

Natural hazards in the Ghaghara River area, Ganga Plain, India

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Abstract The Ganga Plain is one of the most densely populated regions of the world due to its fertile soil and availability of water. The rivers of this plain are the lifeline for millions of people of this vast alluvial plain. All rivers of this plain are characterized by narrow channel confined within wide valley. Continuously increasing pressure of population on this plain has led to the intensification of settlement even into the valley of the river. This unplanned expansion has enhanced the damage due to flooding during high-discharge period and lateral erosion during low-discharge period. Flooding and lateral erosion are identified as fluvial hazards in the Ghaghara River area. Extensive studies have been carried out on flooding, but not much attention has been paid to the phenomenon of lateral erosion. However, it has been observed that lateral erosion is an independent fluvial hazard that operates during low-discharge period. Low degree of compaction due to the presence of sandy and silty facies in the river valley deposits, mass movement, palaeo-current pattern, and fractures initiates and enhances the lateral erosion. The present paper deals with the fluvial hazards in the Ghaghara River area.

Keywords Ganga Plain · Ghaghara River · Natural hazard · Flooding · Lateral erosion · Mitigation

1 Introduction

Man is controlled and guided by rivers everywhere, but this is for the first time that man is also affecting and controlling the rivers up to some extent since last century. Encroachment of man on the natural cycle of the river has polluted the water, disturbed the ecosystem, changed the transporting capacity, increased the bed load, suspended load, and initiated the fluvial hazards. With consequent mounting of demographic pressure and developmental activities, the risks of loss of life and property have increased. In addition to natural phenomena, there are other causative factors such as population growth, ill-planned human

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settlements, imprudently located developmental projects, which give rise to increasing occurrence and intensity of river-born disasters. Natural disasters have occurred throughout the world since the origin of the earth, but increase in population, rapid urbanization, and lack of resources intensify their effect each year.

India is the second most populated country in the world, where a large percentage of world's population (16.4%) is living on limited land area (2.4%). The average population density of India is 324 (2001 census), whereas for Uttar Pradesh state, it is 690 in 2001 when compared to 548 in 1991. It shows continuously increasing pressure of population on land in the Uttar Pradesh.

Many cities, towns, villages, and hamlets of Uttar Pradesh are located at the bank of Ghaghara River. Due to high population growth and its increasing pressure on land, man has started living even within the valley and flood plains of the river. The settlements located in the peril zone of the Ghaghara River are under continuous threat due to flooding and lateral erosion during high- and low-discharge periods, respectively.

Flooding is a common disaster and has been studied extensively for many rivers of the world. The great floods of Huang Ho in China; 1931, in Bangladesh; 1987 and 1988, in US; 1993, of Yangtze in China; 1998, in Mozambique; 2000 are all well known. Next to Bangladesh, India is the most flood-affected country in the world. In India, north Bihar, Brahmaputra, and Sikkim Himalayan rivers have been described for flooding (Kale 1998). The study area lies in the Uttar Pradesh, one of the most flood-affected states in India, the other four being Bihar, West Bengal, Assam, and Orissa. Uttar Pradesh has experienced massive flooding in 1998, 2000, 2001, and 2008. It is estimated that 30 districts of this state are seriously prone to flooding. The incidence of flooding is frequent in eastern Uttar Pradesh, which is broadly the result of spilling of rivers such as Kuwana, Rapti, Chhoti Gandak, Ghaghara, and Great Gandak (Singh 2007a). The Ganga Plain rivers such as Ganga (Singh 2007b), Gandak (Singh and Singh 2005), and Sarda (Mitra et al. 2005) had been analysed for geomorphology, sedimentology, and flood characteristics. Channel migration has been described in the middle Ganga basin (Philip et al. 1989) and along Ghaghara River (Agarwal and Mishra 1987). High water during monsoon, low degree of compaction of the sediments, and a large amount of runoff materials from watershed cause the river channel to shift laterally by more than 300 m in Brahmaputra (Haque and Hossain 1988). It is considered that the stream bank erosion is caused by flooding and erosion is greater on sandy than on silty soils (Geyer et al. 2003).

