in noncohesive sediments. *Water Resources Research* **39**: 1162. DOI: 10.1029/2002WR001434.

Ferguson RI. 1975. Meander irregularity and wavelength estimation. *Journal of* Hydrology **26**: 315-33. DOI: 10.1016/0022-1694(75)90012-8.

Ferguson R. 1987. Hydraulic and sedimentary controls of channel pattern. In *River Channels: Environment and Process*, Richards K (ed). *Institute of British Geographers Special Publication* **18.** Blackwell: Oxford; 129–158.

Ferguson R, Ashmore PE, Paola PA, Prestegaard CK. 1992. Measurements in a braided river chute and lobe 1. Flow pattern, sediment transport, and channel change. *Water Resources Research* **28**: 1877–1886. DOI: 10.1029/92WR00700.

Fielding CR.2008. Sedimentology and Stratigraphy of Large River Deposits: Recognition in the Ancient Record, and Distinction from 'Incised Valley Fills', In *Large Rivers: Geomorphology and Management*, Gupta A (ed). John Wiley & Sons, Ltd: Chichester, UK. DOI: 10.1002/9780470723722.ch7.

Fielding C, Alexander J. 1996. Sedimentology of the upper Burdekin river of North Queensland, Australia - An example of a tropical, variable discharge river. *Terra Nova* **8**: 447–457.

Fisk HN. 1952. Mississippi River valley geology in relation to river regime. *American Society of Civil Engineers Transactions* **117**: 667-689.

Fonstad MA, Marcus WA. 2010. High resolution, basin extent observations and implications for understanding river form and process. *Earth Surface Processes and Landforms* **35**: 680–698.DOI: 10.1002/esp.1969.

Fredsøe J. 1978. Meandering and braiding of rivers. *Journal of Fluid Mechanics* **84**: 609.DOI: 10.1017/S0022112078000373.

Friedkin J. 1945. A laboratory study of the meandering of alluvial rivers. U.S. Army Corps of Engineers, U.S. Waterways Experiment Station, Vicksburg, Mississippi, USA.

Froehlich W, Starkel L. 1993. The effects of deforestation on slope and channel evolution in the tectonically active Darjeeling Himalaya. *Earth Surface Processes and Landforms* **18**: 285-290. DOI: 10.1002/esp.3290180309.

Furbish DJ. 1991. Spatial autoregressive structure in meander evolution. *Geological Society of America Bulletin* **103**: 1576-1589. DOI: 10.1130/0016-7606(1991)103<1576:SASIME>2.3.CO;2.

Gagliano SM, Howard PC. 1984. The neck cutoff oxbow lake cycle along the Lower Mississippi River. In *River Meandering*, Elliott C (ed.). ASCE: New York; 147-158.

Galay VJ. 1983. Causes of Riverbed Degradation. *Water Resources Research* **19**: 1057-1090. DOI: 10.1029/WR019i005p01057.

Ghosh P. 2000. Estimation of Channel Sinuosity from Paleocurrent Data: A Method Using Fractal Geometry. *Journal of Sedimentary Research* **70**: 449-455. DOI: 10.1306/2dc4091d-0e47-11d7-8643000102c1865d.

Ghosh RN, Majumder S. 1990. Geomorphology and Morphostratigraphy of West Bengal - A Database. In Archaeological Studies In *Archaeology Exploration*, Datta A (ed).Books & Books: New Delhi.

Gilvear D. Winterbottom S, Sichingabula H. 2000. Character of channel planform change and meander development: Luangwa River, Zambia. *Earth Surface Processes and Landforms* **25**: 421-436. DOI: 10.1002/(SICI)1096-9837(200004)25:4<421::AID-ESP65>3.0.CO;2-Q.

Gole CV, Chitale SV. 1966. Inland delta building activity of Kosi river. Journal of the Hydraulics Division. *Proceedings of the American Society of Civil Engineers* **92**: 111 – 126.

Goswami DC. 1985.Brahmaputra River, Assam, India: Physiography, basin denudation, and channel aggradation. *Water Resources Research* **21**: 959–78. DOI: 10.1029/WR021i007p00959.

Goswami U, Sarma JN, Patgiri AD. 1999. River channel changes of the Subansiri in Assam, India. *Geomorphology* **30**: 227–44. DOI: 10.1016/s0169-555x(99)00032-x.

Goswamy D. 1998. Fluvial regime and flood hydrology of the Brahmaputra river, Assam. In *Flood Studies in India*, Kale V (ed). Memoir-Geological Society of India **41**: 53–75.

GRDC (The Global Runoff Data Centre), 56068 Koblenz, Germany.

Graf WL. 1984. A Probabilistic Approach to the Spatial Assessment of River Channel Stability, *Water Resources Research* **20**: 953-962. DOI: 10.1029/WR020i007p00953.

Gupta A. 2008. Introduction. In *Large Rivers: Geomorphology and Management*, Gupta A (ed). John Wiley & Sons.

Gupta N, Atkinson PM, Carling PA. 2013. Decadal length changes in the fluvial planform of the River Ganga: bringing a mega river to life with Landsat archives. *Remote Sensing Letters* **4**: 1-9. doi: 10.1080/2150704X.2012.682658.

Güneralp I, Rhoads BL. 2005. The Spatial Structure of Planform Dynamics of Meandering Rivers. In *IAHR Symposium on River, Coastal and Estuarine*

Morphodynamics, Parker G, Garcia MH (eds). International Association of Hydraulic Engineering and Research: Urbana, IL; 773–782.

Gustavson T. 1978. Bed forms and stratification types, Nueces River, Texas. *Sedimentology* **25**: 401–426. DOI: 10.1111/j.1365-3091.1978.tb00319.x.

Gutenberg B, Richter CF. 1956. *Ann. di Geofis.***9**: 1-15.

Ham DG, Church M. 2000. Bed-material transport estimated from channel morphodynamics: Chilliwack River, British Columbia. *Earth Surface Processes and Landforms* **25**: 1123–1142. DOI: 10.1002/1096-9837(200009)25:10<1123::AID-ESP122>3.0.CO;2-9.

Hansen E. 1967. On the formation of meanders as a stability problem. Coast. Engn. Lab., Techn. Univ. Denmark, Basic Res., Progress Report 13, p. 9.

Haque CE. 1998.*Hazards in a Fickle Environment: Bangladesh*. Kluwer Academic Publishers:Dordrecht.

Haque CE, Hossain ZM. 1988. Riverbank Erosion in Bangladesh. *Geographical Review* **78**: 20-31.

Harbor DJ, Schumm SA, Harvey MD. 1994. Tectonic control of the Indus River in Sindh, Pakistan. In: *The Variablilty of Large Alluvial Rivers*, Schumm SA, Winkley BR (eds). A.S.C.E. Press: New York; 161-175.

