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Fluvial dynamics of an anabranching river system in Himalayan foreland basin, Baghmati river, north Bihar plains, India

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Abstract

Anabranching river systems are now regarded as a separate class in river classifications owing to their distinctive morphological/hydrological characteristics and fluvial processes. A better understanding of anabranching rivers still needs detailed data from different environmental and geographical settings. This paper presents a detailed account of an anabranching river system from the Himalayan foreland basin. The Baghmati river system from north Bihar Plains, eastern India provides a typical example of an anabranching river system located in the interfan area between the Kosi and the Gandak megafans. The river system is braided in upstream reaches and meandering in downstream reaches, but the midstream anabranching reach is characterized by low width–depth ratio (11–16), gentle gradient (0.00018–0.00015), variable peak discharge, frequent flooding and high sediment load. The anabranching in the midstream reaches is a response to its inability to transport high sediment load due to gentle channel slope and dominance of aggradation process. The development of anabranches is related to rapid and frequent avulsions of the river channels with eight major avulsions observed in the 30-km-wide floodplain in the last 230 years. The decadal scale avulsion history of the Baghmati river system makes it 'hyperavulsive' and the major causative factors for such channel instability are sedimentological readjustments and active tectonics in the basin area.

Keywords: Anabranching; Avulsion; Indo-Gangetic Plains; Interfan; Himalayan rivers; Neotectonic adjustment

1. Introduction

Anabranching river systems are described as multiple channel systems separated by vegetated, semi-permanent, alluvial islands usually excised from existing floodplain but also sometimes developed by within-channel accretion (Nanson and Knighton, 1996). The understanding of anabranching streams is relatively new in comparison to the other channel patterns. The classical sub-division of channel pattern (after Leopold and Wolman, 1957) distinguished straight, meandering and braided channels, but subsequently, anabranching streams were also identified as a different channel pattern on the basis of sinuosity and sediment load parameters (Mollard, 1973; Rust, 1978; Brice, 1984; Schumm, 1985). Recently, with the input of more data on anabranching streams, this channel system was distinguished as a separate class on the basis of hydrological and channel morphological properties (Nanson and Croke, 1992; Knighton and Nanson, 1993; Rosgen, 1994; Makaske, 2001). Anabranching river systems have been reported from

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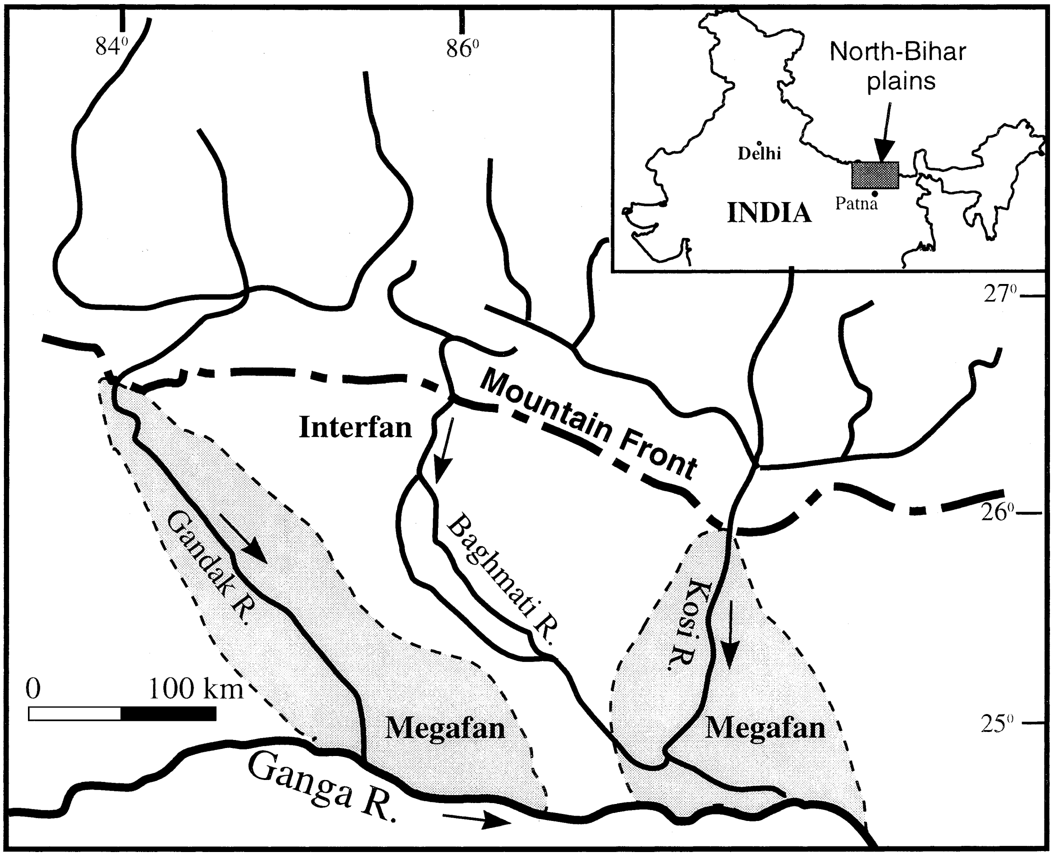


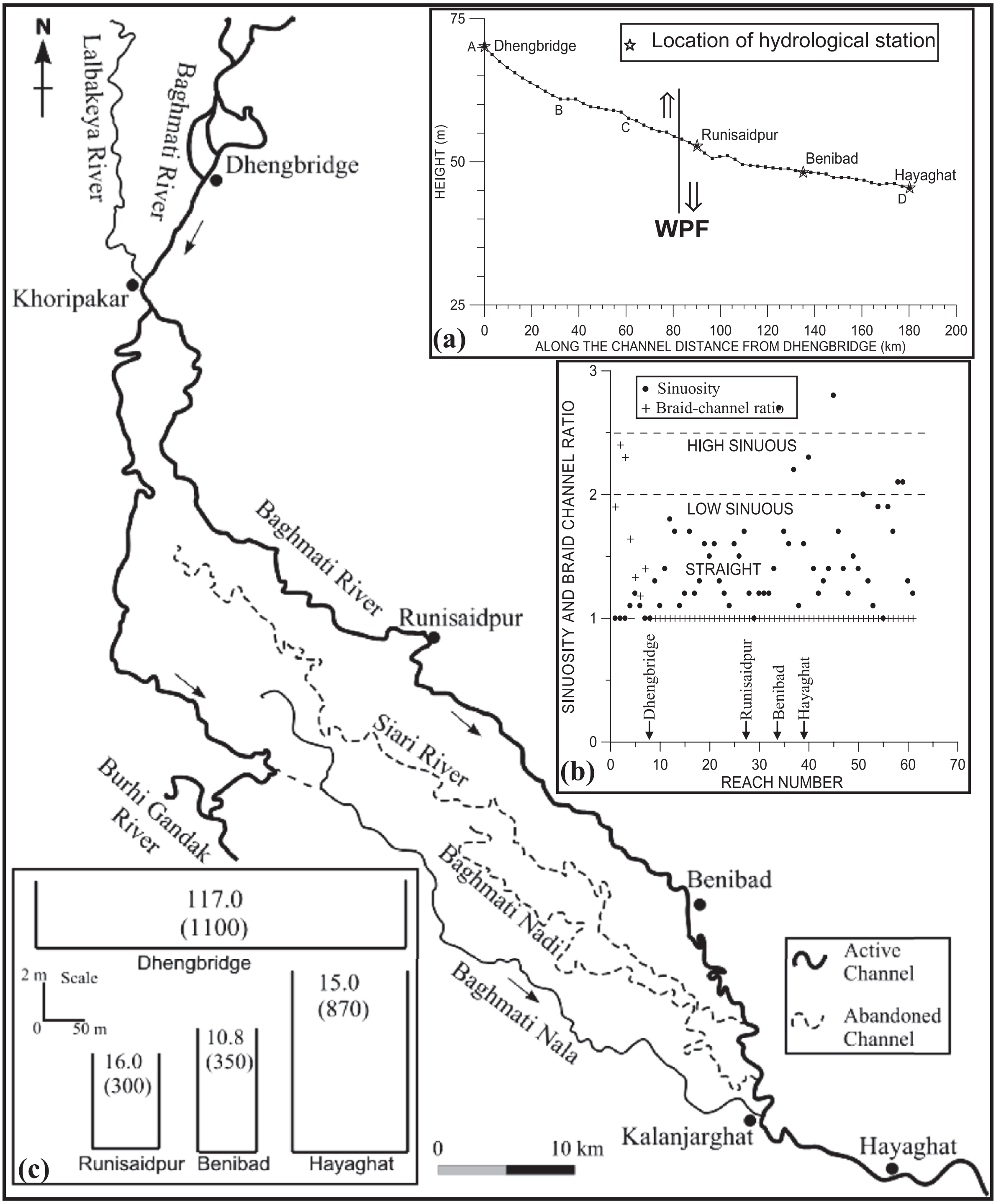
Fig. 1. Location map of the Baghmati river basin, which lies between the two major river systems of the Kosi and Gandak.

various geographic entities including Australia (Schumm, 1968; Rust, 1981; Nanson et al., 1986; Tooth and Nanson, 1999; Gibling et al., 1998), Canada (Smith, 1973, 1983, 1997; Smith and Smith, 1980; Smith and Putnam, 1980; Kong and Martini, 1984), the United States (Schumann, 1989), South America (Baker, 1978; Smith, 1986) and Botswana (Smith et al., 1997) However, anabranching river systems are much less described than the other river systems and little information is available on the hydrology, morphology and dynamics of the full range of anabranching channel systems. In this paper, one such anabranching river system from India is reported and its hydrological, morphological and fluvial characteristics are presented with a detailed discussion on the anabranching process in the area.

2. Geographic and tectonic setting

The Baghmati river rises from the Sheopuri range of hills in Nepal at an elevation of 1500 m (27°47′, 85°17′), flows in the Kathmandu valley, debouches in the alluvial plains of north Bihar in India and finally joins with the Kosi river (Fig. 1). The total basin area of the river system is about 8848 km^2. The average annual

Fig. 2. Anabranching Baghmati river and its morphological characteristics at four hydrological stations. (a) Longitudinal profile. (b) Variation in braiding index and channel sinuosity in downstream direction. The segments are divided into different reaches of 5 km each with braid–channel ratio after Friend and Sinha (1993). (c) Channel cross section, the value in the channel sketch represents the surveyed value of *w*/*d* ratio while bankfull discharge in m^3/s is marked in bracket (source GFCC, 1991).


N
Lalbakeya River
Baghmati River
Dhengbridge
Khoripakar
Baghmati River
Runisaidpur
Siari River
Burhi Gandak River
Baghmati Nadi
Baghmati Nala
Benibad
Kalanjarghat
Hayaghat
Active Channel
Abandoned Channel
0 10 km
(a)
Location of hydrological station
Dhengbridge
Runisaidpur
Benibad
Hayaghat
WPF
HEIGHT (m)
ALONG THE CHANNEL DISTANCE FROM DHENGBRIDGE (km)
(b)
Sinuosity
Braid-channel ratio
HIGH SINUOUS
LOW SINUOUS
STRAIGHT
SINUOSITY AND BRAID CHANNEL RATIO
REACH NUMBER
(c)
117.0
(1100)
Dhengbridge
2 m Scale
0 50 m
16.0
(300)
10.8
(350)
15.0
(870)
Runisaidpur
Benibad
Hayaghat

rainfall in the alluvial plains of the Baghmati river basin is about 1250 mm of which 1120 mm occurs in the monsoon season (June–September) itself. The foothills region (upstream basin area) receives higher rainfall (>2000 mm annually) (GFCC, 1991).