While working on the Ganga Plain rivers, it has been observed that apart from flooding and stream bank erosion during high-discharge period, lateral erosion operates as an independent hazard during low-discharge period. The lateral erosion is common all along the Ghaghara River, but is more prevalent in the in middle reaches where narrow channel is confined within wide valley made up of sandy and silty sediments with low degree of compaction. Lateral erosion during low-discharge period is an acute hazard between Barhaj and Gothani. Such events may become more frequent and severe in future with changes in land use and rapid urbanization. The present paper deals with the natural hazard in the Ghaghara River area with special attention to lateral erosion.

2 Study area

Ganga Plain is one of the main physiographic regions of India lying between the Himalaya in the north and Peninsular Plateau in the south. It is drained by numerous rivers such as

Ganga, Yamuna, Ghaghara, Rapti, Gandak, and Kosi. The study area is located between $26^{\circ}05'55''$ – $26^{\circ}15'01''$ N latitude and $83^{\circ}03'52''$ – $84^{\circ}34'16''$ E longitude near the border of Uttar Pradesh and Bihar states (Fig. 1). It consists of alluvium deposited by various river systems under different climatic conditions and surface processes in which coarser sediments were deposited under high-energy environment and finer sediments during low-energy environment (Singh et al. 2009). Older alluvium (Bhangar) and newer alluvium (Khadar) are the two morpho-stratigraphic units in the classical literature of the Ganga Plain (Pascoe 1917; Pilgrim 1919).

Older alluvium is located at an elevation of 10–20 m above the river level and makes the higher interfluvial areas. It is free from frequent flooding and therefore most suitable for settlement and agriculture. Newer alluvium forms the river valley terrace and is located at an elevation of 5–10 m above river level. This terrace is not suitable for settlement but can be used for agriculture, as it is often affected by flood. The flood plain is located at an elevation of 2–5 m above the river level. Water reaches almost every year on this plain. It is neither suitable for settlement nor for agriculture (Bhardwaj et al. 2010a, b).