Harmar OP, Clifford NJ. 2006. Planform dynamics of the Lower Mississippi River, *Earth Surface Processes and Landforms* **31**: 825–843.DOI: 10.1002/esp.1294.

Harmar OP, Clifford NJ, Thorne CR, Biedenharn DS. 2005.Morphological changes of the lower Mississippi river: Geomorphological response to engineering intervention. *River Res. Applic.* **21**: 1107–1131.DOI: 10.1002/rra.887.

Hayden HH, Pascoe EH. 1910. Note on the Geological Aspect of the Changes that have taken place in the Rivers of Bengal.

Hasnain SI, Thayyen RJ. 1999. Discharge and suspended-sediment concentration of meltwaters, draining from the Dokriani glacier, Garhwal Himalaya, India. *Journal of Hydrology* **218**: 191-198. DOI: 10.1016/s0022-1694(99)00033-5.

Hathaway GA. 1948. Observations on channel changes degradation and scour below dam. 2nd Meeting, Int. Assoc. Hydraul. Res.: Stockholm.

Henderson FM. 1966.*Open Channel Flow*. Macmillan: New York.

Heller PL, Paola C. 1996. Downstream changes in alluvial architecture: an exploration of controls on channel-stacking patterns. *Journal of Sedimentary Research* **66**: 297–306. DOI: 10.1306/D4268333-2B26-11D7-8648000102C1865D.

Heywood I, Cornelius S, Carver S. 2006. *An introduction to geographical information system*, 3rd edition, Pearson Education Limited: 426.

Hickin EJ. 1974. The development of meanders in natural river channels. *American Journal of Science* **274**: 414–442. DOI: 10.2475/ajs.274.4.414.

Hickin E J. 1978. Mean flow-structure in meanders of the Squamish River, British Columbia. *Canadian Journal of Earth Sciences* **15:** 1833-1849. DOI: 10.1139/e78-191.

Hickin EJ, Nanson GC. 1984. Lateral migration rates of river bends. *Journal of Hydraulics Engineering* **110**: 1557 - 67. DOI: 10.1061/(ASCE)0733-9429(1984)110:11(1557).

Hickin EJ, Nanson G. 1975. The character of channel migration on the Beatton River, northeast British Columbia. *Canada Bulletin of the Geological Society of America* **86**: 487–494. DOI: 10.1130/0016-7606(1975)86<487:TCOCMO>2.0.CO;2.

Hirst FC. 1915. *Report on the Nadia rivers*. Bengal Secretariat Book Depot:Calcutta.

Hooke JM. 2007. Complexity, self-organisation and variation in behaviour in meandering rivers. *Geomorphology* **91**: 236-258. DOI: 10.1016/j.geomorph.2007.04.021.

Hooke JM. 2004.Cutoffs galore!: occurrence and causes of multiple cutoffs on a meandering river. *Geomorphology* **61**: 225–238. DOI: 10.1016/j.geomorph.2003.12.006.

Hooke J. 2003. River meander behaviour and instability: a framework for analysis. *Transactions of the Institute of British Geographers* **28**: 238–253.DOI: 10.1111/1475-5661.00089.

Hooke JM. 1997. Styles of channel change. In *Applied fluvial geomorphology for river engineering and management*, Thorne C, Hey R, Newson M (eds). Wiley: Chichester; 237–268.

Hooke JM. 1995.River channel adjustment to meander cutoffs on the River Bollin and River Dane, northwest England.*Geomorphology* **14**: 235-253. DOI: 10.1016/0169-555x(95)00110-q.

Hooke JM. 1991. Non-linearity in river meander development: 'chaos' theory and its implications. Working paper no. 19 Portsmouth Polytechnic Department of Geography.

Hooke JM. 1987. Changes in meander morphology. In *International Geomorphology 1986, Part I*, Gardiner V(ed). John Wiley & Sons: Belfast, Ireland; 591 - 609.

Hooke JM. 1980. Magnitude and distribution of rates of bank erosion. *Earth Surface Processes and Landforms* **5**: 143 - 157. DOI: 10.1002/esp.3760050205.

Hooke JM. 1977. The distribution and nature of changes in river channel patterns: the example of Devon. In *River Channel Changes*, Gregory KJ (ed).John Wiley and Sons: Belfast, Ireland; 265 - 280.

Hooke R, Le B. 1975. Distribution of sediment transport and shear stress in a meander bend. *Journal of Geology* **83**: 543-565. DOI: 10.1016/j.geomorph.2007.04.021.

Howard AD. 1997. Calibration of a meandering simulation model to the Yampa river. Technical Report to the Nature Conservancy. 25pp.

Howard AD. 1992. Modelling channel migration and floodplain sedimentation in meandering streams. In: *Lowland floodplain rivers: Geomorphological perspectives*, Carling PA, Petts GE (eds). John Wiley & Sons: New York; 1–41.

Howard AD, Knutson TR. 1984. Sufficient conditions for river meandering: a simulation approach. *Water Resources Research* **20**: 1659–1667. DOI: 10.1029/WR020i011p01659.

Huang HQ, Nanson GC. 2007. Why some alluvial rivers develop an anabranching pattern. *Water Resources Research* **43**: W07441. DOI: 10.1029/2006WR005223.

Hudson PF, Kesel R. 2000. Channel migration and meander-bend curvature in the lower Mississippi River prior to major human modification. *Geology* **28**: 531 - 534. DOI: 10.1130/0091-7613(2000)28<511:CSANFI>2.0.CO;2.

Hughes ML, Mcdowell PF, Marcus WA. 2006. Accuracy assessment of georectified aerial photographs: Implications for measuring lateral channel movement in a GIS. *Geomorphology* **74**: 1-16. DOI: 10.1016/j.geomorph.2005.07.001.

Hutchins DG, Hutton LG, Hutton SM, Jones CR, Loenhert EP. 1976. A summary of the geology, seismicity, geomorphology, and hydrogeology of the Okavango Delta. *Geol. Surv. Botswana, Bull.* **7**: 1-27.

Ikeda S, Parker G, Sawai K. 1981.Bend theory of river meanders: Part 1. Linear development. *Journal of Fluid Mechanics* **112**: 363–377. DOI: 10.1017/S0022112081000451.

Ikeda S, Hino M, Kikkawa H. 1976. Theoretical study of the free meandering of rivers. *Proc.* JSCE **2SS**: 63-73(in Japanese).

Immerzeel WW, Ludovicus PH, Bierkens MFP. 2010. Climate Change Will Affect the Asian Water Towers.*Science* **328**: 1382-1385. DOI: 10.1126/science.1183188.

Inglis CC. 1949. *The behaviour and control of rivers and canals*. Pune: Central Water, Power, Irrigation and Navigation Research Station. Research Publication No. 13.

Iqbal S. 2010. Flood and Erosion Induced Population Displacements: A Socio-economic Case Study in the Gangetic Riverine Tract at Malda District, West Bengal,India. *Journal of Human Ecology* **30**: 201-211.