The alluvial plains of the Baghmati river lie in the interfan area between the Gandak and Kosi "mega-fans". The dynamic behaviour of the Kosi and Gandak river systems is well documented (Geddes, 1960; Gole and Chitale, 1966; Wells and Dorr, 1987; Gohain and

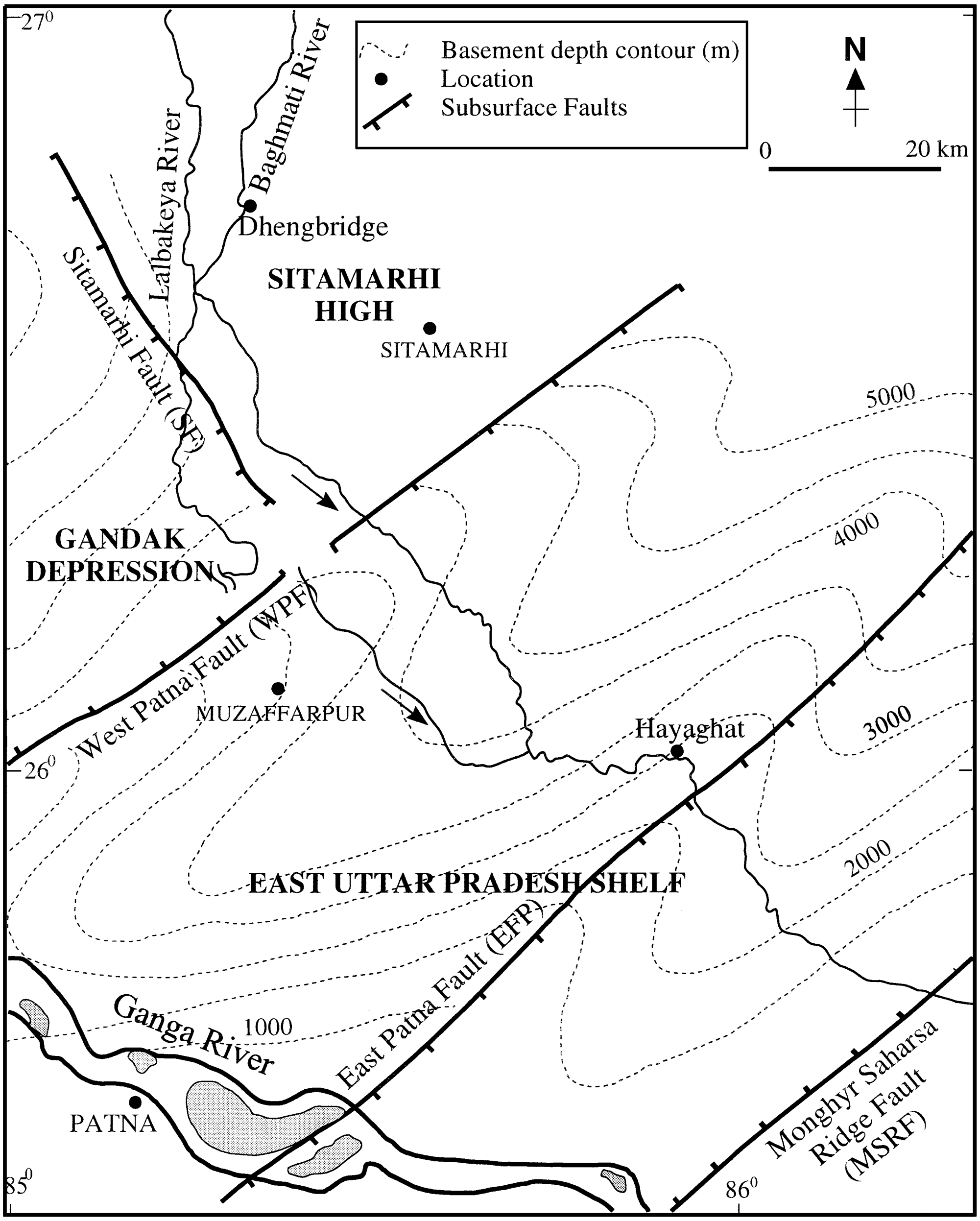


Fig. 3. Structural map of the study area showing how the basin is characterized by NE and SW trending sub-surface active faults.

Parkash, 1990; Agarwal and Bhoj, 1992; Mohindra et al., 1992). Although the Baghmati river is a smaller system than the adjoining megafan systems, it is fairly dynamic with a major drainage area of its own (Jain and Sinha, 2003) and does not lie in an inactive region as is perhaps implicit in Geddes (1960) use of the term "interfan".

In the upstream reaches, the Baghmati river is joined by a tributary named as the Lalbakeya river at Khoripakar (85°14′42″, 26°37′05″) (Fig. 2). However, just after the confluence of these rivers the main channel bifurcates into two channels. The right branch flows southwards and the left branch initially flows southeastwards for nearly 15 km before turning south. In the past, the two branches joined at Kalanjarghat (85°43′18″, 26°03′44″), thus closing a 75-km-long island. Satellite imagery reveals that the right branch of this anabranching reach is quite unstable in the middle reaches, and presently, it joins the Burhi Gandak river to the west instead of rejoining the left anabranch to form an anabranching pattern (Figs. 2 and 3). This phenomenon is related to the avulsive behaviour of the channel. Apart from this major anabranch, there are several smaller anabranches in the Baghmati system, west of the main channel, which are normally short-lived. The systematic analysis of these anabranches and avulsion history clearly highlights the dynamic behaviour of this system. Many of the other smaller rivers in the interfan area viz. Burhi Gandak, Kamla-Balan have also been documented for rapid and frequent avulsion (Phillip et al., 1989; Sinha, 1996).

The upstream source area of the Baghmati river lies in the Kathmandu region, the central part of the Nepal Himalaya. The lithology in the Kathmandu region varies from low to high-grade metamorphic rocks and also includes some sedimentary rocks (Arita et al., 1973). The general structural trend of the lithological units in the Kathmandu region is nearly parallel to that of the Himalayan range, having a N70–80° strike. However, some faults in the region have N–S and NW–SE trends (Arita et al., 1973).

The downstream reaches of the Baghmati river drain the Indo-Gangetic Molasse Basin, which is characterised by about 10,000 m of mainly clastic sediments (Parkash and Kumar, 1991). The Indo-Gangetic Basin has been divided into nine first-order units from east to west, which are traversed by several transverse faults (Eremenko and Negi, 1968). The Baghmati river basin falls mainly in two units namely, East Uttar Pradesh Shelf and Gandak Depression, and ends at Monghyr–Saharsa Ridge (Fig. 3).

The tectonic setting of the region shows four major sub-surface faults namely, Sitamarhi Fault (SF), West Patna Fault (WPF), East Patna Fault (EPF) and Monghyr–Saharsa Ridge fault (Agarwal, 1977; Dasgupta, 1993; GSI, 2000) (Fig. 3). Recent occurrences of Nepal–Bihar earthquakes in 1833, 1934 and 1988 in the region indicate that these faults are active and responsible for neotectonic activity in the basin (Krisnaswamy, 1962; Dasgupta et al., 1987; Banghar, 1991; Dasgupta, 1993; GSI, 2000). The upstream block (area around Sitamarhi) is uplifting, but due to differential vertical movements along the SF and WPF, this area is tilting towards SE. The EPF crosses the river at a point downstream of the anabranching reach and has a SE downthrow.

3. Data used and methods

Hydrological and channel morphological analyses were carried out with the help of data obtained from Government Organisations including the Central Water Commission (CWC), Patna and Ganga Flood Control Commission (GFCC), Patna. River discharge data are available for four stations along the Baghmati river namely, Dhengbridge (upstream), Runisaidpur (midstream), Benibad (midstream) and Hayaghat (downstream), while sediment load data are available for only two stations, i.e. Dhengbridge and Hayaghat station (Fig. 2). The anabranching reach falls between the Dhengbridge and Hayaghat stations and the remaining two midstream stations lie on one of its anabranches. Channel migration history of the Baghmati river for the last 250 years was reconstructed from past records, maps and from digital processing of remote sensing data. For this purpose, the toposheets of 1924 (1:253,440), 1959–1975 (1:50,000) and 1986 (1:250,000) and IRS LISS II remote sensing data of the pre-monsoon period of 1989 and 2000 were used. Remote sensing images were registered with 1:250,000 scale topographic sheets (1986) and the overall root mean square error was 0.783, which corresponds to 28.5 m on the ground. A digital elevation model (DEM) was also generated using 109 elevation points from Survey of India toposheets. The accuracy analysis for the DEM was carried out through 15 random elevation points in the basin with the root mean square error of 1.34 m. Remote sensing analysis was followed by field verification. Neotectonics in the Baghmati river basin and its effect on the Baghmati river were investigated with the help of published maps and available literature on the area. All the above mentioned data were integrated to understand the avulsion processes, the causative factors and anabranching processes in the Baghmati river basin and were supported by further field investigations.