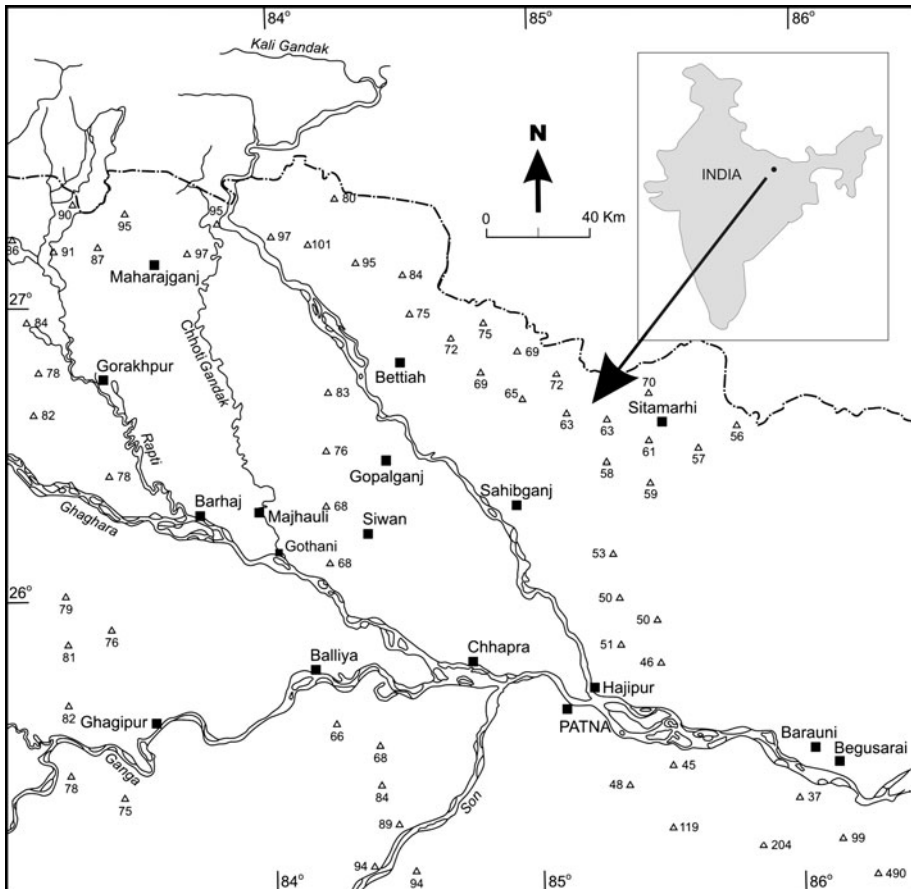


Fig. 1 Location map of the study area

Ghaghara, a significant river of the Ganga Plain, is one of the largest affluents of Ganga. It rises from the Matsang glacier in the Himalaya near Mansarowar Lake in Tibet at an elevation of about 3,962 m. Travelling a distance of about 1,080 km and flowing into NW–SE direction, it joins the Ganga River near Maharajganj, Chhapra district of Bihar state. The main tributaries of Ghaghara are Sharda, Sarju, Chauka, Kuwana, Rapti, Chhoti Gandak, Jharahi, and Daha. Rapti and Chhoti Gandak rivers join with Ghaghara near Barhaj in Deoria district of Uttar Pradesh and Gothani in Siwan district of Bihar state, respectively. Ghaghara is very notorious and is prone to fluvial hazards between these two confluences, Barhaj and Gothani. Ghaghara is a unique river with respect to fluctuation of discharge (Very high discharge during monsoon and very low discharge during dry season), high sediment load, and channel instability. It has higher discharge than the Ganga before its confluence near Maharajganj, Chhapra district of Bihar.

3 Methodology

The study was performed in two stages, (1) field work and (2) laboratory work. Survey of India topographical sheets and satellite data were used for the computation of valley and channel width, bank height, and sand-bar parameters. Detailed field work was carried out at selected stations to document the lithological units for facies analysis and to collect the sample for laboratory analysis, both laterally and vertically in the channel and river bank deposits. The trenches were made at some places on the bar surface for litholog and palaeocurrent measurements. The bank sections were cleaned to document the facies and collection of samples for granulometric analysis. Azimuths were measured for palaeocurrent pattern from the directional sedimentary structures and also for the trend of fractures. Local information was collected from the residents settled at the bank of the Ghaghara River.

4 Results

The data collected reveal many distinctive features.

The valley of Ghaghara is very wide (5–15 km) with narrow channel (100–200 m during summer) (Table 1). The wide valley occupied by the narrow channel provides an unsuitable place for settlement. The sinuosity of the river is 1.25, and so the channel form is braided in nature. At some places, channels are 1–2 km away from each other, and at others anastomosing pattern are visible. The main geomorphic features are giant mid-channel bar, side bar, natural levee, and flood plains. The giant braid bars (5–10 km long and 1–5 km wide) and lateral bars locally known as diara are used for settlement and cultivation of zayad crops. Table 1 shows the size of the channel bar deposits, channel and valley width, and bank heights. Braid bars are the sand bars located within the channel, whereas lateral bars are side bars, denoting sand bar formed in curved braided streams almost attached to the stream bank (Bluck 1974). At the downstream part of the side bar, there is an area of still water slough (Reineck and Singh 1980), which represents an abandoned pool formed by lateral channel migration and filled by muddy sediments.