Iriondo M, Suguio K. 1981. Neotectonics of the Amazon plain. INQUANeotectonic, Bulletin **4**: 72–78.

Jain V, Sinha R. 2005. Response of active tectonics on the alluvial Baghmati River, Himalayan foreland basin, eastern India. *Geomorphology* **70**: 339-356. DOI: 10.1016/j.geomorph.2005.02.012.

Jansen JD, Nanson G. 2004. Anabranching and maximum flow efficiency in Magela Creek, northern Australia. *Water Resources Research* **40**. DOI: 10.1029/2003WR002408.

Jerolmack DJ, Mohrig D. 2007. Conditions for branching in depositional rivers. *Geology* **35**: 463-466. DOI: 10.1130/G23308A.1.

Jerolmack, DJ, Paola C. 2007. Complexity in a cellular model of river avulsion, *Geomorphology* **91**: 259–270, doi:10.1016/j.geomorph.2007.04.022.

Johnson SY, Nur Alam AM. 1991. Sedimentation and tectonics of the Sylhet trough, Bangladesh. *Geological Society of America Bulletin* **103**: 1513-1527. DOI: 10.1130/0016-7606(1991)103<1513:SATOTS>2.3.CO;2.

Jones LS, Schumm SA. 1999. Causes of avulsion: an overview. In: *Fluvial Sedimentology VI*, International Association of Sedimentologists special publication 28, Smith ND, Rogers J (eds). Blackwell Science: Oxford; 171-178.

Journel A, Zhang T. 2006. The Necessity of a Multiple-Point Prior Model. *Mathematical Geology* **38**: 591-610. DOI: 10.1007/s11004-006-9031-2.

Jorgensen DW, Harvey MD, Flamm L. 1994. Morphology and dynamics of the Indus River: implications for the Mohen jo Daro site. In *Himalayas to the sea: geology, geomorphology and quaternary*, Shroder J, Kazmi A (eds). London: Routledge, 288–326.

Jung HC, Hamski J, Durand M, Alsdorf D, Hossain F, Lee H, Hossain AKMA, Hasan K, Khan AS, Hoque AKMZ. 2010. Characterization of complex fluvial systems using remote sensing of spatial and temporal water level variations in the Amazon, Congo, and Brahmaputra Rivers. *Earth Surface Processes and Landforms* **35**: 294-304. DOI: 10.1002/esp.1914.

Junk WJ, Bayley PB, Sparks RE. 1989. The flood pulse concept in river-floodplain systems. In *Proceedings of the International Large River Symposium (LARS)*, Dodge DP (ed.). Canadian Special Publications of Fish and Aquatic Sciences **106**: 110–127.

Kääb A. 2005. Combination of SRTM3 and repeat ASTER data for deriving alpine glacier flow velocities in the Bhutan Himalaya. *Remote Sensing of Environment* **94**: 463-474.DOI: 10.1016/j.rse.2004.11.003.

Kale VS. 2002. Fluvial geomorphology of Indian rivers: an overview.*Progress in Physical Geography* **26**: 400–433. DOI: 10.1191/0309133302pp343ra.

Kemp J. 2004. Flood channel morphology of a quiet river, the Lachlan downstream from Cowra, southeastern Australia. *Geomorphology* **60**: 171–190. DOI: 10.1016/j.geomorph.2003.07.007.

Kinoshita R. 1957. Formation of dunes on river bed. *Trans. Japan SOCC. for Engrs.* **42**.

Kleinhans MG.2010, Sorting out river channel patterns. *Progress in Physical Geography* **34**: 287-326. DOI: 10.1177/0309133310365300.

Kleinhans MG, van den Berg JH. 2011. River channel and bar patterns explained and predicted by an empirical and a physics-based method. *Earth Surface Processes and Landforms* **36**: 721–738. DOI: 10.1002/esp.2090.

Kleinhans MG, Weerts HJT, Cohen KM. 2010. Avulsion in action: Reconstruction and modelling sedimentation pace and upstream flood water levels following a Medieval tidal-river diversion catastrophe (Biesbosch, The Netherlands, 1421-1750 AD). *Geomorphology* **118**: 65-79. DOI: 10.1016/j.geomorph.2009.12.009.

Kleinhans MG, Wilbers A, ten Brinke W. 2007. Opposite hysteresis of sand and gravel transport up- and downstream of a bifurcation during a flood in the River Rhine, The Netherlands. *Netherlands Journal of Geosciences* **86**: 273–285.

Kleinhans MG, Cohen KM, Hoekstra J, Ijmker JM. 2011. Evolution of a bifurcation in a meandering river with adjustable channel widths, Rhine delta apex, The Netherlands. *Earth Surface Processes and Landforms*(Online). DOI: 10.1002/esp.2222.

Kleinhans MG, Ferguson RI, Lane SN, Hardy RJ. 2012. Splitting rivers at their seams: bifurcations and avulsion. *Earth Surface Processes and Landforms* (in press). DOI: 10.1002/esp.3268.

Kleinhans MG, Jagers H, Mosselman E, Sloff C. 2008. Bifurcation dynamics and avulsion duration in meandering rivers by one dimensional and three-dimensional models. *Water Resources Research* **44**: W08454. DOI: 10.1029/2007WR005912.

Kleinhans MG. Schuurman F, Bakx W, Markies H. 2009. Meandering channel dynamics in highly cohesive sediment on an intertidal mud flat in the Westerschelde estuary, the Netherlands. *Geomorphology* **105**: 261–276.DOI: 10.1016/j.geomorph.2008.10.005.

Knighton D. 1998. *Fluvial forms and processes, a new perspective*. Edward Arnold:London, UK.

Knighton D. 1984.*Fluvial Forms and Processes*. Arnold: London, UK.

Lacey G. 1930. Stable channels in alluvium. *Minutes Proc. Inst. Civ. Eng.* **229**: 259-292.

Lambert CP, Walling DE. 1987. Floodplain Sedimentation: A Preliminary Investigation of Contemporary Deposition within the Lower Reaches of the River Culm, Devon, UK, *Geografiska Annaler*:*Series A*,*Physical Geography* **69**: 393-404.

Lane EW. 1957. A study of the shape of channels formed by natural streams flowing in erodible material. US Army Corps of Engrs., Missouri River Div., Sediment Series, 9.

Lane EW. 1934. Retrogression of levels in riverbeds below dams. *Eng. News Rec.* **112**: 836.

Lane SN, Widdison PE, Thomas RE, Ashworth PJ, Best JL, Lunt IA, Sambrook Smith GH, Simpson CJ. 2010. Quantification of braided river channel change using archival digital image analysis. *Earth Surface Processes and Landforms* **35**: 971–985. DOI: 10.1002/esp.2015.

Langbein WB, Leopold LB. 1966. River meanders –theory of minimum variance US Geological Survey Professional Paper 422H.