4. Channel morphology and hydrology of Baghmati river

Channel morphological characteristics of the Baghmati river in the study area were studied through measurements of sinuosity, braiding, width–depth ratio and longitudinal profile. Sinuosity and braid channel ratio were measured for 5 km reaches of the Baghmati river following the parameters defined by Friend and Sinha (1993). The results show that the river is braided only upstream from the anabranching reaches and that the braid–channel ratio varies from 2.4 to 1.4 (Fig. 2). A few kilometers downstream of Dheng-

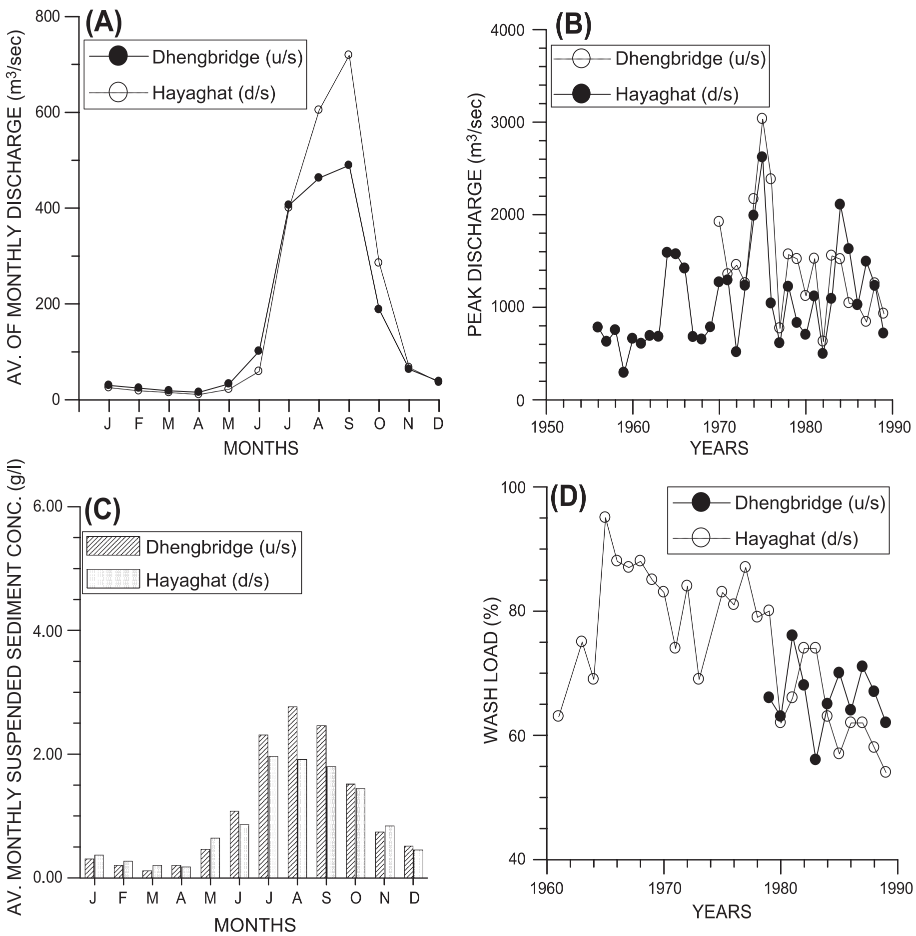


Fig. 4. Hydrological characteristics of Baghmati river system. (A) Variation in average monthly discharge averaged for the period of 1980 to 1989; the peak occurs in the month of August/September. (B) Peak discharge variation in Baghmati river during the period 1956 to 1989; the peak discharge of Baghmati river is quite variable and unpredictable. (C) Variation in the suspended sediment concentration of the Baghmati river. (D) Percentage of fine fraction of total suspended load of Baghmati river basin.

bridge station, the river looses its braiding tendency and the braid–channel ratio is 1.0. The sinuosity of the main Baghmati river channel is extremely variable ranging from 1 to 2.8. Most of the upstream braided reaches are fairly 'straight' (sinuosity 1–1.3), some midstream anabranching reaches show 'high sinuosity channels' (sinuosity 2.8) and other anabranching and single thread reaches are 'low sinuosity channels' (sinuosity 1.2–2.1).

The width–depth ratio of the Baghmati river shows that the channel shape changes from a wide and shallow section (average w/d 117) at the upstream station (Dhengbridge) to a narrow and deep section (average w/d 15) at the downstream station (Hayaghat) (Fig. 2c). Fig. 2c also shows lower width/depth ratio for the midstream stations along the anabranched reach.

The longitudinal profile for the Dhengbridge–Hayaghat reach (Fig. 2a) indicates a downstream decrease in channel slope, which is a manifestation of the relatively flat topography of the plains. The average channel gradient of Dhengbridge to Hayaghat reach is 0.00014 (GFCC, 1991). The channel gradient at Dhengbridge is higher (0.00053) and decrease downstream to 0.00011 at Hayaghat. However, there is a distinct convexity in the longitudinal profile in the midstream reach (segment BC in Fig. 2a). This convexity seems to be related to West Patna Fault, which crosses the channel downstream of this convexity 20 km upstream of Runisaidpur (Figs. 2a and 3).

Average monthly discharge data for Dhengbridge and Hayaghat stations (1980 to 1989) indicate that discharge starts to peak in June and reaches a maximum in August/September, whereas during other months the river is characterised by greatly reduced discharge (Fig. 4A). A significant difference in river discharge between the non-monsoon and monsoon period is one of the major factors responsible for overbank flooding in the area. Peak discharge values for Dhengbridge (1970–1989) and for Hayaghat (1956–1989) suggest that the peak discharges at both stations are variable and unpredictable (Fig. 4B, Table 1). The variation in peak discharge causes significant bank erosion, which in turn results in a high sediment load for the river. A higher peak discharge is generally observed at Dhengbridge than at Hayaghat, which is due to downstream flow loss resulting from overbank flooding in diversions down anabranching. Frequent overbank flooding in the region is also indicated by high values of the Mean Annual Flood and the Most Probable Flood relative to the bankfull discharge (see Table 1). This frequent overbank flooding in the Baghmati river basin favours channel avulsion and anabranching.

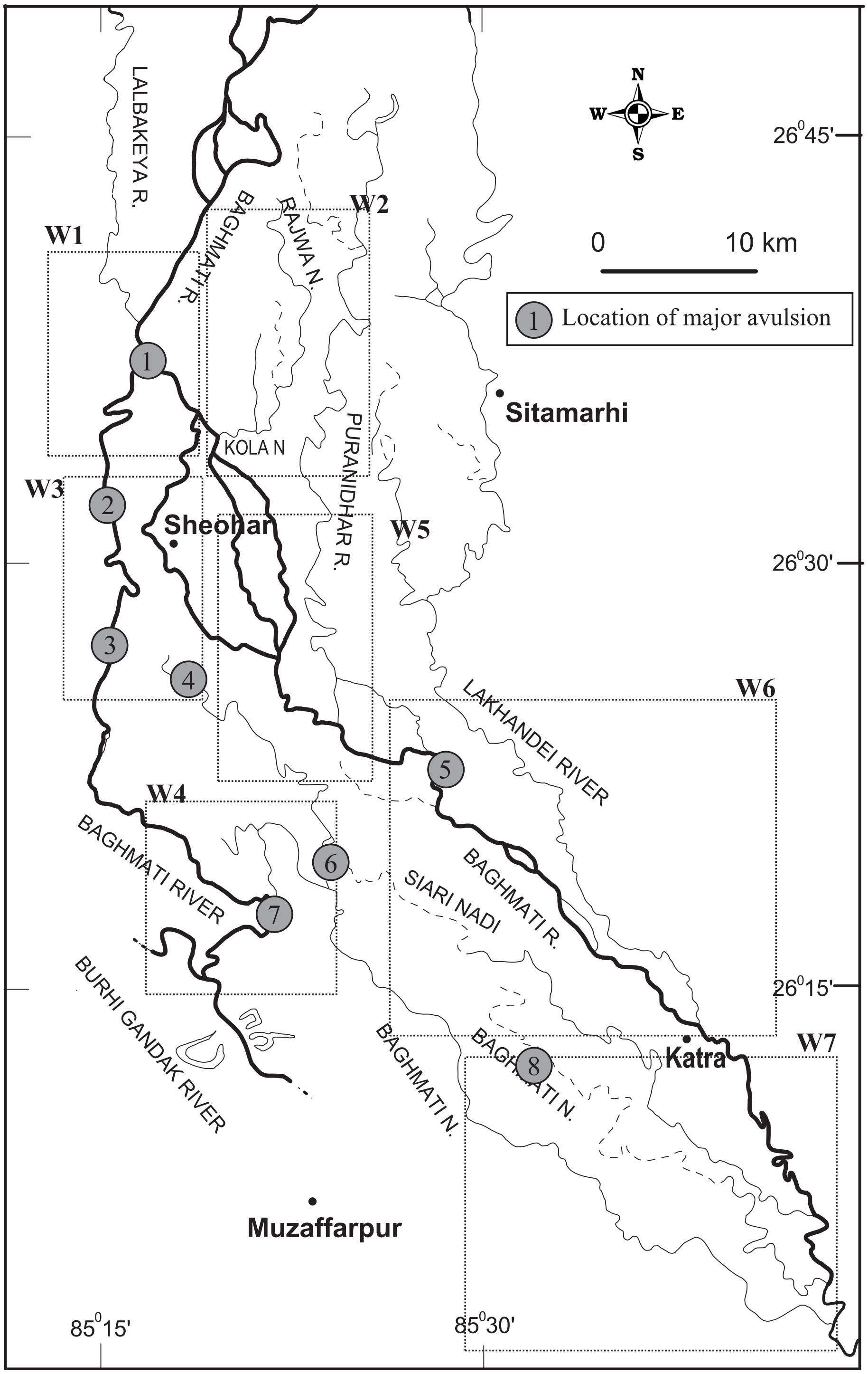
Table 1
Hydrological and sediment transport characteristics of the Baghmati river

Parameter	Dhengbridge (u/s)	Hayaghat (d/s)
Catchment area (km^2)	3790	8439
Average annual discharge (m^3/s)	156	189
Bankfull discharge (m^3/s)	1100	870
Most probable flood (m^3/s)	1155	834
Mean annual flood (m^3/s)	1437	1076
Max. observed discharge (m^3/s)	3033	2617
Total suspended sediment load ($\times 10^6$ tonnes/year)	10.41	7.21
Coarse fraction of suspended sediment load ($\times 10^6$ tonnes/year)	0.744 (7.6%)	0.447 (5.1%)
Average sediment yield (tonnes/year/km^2)	2834	866

Average monthly sediment concentration for the Baghmati river (Fig. 4C) shows a marked increase in sediment concentration at upstream sites during monsoon periods, which suggests that much of the sediment load is supplied from the upstream catchment area. Higher sediment load during the monsoon period is probably related to intense rainfall in the foothills, which erodes the upstream basin area and increases the sediment influx significantly (Sinha and Jain, 1998). Further, sediment budgeting indicates a higher annual suspended load at Dhengbridge (10.4 million tonnes/year) compared to Hayaghat (7.21 million tonnes/year) (Table 1) suggesting an annual deposition of more than 3 million tonnes of sediment in the midstream reaches at a rate of 1200 tonnes/km^2. Sediment deposition in the middle reaches may be related to (a) downstream decrease in channel slope (see Fig. 3), and (b) a very high percentage of 'wash load' (60–90%, see Fig. 4D) increasing the viscosity (Simons et al., 1963) and reducing the flow velocity.