Lanzoni S, Seminara G. 2006. On the nature of meander instability. *Journal of Geophysical Research* **III**: 1-14. DOI: 10.1029/2005JF000416.

Latrubesse E. 2008.Patterns of anabranching channels: The ultimate end-member adjustment of mega rivers.*Geomorphology* **101**: 130–145. DOI: 10.1016/j.geomorph.2008.05.035.

Latrubesse E. 1992. El Cuaternario fluvial de la cuenca del Purus e el Estado de Acre, Brasil. PhD Thesis, Universidad Nacional de San Luis, Argentina.

Latrubesse E, Rancy A. 2000. Neotectonic influence on tropical rivers of southwestern Amazon during the late Quaternary: the Moa and Ipixuna river basins, Brazil. *Quaternary International* **72**: 67– 72. DOI: 10.1016/s1040-6182(00)00022-7.

Latrubesse E, Stevaux JC. 2002. Geomorphology and environmental aspects of Araguaia fluvial basin, Brazil. In South and Central American Rivers, Mossa J, Latrubesse E, Gupta A (eds).*Zeitschrift für Geomorphologie, Supplementbände* **129**: 109– 127.

Latrubesse E, Stevaux JC, Sinha R. 2005. Tropical Rivers. *Geomorphology* **70**: 187-206. DOI: 10.1016/j.geomorph.2005.02.005.

Latrubesse E, Aquino S, de Moraes MJ. 2002. Floods in the city of Rio Branco, Brazil: a case study on the impacts of human activities on flood dynamic and effects. In *Geomorphology and Environmental Impact Assessment*, Marchetti M, Rivas V (eds). Balkema: 163–176.

Leeks GJ, Lewin J, Newson MD. 1988. Channel change, fluvial geomorphology and river engineering: The case of the Afon Trannon, Mid-Wales. *Earth Surface Processes and Landforms* **13**: 207-223. DOI: 10.1002/esp.3290130303.

Leopold LB, Wolman MG. 1957. *River channel patterns: braided meandering and straight*. U.S. Geological Survey Professional Paper **282-b**: 39-85.

Leopold LB, Bagnold RA, Wolman MG, Brush LM. 1960. Flow resistance in sinuous or irregular channels. USGS Professional Paper 282-D: Washington, DC.

Lewin J. 1977. Channel pattern changes. In *River Channel Changes* Gregory KJ (ed).John Wiley and Sons: Belfast, Ireland; 168 - 183.

Lewin J. 1976. Initiation of bed forms and meanders in coarse-grained sediment. *Bulletin of the Geological Society of America* **87**: 281–285. DOI: 10.1130/0016-7606(1976)87<281:IOBFAM>2.0.CO;2.

Lewin J, Brewer PA. 2003. Reply to Van den Berg and Bledsoe's comment on Lewin and Brewer (2001) 'Predicting Channel Patterns'. Geomorphology 40, 329–339. *Geomorphology* **53**: 339–342. DOI: 10.1016/S0169-555X(02)00317-3.

Lewin J, Brewer PA. 2001. Predicting channel patterns. *Geomorphology***40**: 329-339. DOI: 10.1016/s0169-555x(01)00061-7.

Lewis GW, Lewin J. 1983. Alluvial cutoffs in Wales and the Borderlands. In *Modem and Ancient Fluvial Systems*, Collinson JD, Lewin J (eds). Int. Assoc. Sediment. Sp. Publs. **6**: 145-154.

Leys KF, Werritty A. 1999. River channel planform change: software for historical analysis. *Geomorphology* **29**: 107-120. DOI: 10.1016/s0169-555x(99)00009-4.

Li S, Finlayson B. 1993. Flood management on the lower Yellow River: hydrological and geomorphological perspectives. *Sedimentary Geology* **85**: 285-296. DOI: 10.1016/0037-0738(93)90089-N.

Lillesand TM, Kiefer RW, Chipman JW. 2004. Remote sensing and image interpretation, 5th edition. John Wiley & Sons; 763.

Love DW. 1992. Rapid Adjustment of the Rio Puerco to meander cut-off: Implications for effective geomorphic processs, crossing thresholds and timing of events. New Mexico Geological Society Guidebook, 43rd Field Conference, San Juan Basin IV: 399-406.

Makaske B. 2001. Anastomosing rivers: a review of their classification, origin and sedimentary products. *Earth-Science Reviews* **53**: 149–196. DOI: 10.1046/j.1365-3091.2002.00489.x.

Makaske B, Smith D, Berendsen H. 2002. Avulsions, channel evolution and floodplain sedimentation rates of the anastomosing upper Columbia River, British Columbia, Canada. *Sedimentology* **49**: 1049–1071. DOI: 10.1046/j.1365-3091.2002.00489.x.

Makaske B, Smith D, Berendsen H, de Boer A, van Nielen-Kiezebrink M, Locking T. 2009. Hydraulic and sedimentary processes causing anastomosing morphology of the upper Columbia River, British Columbia, Canada. *Geomorphology* **111**: 194–205. DOI: 10.1016/j.geomorph.2009.04.019.

Magilligan FJ, Haynie HJ, Nislow KH. 2008. Channel Adjustments to Dams in the ConnecticutRiver Basin: Implications for Forested Mesic Watersheds. *Annals of the Association of American Geographers* **98**: 267 - 284. DOI: 10.1080/00045600801944160.

Mariethoz G. 2009. Geological stochastic imaging for aquifer characterization, PhD Thesis. Universite de Neuchatel, Neuchatel, Switzerland.

Marston R, Girel J, Pautou G, Piegay H, Bravard JP, Arneson C. 1995. Channel metamorphosis, floodplain disturbance and vegetation development: Ain river, France. *Geomorphology* **13**: 121–131. DOI: 10.1016/0169-555X(95)00066-E.

Mazumder S. 2005. Role of Farakka Barrage on the Disastrous 1998 Flood in Malda (West Bengal). In *The Ganges Water Diversion: Environmental Effects and Implications*, MMQ Mirza (ed).Kluwer Academic Publishers: The Netherlands; 39-48. DOI: 10.1007/1-4020-2480-0_3.

McCarthy TS, Ellery WN, Stanistreet IG. 1992. Avulsion mechanisms on the Okavango fan, Botswana: the control of a fluvial system by vegetation. *Sedimentology***39**: 779-795. DOI: 10.1111/j.1365-3091.1992.tb02153.x.

McDougall W, 1989. Tectonically-induced diversion of the Indus River west of the Salt Range, Pakistan. *Palaeogeography, Palaeoclimatology, Palaeoecology* **71**: 301-307. DOI: 10.1016/0031-0182(89)90057-6.

McFeeters SK, 1996. The use of normalized difference water index (NDWI) in the delineation of open water features. *Int. J. Remote Sensing* **17**: 1425–1432.

McGowen J, Garner L. 1970. Physiographic features and stratification types of coarse-grained point bars: modern and ancient examples. *Sedimentology* **14**: 77–111. DOI: 10.1111/j.1365-3091.1970.tb00184.x.

Meshkova LV, Carling PA. (Online). The geomorphological characteristics of the Mekong River in northern Cambodia: a mixed bedrock-alluvial multi-channel network. Large Rivers Special Issue, *Geomorphology*. DOI: 10.1016/j.geomorph.2011.06.041.

Meybeck M. 1976. Total mineral dissolved transport by world major rivers. *Hydrol. Sci. Bull.* **21**: 265–284. DOI: 10.1080/02626667609491631.

Mika AM. 1997. Three decades of Landsat instruments. *Photogrammetric Engineering & Remote Sensing* **63**: 839-852.

Mike K. 1975. Utilization of the analysis of ancient river beds for the detection of Holocene crustal movements. *Tectonophysics* **29**: 359-368. DOI: 10.1016/0040-1951(75)90162-6.

Miall AD. 1996. The Geology of Fluvial Deposits — Sedimentary Facies, Basin Analysis, and Petroleum Geology. Springer: Berlin.

Millar RG. 2005. Theoretical regime equations for mobile gravel-bed rivers with stable banks. *Geomorphology* **64**: 207–220.

Millar RG. 1999. Grain and form resistance in gravel-bed rivers. *Journal of Hydraulic Research* **37**: 303–312. DOI: 10.1080/00221686.1999.9628249.

Milliman JD, Meade RH. 1983. World-wide delivery of river sediment to the oceans. *Journal of Geology* **91**: 1-21.

Miori S, Repetto R, Tubino M. 2006. A one-dimensional model of bifurcations in gravel-bed channels with erodible banks. *Water Resources Research* **42**, W11413. DOI: 10.1029/2006WR004863.

Monirul Qader Mirza M. 2005. The Ganges Water Diversion: Environmental Effects and Implications - An Introduction The Ganges Water Diversion: Environmental Effects and Implications. In *Water Science and Technology Library*, Mirza MMQ (ed). Springer: Netherlands; 1-12.

Monir MMU, Khan YA. 2004. Seasonal potential seepage analysis of Rajshahi city protection embankment, Rajshahi, Bangladesh, Proceedings of the Ninth International Symposium on River Sedimentation, October 18-21, Yichang, China.

Moorman RK. 1990. An investigation into the uses and usefulness of R I Ferguson's simple kinematic model in the study of meander behaviour and development BSc Dissertation Department of Geography, Portsmouth Polytechnic.

Morgan JP, McIntire WG. 1959. Quaternary geology of the Bengal basin, East Pakistan and India. *Geological Society of America Bulletin* **70**: 319-342. DOI: 10.1130/0016-7606(1959)70[319:QGOTBB]2.0.CO;2.

Mosley MP. 1983. Response of braided rivers to changing discharge. *Journal of Hydrology N.Z.***22**:18–67.

Mosselman E. 1995. A review of mathematical models of river planform changes. *Earth Surface Processes and Landforms* **20**: 661-670. DOI: 10.1002/esp.3290200708.

Mostafa MG. 1978. Sediment processes in the Nile River. Report to World Bank: Washington, DC.

Mount N, Louis J. 2005. Estimation and propagation of error in measurements of river channel movement from aerial imagery. *Earth Surface Processes and Landforms* **30**: 635-643. DOI: 10.1002/esp.1172.

Mount NJ, Louis J, Teeuw RM, Zukowsky JPM, Stott T. 2003. Estimation of error in bankfull width comparisons from temporally sequenced raw and corrected aerial photographs. *Geomorphology* **56:** 65-77. DOI: 10.1016/s0169-555x(03)00046-1.

Mukhopadhyay S, Mukhopadhyay M. 2007. Bank erosion of river Ganga, Eastern India: a threat to environmental systems management, Histoire de voir le monde : le Geo Congres International, 2-5 October, Quebec, Canada.

Murphy WL. 1983. Surface and subsurface geologic conditions along selected reaches of the Mississippi from Rosedale, Mississippi to Lake Providence, Louisiana. US Army Corps of Engineers: Vicksburg, MS.

Nandy DR. 1994. Earthquake hazard potential of the central and south Bengal, *Indian Journal of Earth Science* **21**: 59-68.

Nanson G. 1980. Point bar and floodplain formation of the meandering Beatton River, northeastern British Columbia, Canada. *Sedimentology* **27**: 3–29. DOI: 10.1111/j.1365-3091.1980.tb01155.x.

Nanson G, Croke J. 1992. A genetic classification of floodplains. G*eomorphology* **4**: 459–486. DOI: 10.1016/0169-555x(92)90039-q.

Nanson GC, Hickin EJ. 1983. Channel migration and incision on the Beatton River. *Journal of Hydraulic Engineering* **109**: 327 -337. DOI: 10.1061/(ASCE)0733-9429(1983)109:3(327).

Nanson GC, Knighton AD. 1996. Anabranching rivers: Their cause, character and classification. *Earth Surface Processes and Landforms* **21**: 217-239. DOI: 10.1002/(SICI)1096-9837(199603)21:3<217::AID-ESP611>3.0.CO;2-U.

Neill C. 1973. Hydraulic and morphologic characteristics of Athabasca River near Forth Assiniboine: the anatomy of a wandering gravel bed river. Technical report REH/73/8. Alberta Research Council, Highways and River Engineering Division: Edmonton.

Nittrouer JA, Mohrig D, Allison MA, Peyret APB. 2011. The lowermost Mississippi River: A mixed bedrock-alluvial channel. *Sedimentology* **58**: 1914-1934. DOI: 10.1111/j.1365-3091.2011.01245.x.

O'Malley LSS. 1914.*Bengal District Gazetteers, 24 Parganas*. The Bengal Secretariat Book Depot: Kolkata.

Ouchi S. 1985. Response of alluvial rivers to slow active tectonic movement. *Geological Society of America Bulletin* **96**: 504-515. DOI: 10.1130/0016-7606(1985)96<504:ROARTS>2.0.CO;2.

Parker G. 1976, On the cause and characteristic scales of meandering and braiding in rivers. *Journal of Fluid Mechanics* **76**: 457–480. DOI: 10.1017/S0022112076000748.

Parker G, Andrews ED. 1986. On the time development of meander bends. *Journal of Fluid Mechanics* **162**: 139–156.DOI: 10.1017/S0022112086001970.

Parker G, Paola C, Whipple KX, Mohrig D. 1998. Alluvial fans formed by channelized fluvial and sheet flow- I: Theory. *Journal of Hydraulic Engineering* **124**: 985–995.DOI: 10.1061/(ASCE)0733–9429 (1998)124:10(985).

Parua PK. 2009. *The Ganga – Water Use in the Indian Suncontinent*. Springer: Dordrecht, Heidelberg, London, New York.