5. Reconstruction of avulsion events and channel configurations

The Baghmati river has been shifting its course constantly. Owing to this dynamic nature, several


N
S
W
E
26°45'
26°30'
26°15'
85°15'
85°30'
0 10 km
1 Location of major avulsion
W1
W2
W3
W4
W5
W6
W7
LALBAKEYA R.
BAGHMATI R.
RAJWA N.
KOLA N
PURANIDHAR R.
Sitamarhi
Sheohar
LAKHANDEI RIVER
BAGHMATI RIVER
SIARI NADI
BAGHMATI R.
BURHI GANDAK RIVER
BAGHMATI N.
BAGHMATI N.
Katra
Muzaffarpur
1
2
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6
7
8

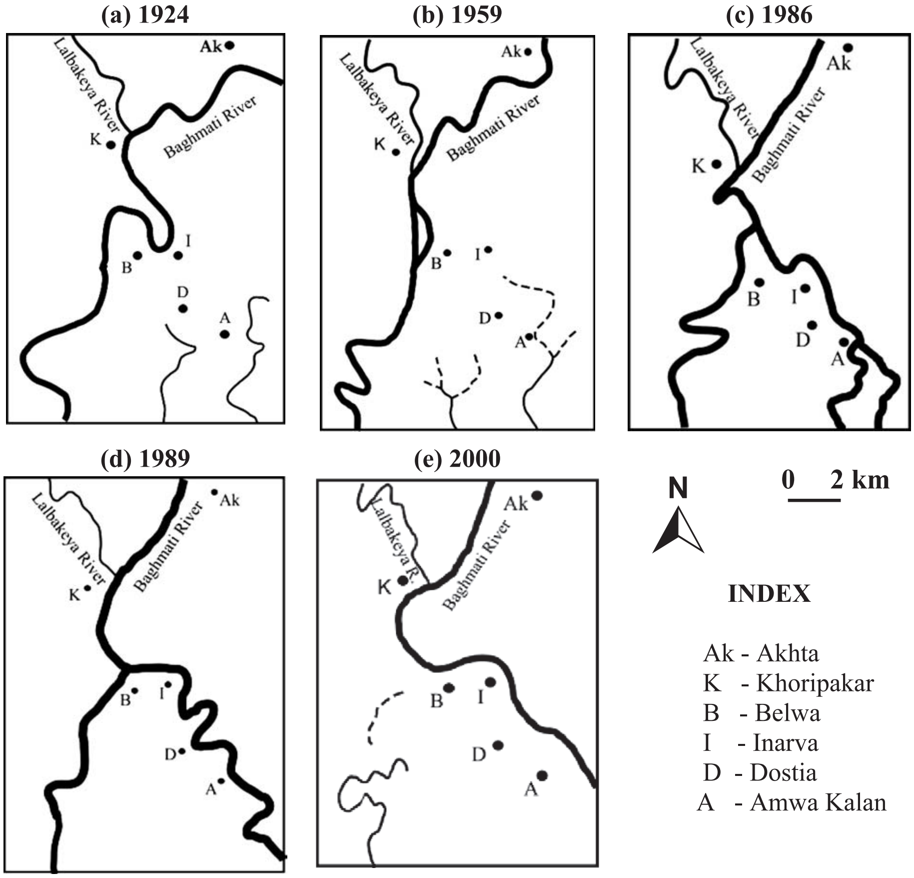

Fig. 6. Window 1: Confluence of Baghmati and Lalbakeya River as seen in different years: (a) 1924, (b) 1959, (c) 1986, (d) 1989, and (e) 2000. The figure shows the different phases of avulsion events and its effect on the anabranching river system and how the Baghmati river has migrated in an easterly direction downstream of the confluence with the Lalbakeya.

abandoned channels exist in the basin, which are known by the name of the Baghmati river itself, assume an altogether different name, or are known by the name of the old channel into which the river avulsed (Fig. 5). The abandoned courses are either full courses of the river or isolated segments. A detailed study of the anabranched reach has been carried out and the chronological avulsion events in seven different windows (Fig. 5) have been reconstructed for a time span of 76 years (1929–2000) using a variety of data sources.

5.1. Window 1: confluence of Lalbakeya river and Baghmati river

Window 1 marks the area around the confluence point of the Baghmati and Lalbakeya rivers. Sequential reconstruction of channel positions in this window (Fig. 6) suggests a gradual westward migration of the Baghmati river since 1924 upstream from the confluence point. In 1924, the Baghmati river flowed in a southerly direction after joining the Lalbakeya river (Fig. 6a), but owing to avulsion in a SE direction in

Fig. 5. Drainage map of the Baghmati river for 1986. The map was prepared from the Survey of India toposheet of 1986 of 1:250,000 scale and shows the anabranching reach of the Baghmati river, system, location of major avulsion points and the location of seven windows in which fluvial dynamics have been studied in detail. The location of avulsion points is corresponding to the following villages—(1) Belwa, (2) Sugia, (3) Paharpur, (4) Hiramma, (5) u/s of Janar, (6) Bilindpur, (7) Raghopur, (8) Lalauna.

1970 (GFCC, 1991) and the reoccupation of smaller channels, the Baghmati river developed an anabranching pattern by 1986. The present-day channel configuration shows that the earlier south-flowing channel is now being abandoned (activated only during the monsoon season) and the Baghmati river has changed into a single channel river with a dominant SE flow (Fig. 7). The DEM of this window shows that the regional slopes upstream and downstream of the confluence are in SW and SE directions, respectively (Fig. 8a).

The avulsion history and anabranching in this window seem to be related to sedimentological and neotectonic readjustments. First, this is a zone of deposition causing significant change in channel configuration, thereby triggering channel movements, helped by local slope conditions. The satellite images show sedimentation around the anabranching point (Fig. 7), which is also confirmed from field observations (Fig. 8b). Rapid aggradation within the channel at that point up to a level higher than the normal water level allows only the monsoonal flow through this abandoned channel.

Second, as inferred from the tectonic setting (Fig. 3), the upstream block of the Baghmati basin has been tilting towards the SE due to differential movement along the faults. This may have reduced the channel gradient of the pre-existing south flowing channel (S_e) and increased the slope of the potential avulsion course (S_a) in a SE direction. Thus, this movement would have caused an increase in the ratio S_a/S_e (Jones and Schumm, 1999) and hence the area probably became

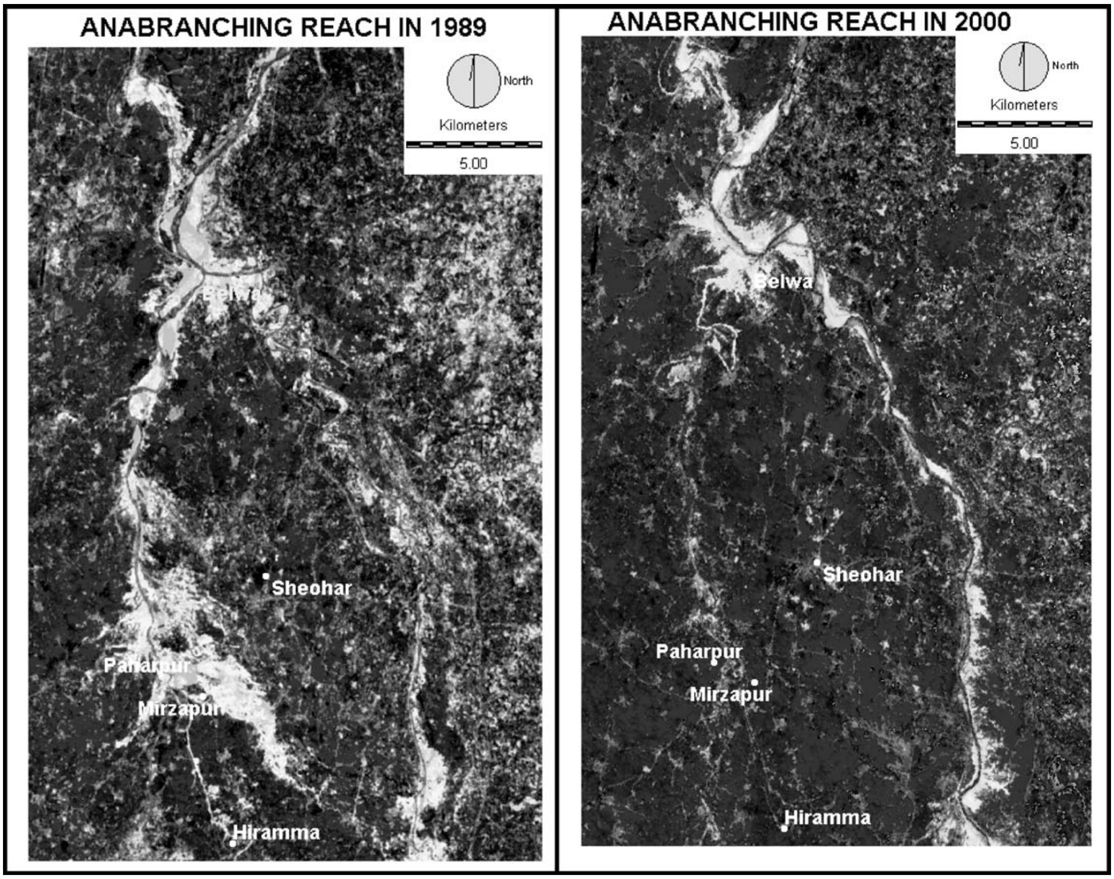

Fig. 7. Standard False Colour Composite (FCC) of the anabranching reach of the Baghmati river basin in 1989 and in 2000 (prepared from bands 2, 3, and 4 of IRS LISS II data and shown as grey scale image); owing to abandonment of the south flowing channel the river system is changing into a single channel system.

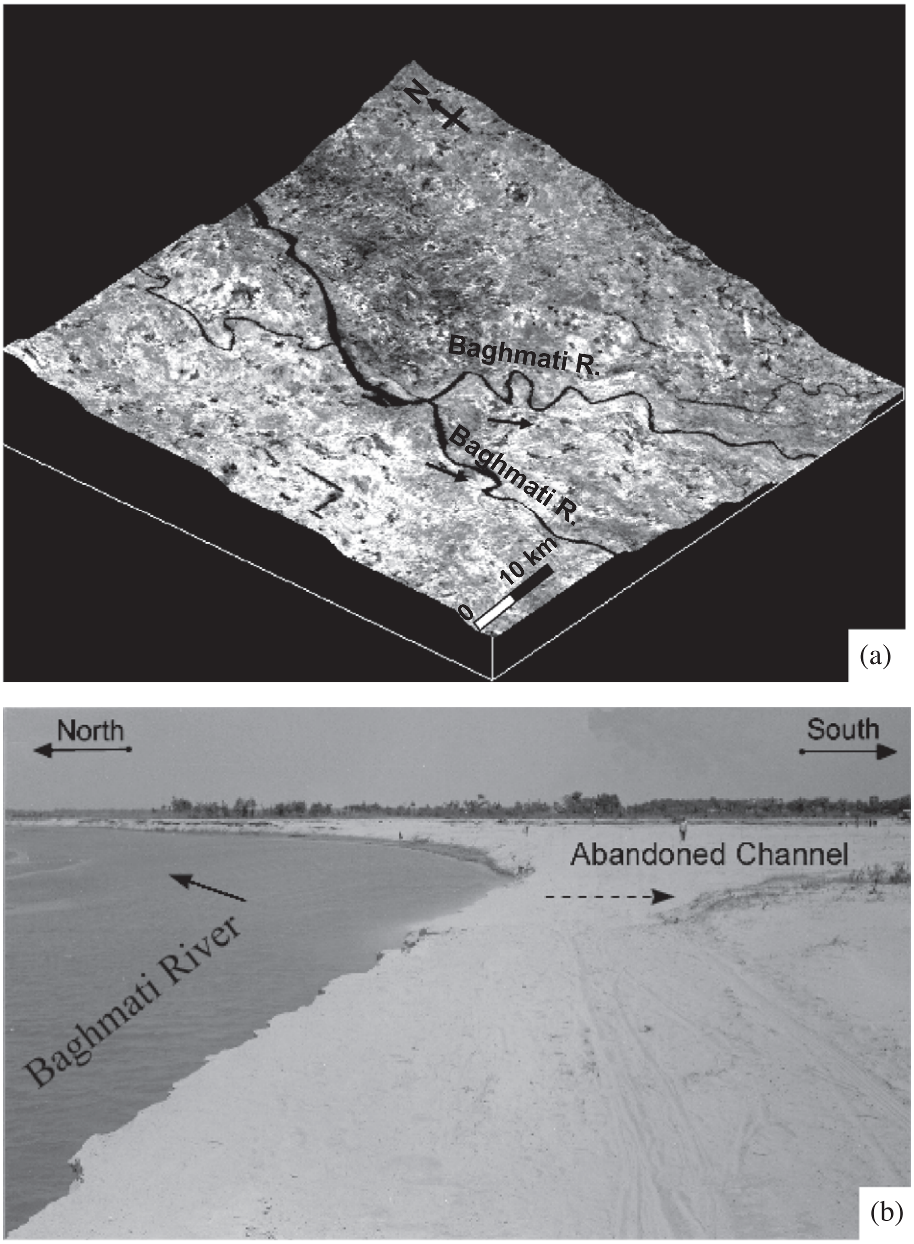

Fig. 8. (a) Satellite image (band 4, IRS LISS II) of window 1 draped over the DEM indicating the SE slope direction. (b) Photograph of the anabranching point showing the sedimentation at the area (direction of flow is southeast).

favourable for channel avulsion in a SE direction (Jain and Sinha, 2000). Some earlier workers have also suggested that anabranching sometimes develops as an initial response to uplift in a downthrown reach (Ouchi, 1985; Gregory and Schumm, 1987).