Peakall J. 1996. The influence of lateral ground tilting on channel morphology and alluvial architecture. Ph.D. Dissertation. University of Leeds, UK.

Petit CC, Lambin EF. 2001. Integration of multi-source remote sensing data for land cover change detection. *International Journal of Geographical Information Science* **15**: 785-803. DOI:10.1080/13658810110074483.

Potter PE. 1978. Significance and origin of big rivers. *Journal of Geology* **86**: 13–33.

Rashid H, Paul BK. 1987. Flood problems in Bangladesh: is there any indigenous solution? *Environmental Management* **11**: 155-173.

Reaks HG. 1919. *Alleged Deterioration of the Hooghly and Projects for its Improvements*. Bengal Secretariat Book Depot: Calcutta.

Rennell J, Banks J. 1781. An Account of the Ganges and Burrampooter Rivers. *Philosophical Transactions of the Royal Society of London* **71**: 87-114.

Richard GA. 2001. Quantification and Prediction of Lateral Channel Adjustments Downstream from Cochiti Dam, Rio Grande, NM. PhD Dissertation. Colorado State University Fort Collins, CO, USA.

Richards JE. 1986.*Remote Sensing Digital Image Processing: An Introduction*. Springer: New York.

Richards K, Chandra S, Friend P. 1993. Avulsive channel systems: characteristics and examples. In *Braided Rivers*, Best JL, Bristow CS (eds). Geological Society, Special Publications: London; 195-203.

Roy NR. 1952.*Bangalir Itihas (in Bengali)*. Book Emporium: Calcutta.

Roy DP, Ju J, Mbow C, Frost P,Loveland T. 2010. Accessing free Landsat data via the Internet: Africa's challenge. *Remote Sensing Letters* **1**: 111-117. DOI: 10.1080/01431160903486693.

Roy DP, Ju J, Kline K, Scaramuzza PL, Kovalskyy V, Hansen M, Loveland TR, Vermote E, Zhang C. 2010. Web-enabled Landsat Data (WELD): Landsat ETM+ composited mosaics of the conterminous United States. *Remote Sensing of Environment* **114**: 35-49. DOI: 10.1016/j.rse.2009.08.011.

Rudra K.2010. Dynamics of the Ganga in West Bengal, India (1764–2007): Implications for science–policy interaction. *Quaternary International* **227**: 161–169. DOI: 10.1016/j.quaint.2009.10.043.

Rudra K. 2006. Shifting of the Ganga and land erosion in West Bengal – A socio-ecological viewpoint, *Centre for Development and Environment Policy- Occasional Paper,* Indian Institute of Management Calcutta: Kolkata.

Rutherford ID. 1994. Inherited controls on the form of a large, low energy river: the Murray River, Australia. In *The variability of large alluvial rivers*, Schumm SA, Winkley BR (eds). ASCE Press: New York; 177–97.

Rutherford I, Bishop P. 1996. Morphology and bank potection of the Mekong River in the Vientaine-Nong Khai reach, LAO PDR and Thailand. Report to the Mekong River Commission.

Rust B. 1978. Fluvial Sedimentology: A classification of alluvial channel systems. Memoir-Canadian Society of Petroleum Geologists: Calgary, Canada; 187–198.

Salo J, Kalliola R, Hakkinen I, Makinen Y, Niemala P, Puhakka M, Coley PD. 1986. River dynamics and the diversity of Amazon lowland forest. *Nature* **322**: 254-258. DOI: 10.1038/322254a0.

Santos ML, Stevaux JC. 2000. Facies and architectural analysis of channel sandy macroforms in the upper Parana river. *Quaternary International* **72**: 87– 94. DOI: 10.1016/s1040-6182(00)00024-0.

Sapozhnikov VB, Foufoula-Georgiou E. 1997. Experimental evidence of dynamic scaling and indications of self-organized criticality in braided rivers. *Water Resources Research* **3**: 1983–1991. DOI: 10.1029/97WR01233.

Sarker MH. 2004. Impact of upstream human interventions on the morphology of the Ganges-Gorai system. In *The Ganges Water Diversion: Environmental Effects and Implications,* Mirza MMQ (ed). Kluwer Academic Publishers: The Netherlands; 49-80.

Sarma JN, Basumallick S. 1986. Channel form and process of the Burhi Dihing River, India. *Geografiska Annaler: Series A, Physical Geography* **68**: 373–381.

Schumm S. 1985. Patterns of alluvial rivers. *Annual Review of Earth and Planetary Sciences* **13**: 5–27. DOI: 10.1146/annurev.ea.13.050185.000253.

Schumm SA. 1979. Geomorphic Thresholds: The Concept and Its Applications. *Transactions of the Institute of British Geographers*, New Series **4**: 485-515.

SchummSA.1977. *The fluvial system*. Wiley: New York.

Schumm SA. 1973. Geomorphic thresholds and complex response of drainage systems. In *Fluvial Geomorphology*, Morisawa M (ed). New York State Univ. Pub. Geomorph: Binghamton; 299-310.

Schumm S. 1968. River adjustment to altered hydrologic regime - Murrumbidgee River paleochannels. Tech. Rep., U.S. Geological Survey Prof. Pap.

Schumm SA. 1963. Sinuosity of alluvial rivers on the Great Plains. *Geological Society of America Bulletin* **74**:1089-1100. DOI: 10.1130/0016-7606(1963)74[1089:SOAROT]2.0.CO;2.

Schumm SA, Khan HR. 1972. Experimental study of channel pattern. *Geological Society of America Bulletin* **83**: 1755-1770. DOI: 10.1130/0016-7606(1972)83[1755:ESOCP]2.0.CO;2.

Schumm S, Dumont J, Holbrook J. 2000. *Active Tectonics and Alluvial Rivers*. Cambridge University Press: Cambridge, UK.

Schumm SA, Rutherfurd ID, Brooks J. 1994. Pre cut-off morphology of the Lower Mississippi River. In *The variability of large alluvial rivers*, Schumm SA, Winkley BR (eds). ASCE Press: New York; 13–44.

Schumann RR. 1989. Morphology of Red Creek, Wyoming, an arid-region anastomosing channel system. *Earth Surface Processes and Landforms* **14**: 277-288. DOI: 10.1002/esp.3290140404.

Schweizer S, Borsuk ME, Reichert P. (under publication). Predicting the Hydraulic and Morphological Consequences of River Rehabilitation, Swiss Federal Institute for Environmental Science and Technology.

Seijmonsbergen AC. 1999. The influence of neo-tectonics on river patterns in Bangladesh; a preliminary study based on Landsat MSS imagery. *Geologie & Mijnbouw* **77**: 129-135.DOI: 10.1023/A:1003534300984.

Sella GF, Dixon TH, Mao A. 2002. REVEL: A model for Recent plate velocities from space geodesy. *Journal of Geophysical Research* **107**: 2081. DOI: 10.1029/2000JB000033.