5.2. Window 2: Kola Nadi and Baghmati Nadi/Puranidhar river

Window 2 shows the upstream reaches of the Kola Nadi and Baghmati Nadi/Puranidhar (Fig. 9). The NW

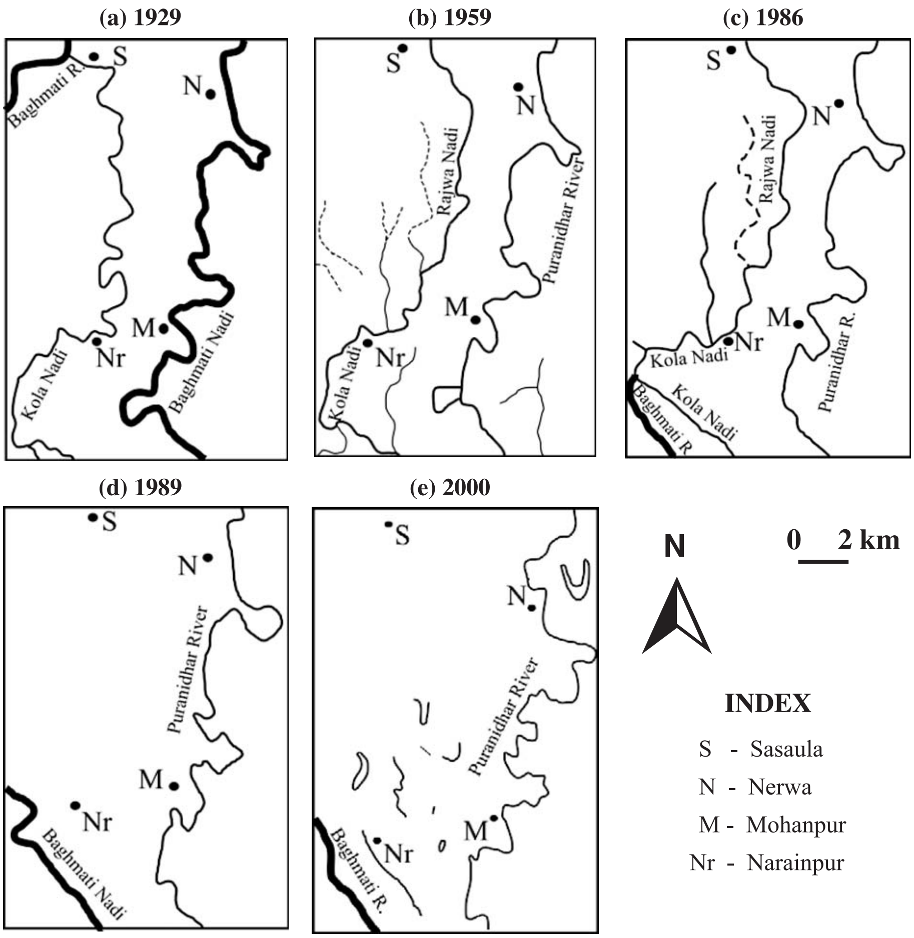

Fig. 9. Window 2: Kola Nadi and Baghmati Nadi/Puranidhar River as seen in different time periods: (a) 1924, (b) 1959, (c) 1986, (d) 1989, and (e) 2000. The area in this window is marked by abandonment of S flowing streams and capture of a part of the Kola Nadi by the Baghmati river at the lower left corner of the window.

shifting of the Baghmati in post-1929 period caused partial abandonment of the Kola Nadi, which however received a small discharge from Rajwa Nadi until 1986. The downstream reaches of the Kola Nadi was then captured by the Baghmati river, whereas the upstream reaches were abandoned completely by 1989 (Fig. 10). The capture of Kola Nadi was related to avulsion, i.e. easterly shifting of the Baghmati river at Belwa (window 1).

Another south-flowing tributary, the Baghmati Nadi/Puranidhar river, which originates around 15 km north of Nerwa village, was active in 1929. However, the upstream source of the Baghmati Nadi silted up during the 1929–1959 period, resulting in abandonment of this course, which is now called Puranidhar (which means 'old channel'). The Puranidhar channel shows large point bars in some sections reflecting a reduction in channel size, which could have inhibited any further movement of this channel since 1959. This channel is characterised by low width–depth ratio. It still receives significant discharge during monsoon periods and causes overbank flooding in the adjoining areas.

5.3. Window 3: Baghmati river near Sheohar

This window shows anabranching in the main Baghmati river in 1924 (Fig. 11), which probably

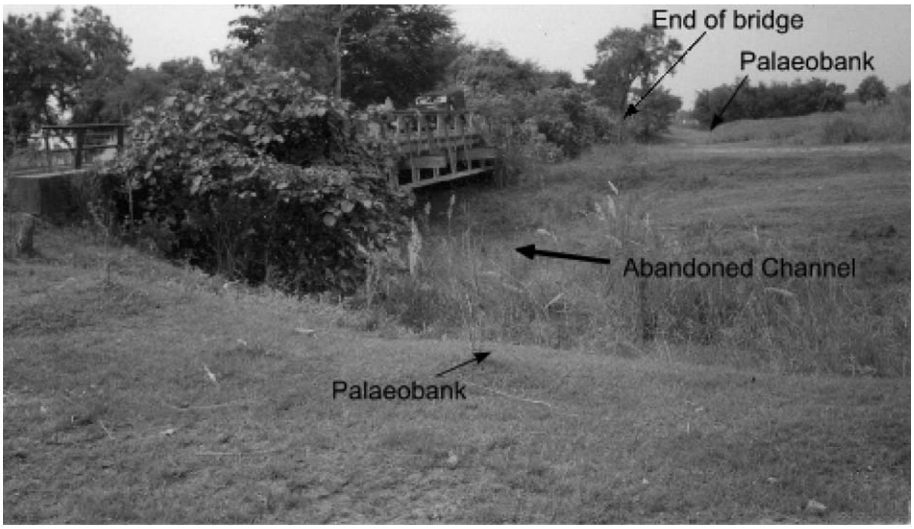

Fig. 10. Abandoned channel of the Kola Nadi; the 80-m-long bridge over this channel indicates the high flow conditions in the past.

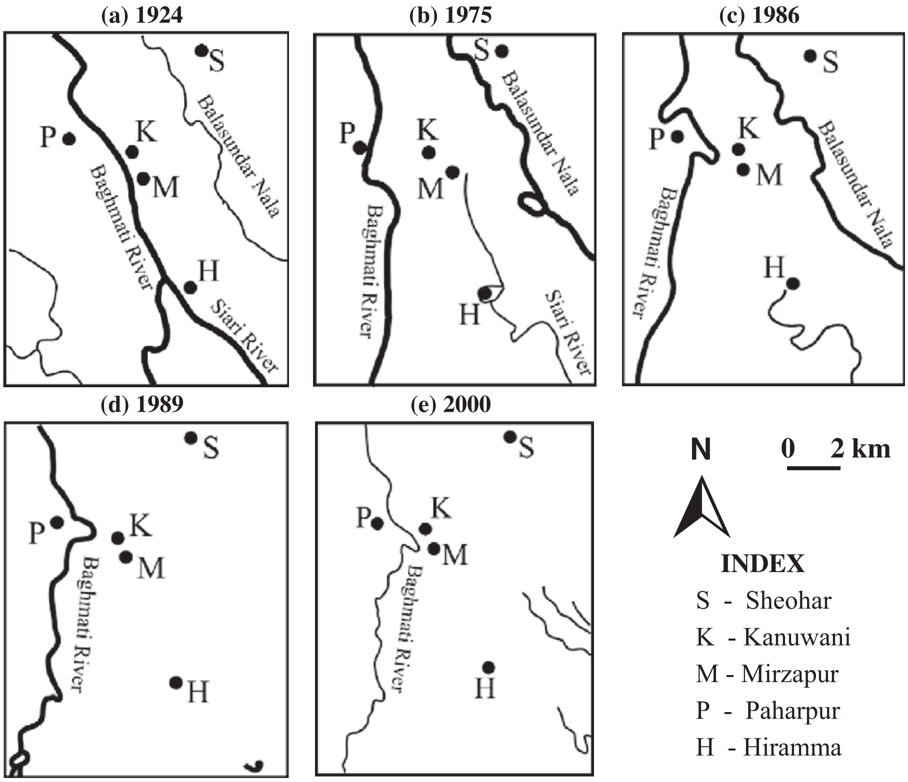

Fig. 11. Window 3: Baghmati river near Sheohar as seen in different years: (a) 1924, (b) 1975, (c) 1986, (d) 1989, and (e) 2000. The river used to anabranch near Hiramma village, but now all the channels have become abandoned, which also caused the disappearance of some channels in the satellite data.

developed in 1915 near Hiramma village (GFCC, 1991), when the Baghmati river avulsed into the SE-flowing Siari Nadi. Subsequently, the river channel upstream of the old anabranching point avulsed near Paharpur and by 1975, the anabranching pattern was destroyed, leaving behind a palaeochannel between Mirzapur and Hiramma. This avulsion at Paharpur in 1974 (GFCC, 1991) developed a south-flowing channel of the Baghmati and the Belwa (window 1)–Paharpur–Minapur (window 4) channel came into existence. The 1970 avulsion near to Belwa village (window 1) resulted in the SE anabranch originating at