Seminara G. 2006. Meanders. *Journal of Fluid Mechanics* **554**:271–297. DOI: 10.1017/S0022112006008925.

Seminara G, Tubino M. 1989. Alternate bars and meandering: free, forced or mixed interactions.In *River Meandering*, Ikeda S, Parker G(eds). American Geophysical Union, Water Resources Monograph **12**: 267–320.

Sen P. 2008. River Bank Erosion and Protection in Gangetic Delta. In *River Bank Erosion and Land Loss*,Rahim KMB, Mukhopadhyay M, Sarkar D (eds). Visva Bharati: Kolkata.

Sengupta JC. 1969.*West Bengal District Gazetteers: Malda*. Government of West Bengal: Calcutta.

Singh IB. 1996. Geological evolution of Ganga Plain – an overview. *Journal of the Palaeontological Society of India* **41**: 299–137.

Singh IB. 1987. Sedimentological History of Quaternary Deposits in Gangetic Plain. *Indian Journal of Earth Sciences* **14**: 272-282.

Singh M, Singh IB, Muller G. 2007. Sediment characteristics and transportation dynamics of the Ganga River. *Geomorphology* **86**: 144–175. DOI: 10.1016/j.geomorph.2006.08.011.

Sinha R. 1996. Channel avulsion and floodplain structure in the Gandak-Kosi interfan, north Bihar plains, India. *Zeitschrift für Geomorphologie, Supplementbände* **103**: 249–268.

Sinha R, Friend PF. 1994. River systems and their sediment flux, Indo-Gangetic Plains, northern Bihar, India. *Sedimentology* **41**: 825– 845.DOI: 10.1111/j.1365-3091.1994.tb01426.x.

Sinha R, Jain V. 1998. Flood hazards of north Bihar rivers, Indo-Gangetic Plains. *Memoir-Geological Society of India* **41**: 27– 52.

Slama CC, Theurer C, Henriksen SW. 1980. Manual of Photogrammetry, *American Society of Photogrammetry*: Falls Church, VA.

Slingerland R, Smith ND.2004.River avulsions and their deposits. *Annual Review of Earth and Planetary Sciences* **32**: 257–285. DOI: 10.1146/annurev.earth.32.101802.120201.

Smith LC. 1997. Satellite remote sensing of river inundation area, stage, and discharge: a review. *Hydrological Processes* **11**: 1427-1439. DOI: 10.1002/(sici)1099-1085(199708)11:10<1427::aid-hyp473>3.0.co;2-s.

Smith DG. 1986. Anastomosing river deposits sedimentation rates and basin subsidence, MagdalenaRiver, northwestern Colombia, South America. *Sedimentary Geology* **46**: 177– 196. DOI: 10.1016/0037-0738(86)90058-8.

Smith DG. 1983. Anastomosed Fluvial Deposits: Modern Examples from Western Canada. In *Modern and Ancient Fluvial Systems*, Collinson JD, Lewin J (eds). Blackwell Publishing Ltd.: Oxford; 155-168.

Smith DG, Smith ND. 1980. Sedimentation in anastomosed river systems; examples from alluvial valleys near Banff, Alberta. *Journal of Sedimentary Research* **50**: 157-164.

Smith ND. 1974. Sedimentology and bar formation in the Upper Kicking Horse River, a braided outwash stream. *Journal of Geology* **82**: 205–223.

Smith ND, Cross TA, Dufficy JP, Clough SR. 1989. Anatomy of an avulsion. *Sedimentology* **36**: 1-23.DOI: 10.1111/j.1365-3091.1989.tb00817.x.

Smith ND, Slingerland RL, Pérez-Arlucea M, Morozova GS. 1998. The 1870s avulsion of the Saskatchewan River. *Canadian Journal of Earth Sciences* **35**: 453-466. DOI: 10.1139/e97-113.

Smith ND, McCarthy TS, Ellery WN, Merry CL, Rüther H. 1997. Avulsion and anastomosis in the panhandle region of the Okavango Fan, Botswana. *Geomorphology* **20**: 49-65. DOI: 10.1016/S0169-555X(96)00051-7.

Speight JG. 1965. Flow and channel characteristics of the Angabunga River, Papua. *Journal of Hydrology* **3**: 16-36. DOI: 10.1016/0022-1694(65)90064-8.

Spring FJE. 1935.*River training and control of great alluvial rivers*. The East India Railway Press: Calcutta.

Singh IB. 1987. Sedimentological History of Quaternary Deposits in Gangetic Plain. *Indian Journal of Earth Sciences* **14**: 272-282.

Stølum HH. 1998. Planform geometry and dynamics of meandering rivers. *Geological Society of America Bulletin* **110**: 1485–98. DOI: 10.1130/0016-7606(1998)110<1485:PGADOM>2.3.CO;2.

Stølum HH. 1996.River meandering as a self-organization process. *Science* **271**: 1710–1713. DOI: 10.1126/science.271.5256.1710.

Stouthamer E. 2005. Reoccupation of channel belts and its influence on alluvial architecture in the holocene Rhine-Meuse Delta, the Netherlands. In *River Deltas-Concepts, Models, and Examples*, Giosan L, Bhattacharya J (eds). SEPM, Tulsa: Oklahoma; 319-339.

Stouthamer E, Berendsen HJA. 2001. Avulsion Frequency, Avulsion Duration, and Interavulsion Period of Holocene Channel Belts in the Rhine-Meuse Delta, The Netherlands. *Journal of Sedimentary Research* **71**: 589-598. DOI: 10.1306/112100710589.

Strebelle S. 2000. Sequential simulation drawing structure from training images. PhD Thesis. Stanford University, Stanford, CA, USA.

Strebelle S, Journel AG. 2001. Reservoir modelling using multiple-point statistics. SPE Annual Technical conference and Exhibition, New Orleans, Sept. 30 – Oct. 3, 2001, SPE # 71324.

Struiksma N, Klaassen GJ. 1988. On the threshold between meandering and braiding. Proc. Int. Conf. on River Regime: Wallingford, England; 107-120.

Struiksma N, Olesen K, Flokstra C, De Vriend H. 1985. Bed deformation in curved alluvial channels. *Journal of Hydraulic Research* **23**: 57–79. DOI: 10.1080/00221688509499377.

Tal M, Paola C. 2010. Effects of vegetation on channel morphodynamics: results and insights from laboratory experiments. *Earth Surface Processes and Landforms***35**: 1014–1028. DOI: 10.1002/esp.1908.

Tal M, Paola C. 2007. Dynamic single-thread channels maintained by the interactions of flow and vegetation. *Geology* **35**: 347–350. DOI: 10.1130/G23260A.1.

Tangri AK. 1992. Satellite remote sensing as a tool in deciphering the fluvial dynamics and applied aspects of Ganga plain. In *Gangetic Plain: terra incognita*, Singh IB (ed.). Department of Geology, Lucknow University, Lucknow: 73–84.

Tao CV, Hu Y, Mercer .JB, Schnick S, Zhang Y. 2000. Image Rectification Using a Generic Sensor Model – Rational Function Model. *International Archives of Photogrammetry and Remote Sensing* **XXXIII(B3)**: 874 – 881.

Thorne CR. 1992. Bend scour and bank erosion on the meandering Red River, Louisiana. In *Lowland Floodplain Rivers*, Carling PA,Petts GE (eds). John Wiley & Sons: New York; 95 - 116.

Thorne CR, Russell APG, Alam MK. 1993. Planform pattern and channel evolution of the Brahmaputra river, Bangladesh. In *Braided Rivers.* Best JL, Bristow CS (eds). Geol. Soc. London: 257–276. DOI: 10.1144/gsl.sp.1993.075.01.16

Townshend JRG. 1980. The Spatial Resolving Power of Earth Resources Satellites: A Review, NASA Goddard Space Flight Centre TM 82020, Greenbelt, MD.

Törnqvist TE. 1994. Middle and late Holocene avulsion history of the River Rhine (Rhine-Meuse delta, Netherlands). *Geology* **22**: 711-714. DOI: 10.1130/0091-7613(1994)022<0711:MALHAH>2.3.CO;2.

Van den Berg JH. 1995. Prediction of alluvial channel pattern of perennial rivers.*Geomorphology* **12**: 259-279. DOI: 10.1016/0169-555X(95)00014-V.

Van den Berg JH, Middelkoop H. 2007. Scroll bar and chute bar development in meandering rivers. Two contrasting examples: the lower Volga (Russia) and the Allier (France). Proc. of the 10th Int. Symp. on River Sedimentation: Moscow, Russia. August 1-4, **5**: 282–300.

Vorosmarty CJ, Meybeck M, Fekete B, Sharma K, Green P, Syvytski JPM. 2003. Anthropogenic sediments retention: major global impact from registered river impoundments. *Global and Planetary Change* **39**: 169– 190. DOI: 10.1016/s0921-8181(03)00023-7.

Walters WH and Simons DB. 1984: Long-term changes of lower Mississippi river meander geometry. In *River meandering*, Elliott CM (ed). ASCE:New York; 318–329.

Warne A, Meade R, White WA, Guevara EH, Gibeaut J, Smyth Aslan A, Tremblay T. 2002. Regional controls on geomorphology, hydrology, and ecosystem integrity in the Orinoco delta, Venezuela. *Geomorphology* **44**: 273– 307. DOI: 10.1016/s0169-555x(01)00179-9.

Wasson J. 2003. A sediment budget for the Ganga–Brahmaputra catchment. *Current Science* **84:** 1041-1047.

WeibelR, Jones CB. 1998. Computational perspectives on map generalization. *GeoInformatica* **2**: 307-314. DOI: 10.1023/a:1009748903798.

Wells NA, Dorr JA. 1987. Shifting of the Kosi River, northern India. *Geology* **15**: 204-207. DOI: 10.1130/0091-7613(1987)15<204:SOTKRN>2.0.CO;2.

Williams GP. 1986.River meanders and channel size. *Journal of Hydrology* **88**:147-64. DOI: 10.1016/0022-1694(86)90202-7.

Williams GP. 1978. Bankfull discharge of rivers. *Water Resources Research* **14**:1141 - 1154. DOI: 10.1029/WR014i006p01141.

Williams DL, Goward S, Arvidson T. 2006. Landsat: Yesterday, today, and tomorrow. *Photogrammetric Engineering and Remote Sensing* **72**: 1171-1178.

Wilson BH. 1973. Some natural and man-made changes in the channels of the Okavango Delta. *Botswana Notes Records* **5**: 132-153.

Winslow N. 1997.Introduction to Self-Organized Criticality and Earthquakes, Discussion paper, Dep. of Geological Sciences, University of Michigan. http://www.geo.lsa.umich.edu/~ruff/Geo105.W97/SOC/SOCeq.html

Winterbottom SJ. 2000. Medium and short-term channel planform changes on the Rivers Tay and Tummel, Scotland. *Geomorphology* **34**: 195-208. DOI: 10.1016/s0169-555x(00)00007-6.

Winterbottom SJ, Gilvear DJ. 2000. A GIS Based Approach to Mapping Probabilities of River Bank Erosion: Regulated River Tummel, Scotland. *Regulated Rivers: Research & Management* **16**: 127-140. DOI: 10.1002/(SICI)1099-1646(200003/04)16:2<127::AID-RRR573>3.0.CO;2-Q.

Woodcock CE, Allen AA, Anderson M, Belward AS, Bindschadler R, Cohen WB, Gao F, Goward SN, Helder D, Helmer E, Nemani R, Oreapoulos L, Schott J, Thenkabail PS, Vermote EF, Vogelmann J, Wulder MA, Wynne R. 2008. Free access to Landsat imagery. *Science* **320**: 1011. DOI: 10.1126/science.320.5879.1011a.

Woodcock CE, Strahler AH. 1987. The Factor of Scale in Remote Sensing. *Remote Sensing of Environment* **21**: 311-332. DOI: 10.1016/0034-4257(87)90015-0.

Woodcock CE, Strahler AH, Jupp DLB. 1988. The use of variograms in remote sensing: I. Scene models and simulated images. *Remote Sensing of Environment* **25**: 323-348. DOI: 10.1016/0034-4257(88)90108-3.

Yang X, Wen X. 2010. Atmospheric correction of Landsat ETM+ remote sensing data using 6S code and its validation. *Applied Mechanics and Materials* **29-32**: 2365-2368. DOI: 10.4028/www.scientific.net/AMM.29-32.2365.

Young WJ, Ogden RW, Prosser IP, Hughes AO. 2001. Predicting river channel type from flow and sediment regime attributes, *Marine Fresh Water Research* **52**: 855-860.

Zebker HA, Amelung F, Jonsson S. 2000. Remote sensing of volcano surface and internal processes using radar interferometry. *Geophysical Monograph* **116**: 179-205. DOI: 10.1029/GM116p0179.

Zinger JA, Rhoads BL, Best JL. 2011. Extreme sediment pulses generated by bend cutoffs along a large meandering river, *Nature Geoscience* **4**: 675-678.DOI: 10.1038/NGEO1260.

Zolezzi G, Seminara G. 2001. Upstream influence in erodible beds: Physics and Chemistry of the Earth. *Part B: Hydrology, Oceans and Atmosphere* **26**: 65–70. DOI: 10.1016/S1464-1909(01)85016-4.

Web Resources:

Landsat Data: http://glovis.usgs.gov/

Free Spatial Data: http://www.diva-gis.org/Data
http://www.naturalearthdata.com/

Geology Map of Bangladesh:
http://certmapper.cr.usgs.gov/data/we/ofr97470h/spatial/shape/geo8bg.zip