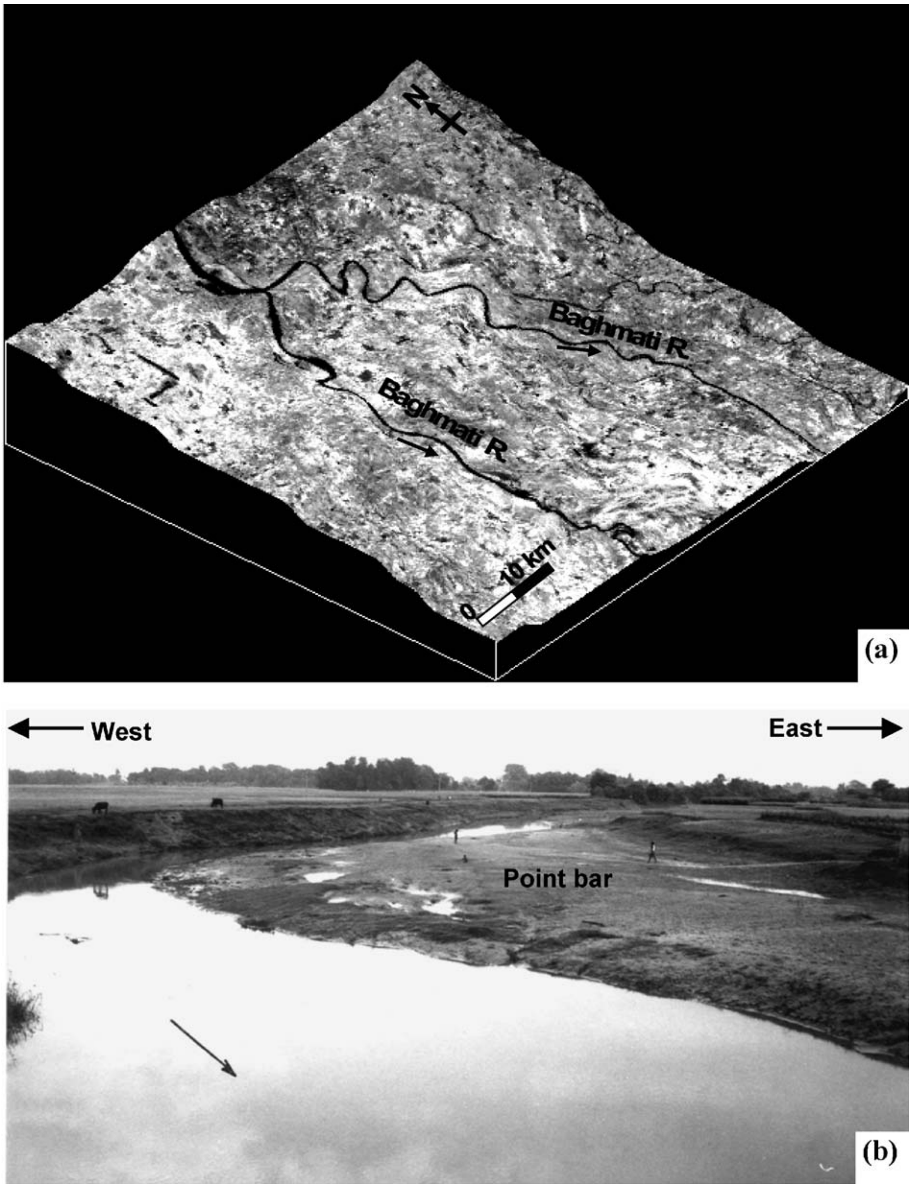

Fig. 12. (a) Satellite image (band 4, IRS LISS II) of the area around Sheohar draped over the DEM showing the regional slope to the SE. (b) Partially abandoned Baghmati river at Shiwaipatti. The growth of the point bar in the area indicates aggrading stage of the channel (flow direction is towards south).

Belwa. It was represented by the Balasundar Nala and two other smaller anabranches west of this window (see Fig. 5) during 1986. However, during 1989, the Balasundar Nala and the palaeochannel flowing through Mirzapur gradually disappeared through sedimentation. Further changes in channel configurations occurred after 1989 and the south-flowing left anabranch is now partially abandoned due to sedimentation at Belwa village (discussed above).

The avulsion history in this window is substantiated by the remote sensing investigations. The old SSE aligned Mirzapur–Hiramma channel is seen in the 1989 False Colour Composite (FCC) as a thin white line near Paharpur (Fig. 7). At the same place, a large, SE aligned white channel of sand is seen in the 1989 FCC. It marks a recent avulsion event in a SE direction, followed by abandonment of this reach. The SE slope of the area, as seen in the DEM (Fig. 12a), would encourage the river to avulse in the SE direction during flood periods. The present-day scenario is represented by the FCC prepared from the 2000 data (Fig. 7), which clearly shows that the right anabranch of the Baghmati river originating at Belwa village is now partially abandoned. The field photograph of this partially abandoned channel (Fig. 12b) at Shiwaipatti bridge (downstream of Paharpur) shows that the channel carries only a meager flow during the non-monsoon period, and therefore, it is not picked up on the 2000 image. However, during monsoon season, this channel carries significant flow and floods the nearby agricultural area.

5.4. Window 4: Baghmati river near Minapur

The 1924 map (Fig. 13) shows four channels: the SE flowing Siari Nadi in the NE part of the window, the SE flowing Baghmati river from Turki to Tengraha, the E–SE flowing overspill channel in the middle part of the window and the Burhi Gandak river in the SW portion of the window. In 1924, most of these channels

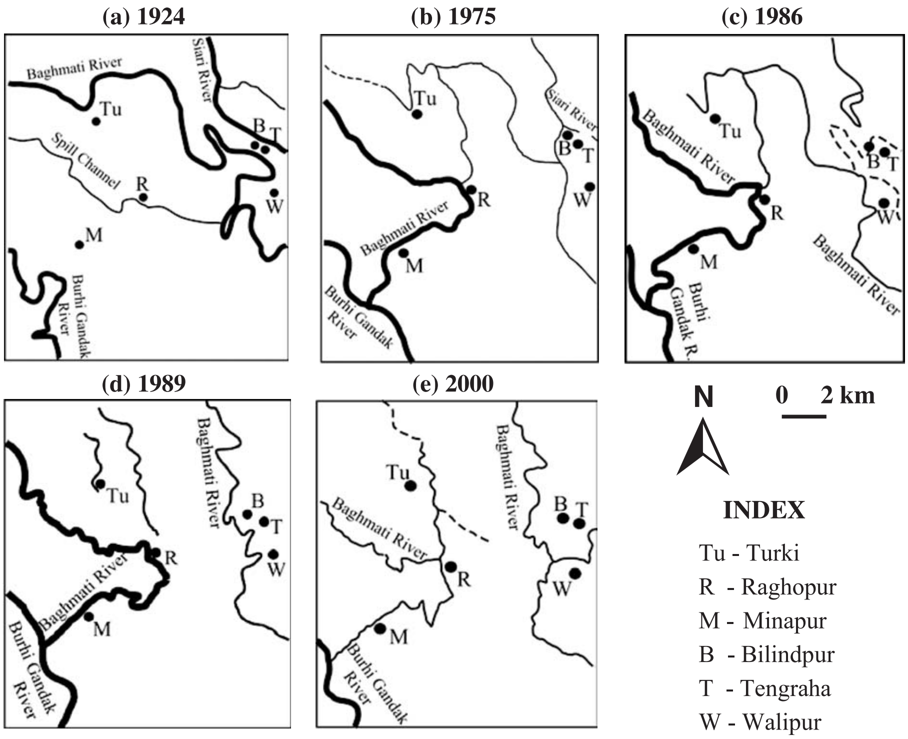

Fig. 13. Window 4: Baghmati river near Minapur as seen in (a) 1924, (b) 1975, (c) 1986, (d) 1989, and (e) 2000. In 1924, both anabranches of the river were flowing in a SE direction. In the following periods, river flow has shifted into the spill channels and one of the main anabranches has joined the Burhi Gandak River. Presently, all these channels are largely abandoned, because of avulsion in the upstream region.

were separated and there was no apparent connection between them.

A series of westward avulsions occurred in this window between 1924 and 1975. The Siari Nadi avulsed into the south flowing Baghmati Nala at Bilindpur in 1934 and the Baghmati river avulsed at Paharpur (window 3) and Raghopur in 1974 to join the Burhi Gandak river via Minapur. Since 1975, there has not been any major change in the channel positions in this window except for the abandonment of a few minor channels. The sudden change in flow direction of the Baghmati river from SE to SW at Raghopur is quite dramatic. The present-day SW flow does not confirm to the regional SE slope of the region. When a SE aligned canal was trenched at Raghopur in 1976 to join the Baghmati river with the Baghmati Nala, it became silted in 2–3 years. This particular avulsion may have been triggered by uplift along the West Patna Fault (WPF).

Owing to avulsions at Bilindpur in 1934 and at Paharpur (window 3) in 1974, the Siari Nadi, Baghmati river of 1924 and Baghmati Nala became largely abandoned. The Siari Nadi is presently full of vegetation with greatly reduced river flow. At present, the depth and width of the river is around 2 and 18 m, respectively. However, local information suggest that

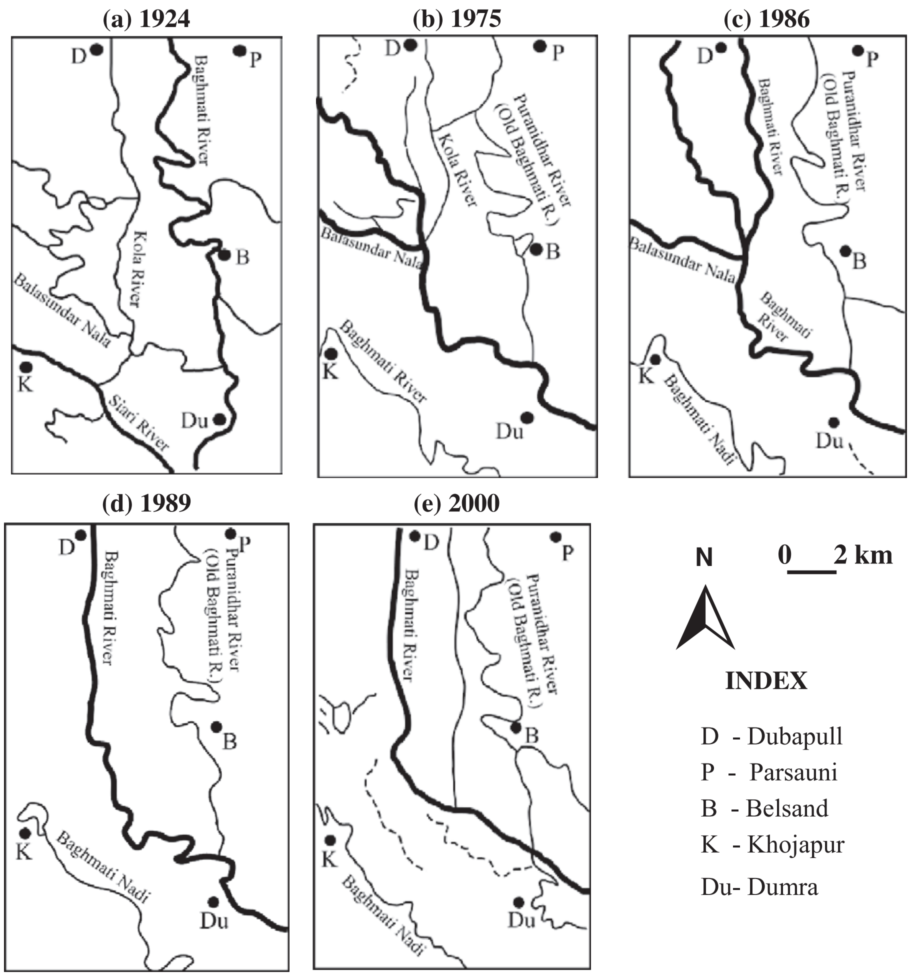

Fig. 14. Window 5: Confluence between the Kola Nadi, Puranidhar River and Siari Nadi as seen in different years: (a) 1924, (b) 1975, (c) 1986, (d) 1989, and (e) 2000. The area shown is marked by frequent switching and river capturing in this period of 76 years.

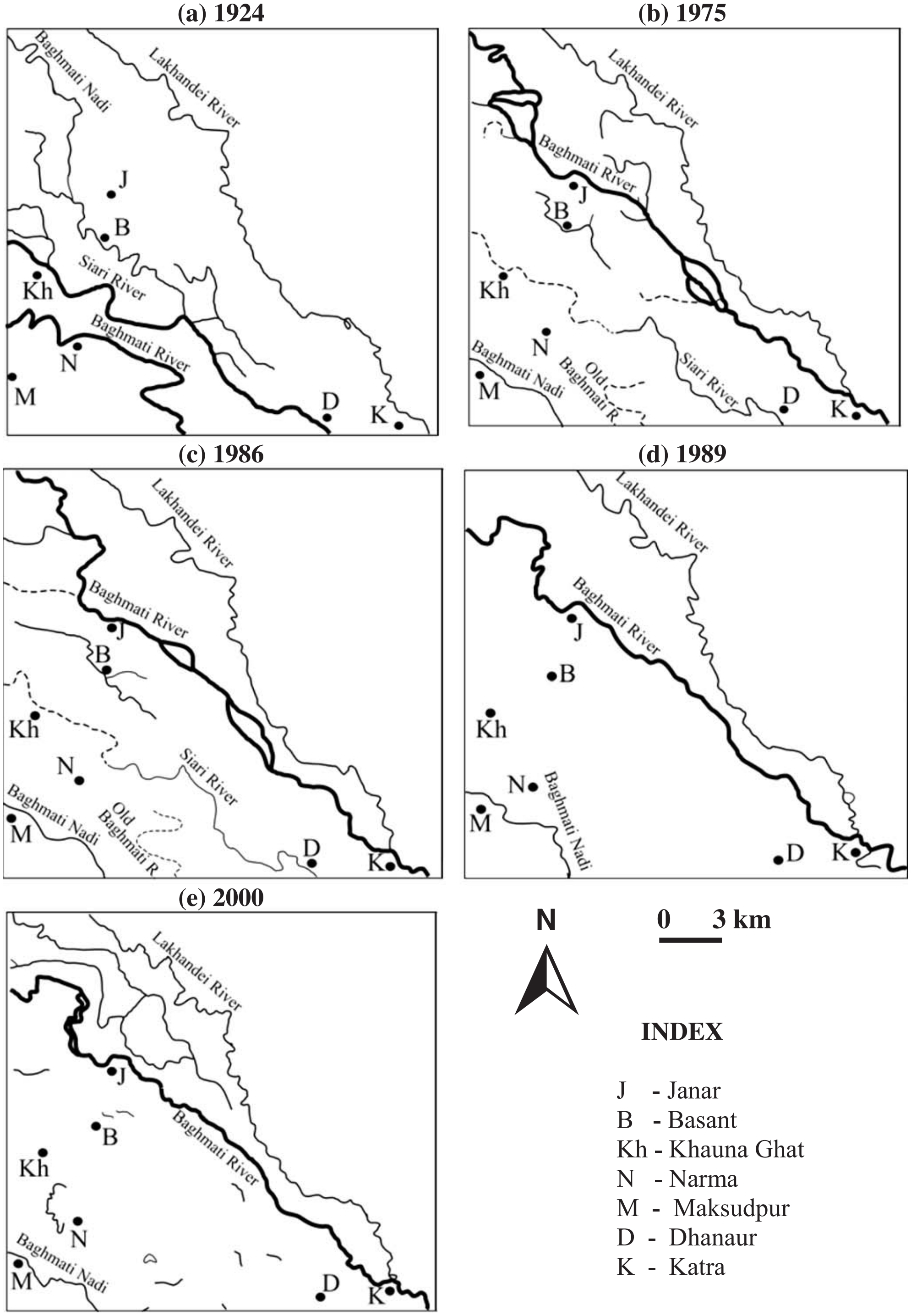

Fig. 15. Window 6: Midstream reach of the Baghmati river, Siari Nadi and Lakhandei Nadi as seen in different years: (a) 1924, (b) 1975, (c) 1986, (d) 1989, and (e) 2000. The window shows the initiation of a new channel from Janar to Katra, which finally became the main Baghmati river. Further, owing to avulsion in the upstream region, various channels became abandoned.

the river was around 50–60 m wide and 5–6 m deep in 1930.

5.5. Window 5: confluence between Kola Nadi, Puranidhar river and Siari Nadi

The 1924 map of this window (Fig. 14) shows several tributaries namely, Kola river, Balasundar Nala and Baghmati river, all of them ultimately meeting the Siari river at different points. The Baghmati river was also connected to the Lakhandei Nadi through an east flowing overspill channel upstream of Belsand. Between 1924 and 1975, many of these links dried up and a major reorganization of channels resulted in drying up of major portion of the Siari Nadi and shifting the confluence points. By 1989, the Balasundar Nala and

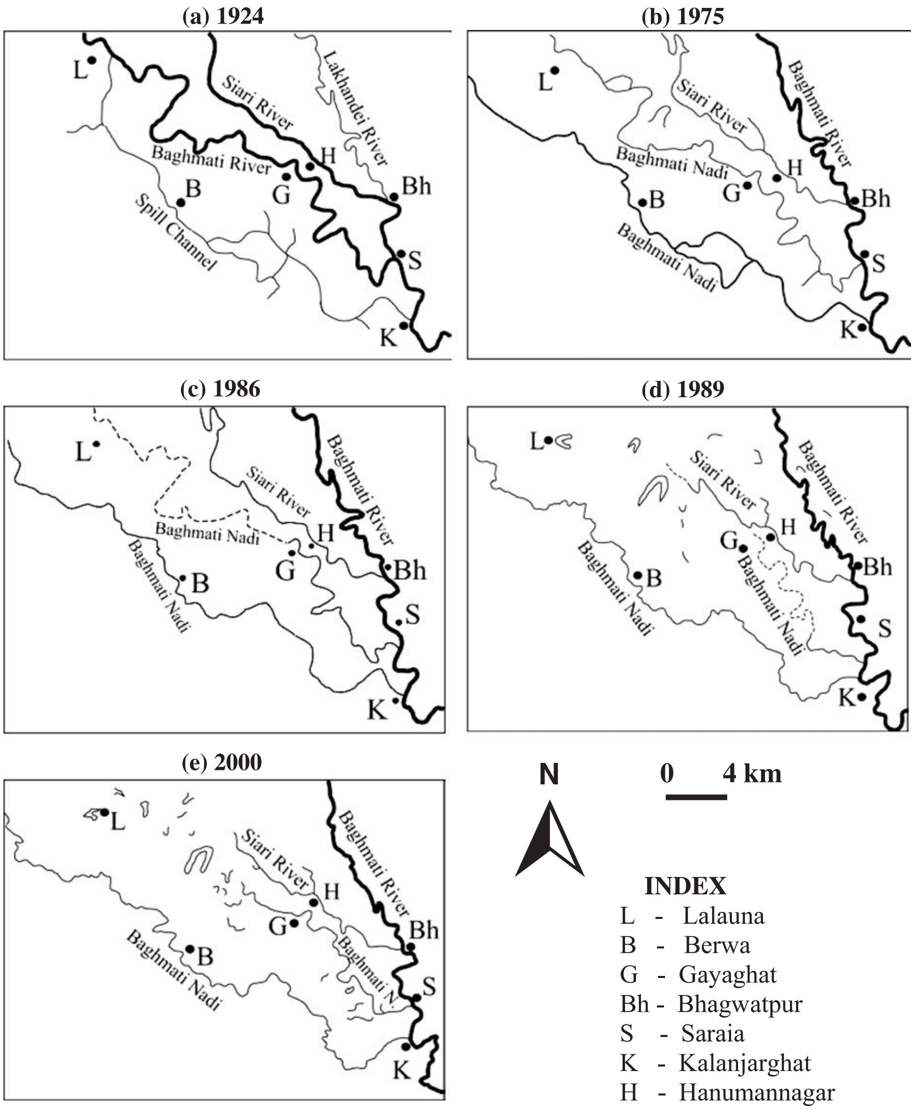

Fig. 16. Window 7: The confluence points between Baghmati river and its old channels as seen in different years: (a) 1924, (b) 1975, (c) 1986, (d) 1989, and (e) 2000. Owing to frequent avulsion and switching of channel flow, the name of the river channels and the location of major confluence points have changed over time.

Kola Nadi were completely abandoned and the Baghmati river emerged as the major channel in the region. The dimension of the abandoned channel of Baghmati Nadi (Puranidhar) as seen in the field and a 110-m-long bridge on the river section at Parsauni village vouch for its past importance among the channel assemblage.

5.6. Window 6: the confluence at Katra

This window shows the confluence of major tributaries of the Baghmati river system, namely the Baghmati river, Siari Nadi, and Lakhandei Nadi at Katra (Fig. 15). This window shows the development of a new channel and the effect of upstream avulsion events. In 1924, three tributaries flowed separately and met downstream of this window. A SE course of the Baghmati river through Janar and its confluence with the Lakhandei at Katra developed during 1924–1975, which is still maintained today. The combined flow of Baghmati and Lakhandei downstream of Katra is presently very active and has caused extensive damage due to flooding and lateral movements in recent years.

In this window, the old Baghmati river (in 1924) shifted in a SW direction and a new channel through Maksudpur came into existence. The other notable changes reflected in this window are the partial abandonment of Baghmati Nadi (lower left corner) and the major channel of Siari Nadi. Presently, both these channels carry meager discharge during non-monsoon periods and their cross section at present have reduced significantly due to sedimentation and growth of vegetation. The channel flowing through Janar and Katra is presently the major channel and particularly after the Belwa (window 1) avulsion, most of the discharge was diverted through this channel causing development of overspill channels and extensive flooding in the nearby area.

5.7. Window 7: the final confluence of Baghmati tributaries

This window shows the final confluence of all the major tributaries of the Baghmati river system at different points. The Baghmati river, after its confluence with the Lakhandei at Katra, meets the Siari Nadi at Bhagwatpur, the Baghmati Nadi at Saraia and another Baghmati Nadi at Kalanjarghat (Fig. 16). The most remarkable feature of this window is that the geographical locations of the confluence points have remained unchanged since 1924. However, the flow conditions at these confluence points have been affected significantly by avulsion events in the upstream reaches.

In 1924, the Bhagwatpur and Saraia were the main confluence points where the main channels of Lakhandei, Siari and Baghmati met. During 1924–1975, the Baghmati Nadi avulsed westward into a spill channel (Baghmati Nala), thereby reducing the flow significantly at Saraia confluence. The abandoned river still carries a high discharge in its downstream reaches. Hence, the Bhagwatpur confluence is still very active and causes extensive flooding and damage. Kalanjarghat later developed as the major confluence point assisted by the avulsion into Baghmati Nala. Downstream of Kalanjarghat, the Baghmati river system essentially flows as a single channel system, finally meeting the Kosi river.

6. Discussion

The causative factors and mechanisms of anabranching are quite different from the better-known multi-channel braided system (Knighton and Nanson, 1993). Braided channels are formed due to deposition of coarse sediment load, especially sand and gravel grade, within the channel to form bars, which are small relative to the size of the channels, (Brice, 1964; Cant and Walker, 1978; Smith and Smith, 1984; Friend and Sinha, 1993). However, an anabranching system consists of multiple channels separated by islands, which are usually formed by incision from existing floodplain and are large relative to the size of the channels. The Baghmati river is braided in its upstream reaches, reflecting its high and coarser sediment load and relatively high channel gradient (>0.00050). The braided reach of the Baghmati river at Dhengbridge station ($w/d = 117$) carries an average annual sediment load of 10.4 million tonnes, which is quite high with respect to available discharge and suggest the dominance of aggradation process. Indeed, the ratio of annual sediment load to average annual discharge for the Baghmati river is quite high (0.07) in comparison to other rivers in the world (e.g. Amazon 0.005, Mississippi 0.005, Nile 0.013, Danube 0.013, Rhine 0.002, Kosi 0.021) (Czaya, 1983; Milliman and

Meade, 1983; Sinha and Friend, 1994). Further, bankfull discharge (1100 m^3/s), sediment grain size (D_{50} = 0.083 mm) and slope data (0.00053) at Dhengbridge also suggest a braided channel pattern in this reach (Ferguson, 1984).

A few kilometers downstream, the Lalbakeya river, one of the major tributaries of the Baghmati river, also introduces additional sediment load to the river. After the confluence with the Lalbakeya, the channel needs to increase its capacity to maintain or increase sediment transport. Low sediment transport capacity related to the available sediment load is reflected in extensive deposition at the confluence point itself (Fig. 7). The transport capacity is related to the stream power per unit area, which is defined as the product of discharge (Q) and channel slope (s) divided by channel width (Bagnold, 1966). Hence, the sediment transport capacity can be increased by increasing the channel slope or discharge (through increase in velocity) or both. The channel is almost straight (P = 1.0–1.2) in this reach, and therefore, the gradient cannot be increased by reducing the channel sinuosity. The uplift along the Sitamarhi Fault and West Patna Fault has further reduced the channel gradient. It appears therefore that after the confluence with the Lalbakeya, the Baghmati channel is not able to increase its gradient.

In this low gradient area, the anabranching pattern is explained on the basis of sediment transport capacity as well as channel sedimentation process. One way to increase the transport capacity is by increasing the velocity of the river either by changing the channel shape (w/d ratio) or by increasing the number of channels, i.e. through anabranching at a constant discharge and channel roughness (Nanson and Huang, 1999). As discharge and channel roughness parameters are fixed for a particular reach, the transport capacity can be increased by either changing the channel shape or the number of channels. On the basis of theoretical model results, Nanson and Huang (1999) suggested that for a given channel, the optimum velocity would be at the width–depth ratio of 2, which may not be feasible to achieve. Further, for channels of width–depth ratio higher than 2, the velocity can be increased by reduction in width or increase in the channel depth at constant discharge and channel roughness. Although the width/depth ratio of the Baghmati river is reduced from Dhengbridge to Khoripakar, as observed in the field, it appears that the channel is still not able to transport all the available sediment load. Hence, the initiation of new anabranches may be the only way to increase the sediment transport capacity of the Baghmati river.

Further, dominance of aggradation process is evident from high sedimentation rate in modern rivers (1192 tonnes/km^2 by hydrological data) as well as Holocene sedimentation rate (0.7–1.2 mm/year; Sinha et al., 1996). High sedimentation load is responsible for plugging of channel followed by crevasse splays and formation of new anabranch. Therefore, in this strongly aggradational setting, anabranching is a by-product of relative dominance of sedimentation relative to onward transport of sediments.

Downstream of Hayaghat station, the river again changes into a single channel system. The main reason is reduction in sediment load specially the coarser fraction (see Table 1) which is accompanied by a decrease in width/depth ratio (15 at Hayaghat) and increase in Manning's roughness coefficient (0.03 at Dhengbridge to 0.06 at Hayaghat; source: CWC). Decrease in width/depth ratio is responsible for increase in velocity, as for channel having width/depth >2, the increase in flow velocity can be achieved most readily by increasing depth and reducing width (Nanson and Huang, 1999). Further, the increase in roughness reduces the effect of anabranching on the increase of sediment transport capacity.

New anabranches, generally initiated during flood events, are characterised by wide and shallow channels with gradient equal to that of the floodplain. One such event was observed in the field, a few kilometers downstream of Katra where a small, wide and shallow anabranch was initiated during a flood event in 1998 and now follows the floodplain gradient. After initiation, the development of any new anabranch depends on the base level adjustments with respect to the channel it joins. At the confluence with a pre-existing channel, a knickpoint is formed in the anabranch, which triggers channel degradation in the downstream reach of the anabranch and migrates upstream (Schumann, 1989). The upstream knickpoint migration through degradational processes results in steeper channel gradient and lower width–depth ratio at downstream of the knickpoint. In this process, the width–depth ratio of the upstream end of the reach remains higher than that of the downstream reach for some period.

In the present case, the development of anabranches of the Baghmati river is governed by base-level adjustments between the Baghmati river and the older, entrenched Lakhandei Nadi. In the anabranched reach, the upstream station (Runisaidpur) is characterised by higher width–depth ratio (16) than the width–depth ratio (10.8) of the downstream reach (Benibad).

Further, the average channel gradient keeps on decreasing with the progressive upstream knickpoint migration. Over time, the average channel gradient will be less than the initial degradational phase and channel will be characterized by low width/depth ratio. Finally, the channel would attain base level, i.e. the bed level of the pre-existing older channel. Hence, low width–depth ratio and gentler gradient would normally indicate the mature stage of the anabranch, as is the case with all the abandoned channels (older anabranches) of the Baghmati river (Table 2).

After attaining its base level and achieving a low gradient (similar to that of the pre-existing older channel), aggradational processes start. Aggradation processes reduce the channel bankfull capacity and hence a new avulsion may take place during overbank flooding. After an avulsion event, the main flow mostly reoccupies a pre-existing channel. The development of a new anabranch causes a reduction in discharge along the anabranch, which in turn increases the aggradation in the channel, and often leads to abandonment. This abandoned channel would later be "infilled", i.e. incorporated into the floodplain (Nanson and Croke, 1992), e.g. the Kola Nadi in the middle reaches of the Baghmati system (Fig. 10).

Table 2
Width–depth ratio of abandoned channel

No.	Channel (location)	Abandonment	Stage	Width (m)	Depth (m)	*w/d* ratio
1	Kola Nadi (Dhankaul)	Before 1959	A	6	1.3	4.6
2	Baghmati River (Shiwaipatti bridge)	1989–2000	PA	30	5	6
3	Baghmati Nala (Berwa)	1974	PA	8	1.5	5.3
4	Baghmati River (Gayaghat)	1974	PA	9	1.35	6.67
5	Puranidhar Nadi (Parsauni)	1924–1959	PA	30	5.5	5.5
6	Siari Nadi (Muzz–Sitamarhi Road)	1934–1937	PA	18	2.5	7.2

A—Abandoned; PA—partially abandoned.

It is clear that avulsion is the main process for the initiation of anabranches and the dynamic behaviour of the Baghmati river. Our studies show that the length of new anabranches, initiated by avulsion is variable (25–72 km) (see Fig. 5). A total of eight major avulsions has occurred Baghmati river in the last 230 years. These avulsions are not concentrated at a single nodal point, but they occur throughout the anabranching reach of the river (see different windows in Fig. 5). Lateral shifting during an avulsion event, mostly E to NE, varies from 5 to 6 km. Such decadal-scale avulsion events characterize the Baghmati river as "hyper-avulsive". After an avulsion event, the main flow mostly reoccupies a pre-existing channel but abandons its previous course only partially. During the monsoon period, all the channels are active due to the high discharge resulting in a complex anabranched pattern. However, during the non-monsoon period, the flow is confined to the main channel only.

In the Baghmati river basin, "channel reoccupation" is the main avulsion mechanism. It is in line with the observations of Aslan and Blum (1999) in the Trinity, Nueces and Colorado river in USA. Our study supports their observation that such avulsions are prevalent during early stage of valley filling when there exists an unfilled accommodation space. The interfan area in north Bihar plains signifies such an unfilled accommodation space in spite of a rapidly aggradational setting. Shallow (2–3 m) as well as moderately deep (~ 100 m) sedimentary records from the Baghmati plains have also recognized "repeated flood deposits" (Sinha et al., in press) and crevassing and channel reoccupation have been recognized as main avulsive processes.

The upstream limit of the anabranched reach of the Baghmati river is fairly dynamic too. Historical reconstruction of the channel configuration shows that the position of the first anabranch at Khoripakar has shifted upstream by about 21 km in a period of 76 years (1924–2000) resulting in an increase in the length of the anabranched reach by about 25 km. A close examination of the recent satellite image (2000) also reveals that the left anabranch is only partially active at present (Fig. 7). The Belwa avulsion (window 1) has reduced the flow and another avulsion at Raghopur (window 4) now diverts a significant portion of the Baghmati into the adjoining Burhi Gandak river (Fig. 13). These evidences point to the highly dynamic nature of the hyperavulsive and anabranching Baghmati river system.

7. Conclusions

The anabranching Baghmati river located in an interfan setting in north Bihar Plains shows hyperavulsive behaviour. The major conclusions from this paper are as follows:

1. The anabranching reaches of the Baghmati river are characterized by medium to high sinuosity, low width–depth ratio, gentle channel gradient, variable peak discharge, frequent overbank flooding and high sediment load.
2. Channel migration history mapped through a series of maps and satellite images shows a dominant eastern trend and we record eight major avulsions and several minor avulsions in the last 230 years. This reflects a decadal scale of avulsion events (20–60 years) and characterizes the dynamic behaviour of this river system.
3. Lateral movements of channels during a major avulsion event vary from 5 to 6 km.
4. The anabranching and avulsion processes are interrelated and the actual position of anabranching has also changed several times. The start of the anabranching reach has shifted upstream by about 21 km in a period of 76 years (1924–2000) resulting in an increase in the length of the anabranched reach of about 25 km.
5. Avulsion is not concentrated at a single nodal point but occurs at different locations throughout the anabranching reach of the river.
6. Sedimentological readjustment and neotectonic tilting are the triggering mechanisms for avulsion and "reoccupation" of an old channel is the most preferred mode of avulsion in this region.

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