A prominent braid bar (6 km long and 1–1.25 km wide), lateral bar (2.5 km in length and 1.0 km in width located 5 km downstream of Barhaj), and river bank section exposed near Barhaj were analysed for granulometric, palaeocurrent, fracture, and facies analysis. Lithologs were prepared for the channel bar and river bank deposits to describe the facies

Table 1 Parameters of Ghaghara river and its sand-bar deposits between Barhaj and Gothani

S.N.	Latitude	Longitude	Sand-bar size in km		Valley width in km	Banks height in m	
			Length	Width		Left	Right
1	26°16'01"	83°34'16"	6.73	3.31	7.51	70	71
2	26°14'38"	83°38'29"	4.69	2.49	6.36	70	17
3	26°16'34"	83°40'45"	3.91	1.64	4.62	68	70
4	26°15'47"	83°45'24"	4.89	1.77	5.13	67	68
5	26°13'27"	83°46'15"	1.72	0.50	6.32	67	66
6	26°12'01"	83°49'14"	3.33	1.62	5.04	66	66
7	26°11'36"	83°51'14"	2.07	0.63	2.05	67	66
8	26°08'04"	83°59'46"	10.06	3.03	5.82	64	65
9	26°07'50"	84°02'11"	4.22	0.87	5.22	64	66
10	26°05'55"	84°03'52"	3.46	1.24	5.29	63	63

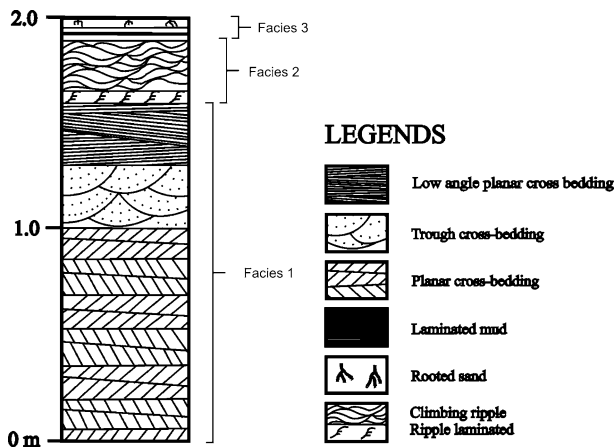


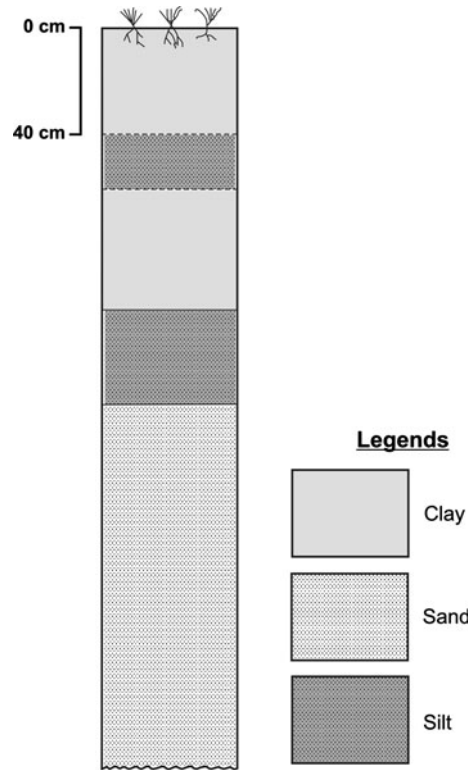
Fig. 2 Litholog showing facies of the channel bar deposits

and their association. The lithologs prepared provide information about the facies and substrate for sand-bar deposits (Fig. 2). Three major facies in the channel bar deposits and three in the river bank deposits have been identified.

Facies 1: sandy facies It is very common and present in the lower to middle part of the channel bar deposits. It consists of 0.20- to 2-m thick lensoid/tabular units, which are laterally persistent for several hundreds of metres. It occurs mostly in co-sets where thickness of individual unit varies from 10 to 20 cm. This unit shows sedimentary structures such as planar cross-bedding, trough cross-bedding, and ripple laminations. The azimuths of the planar cross-bedding were measured for palaeocurrent analysis.

Facies 2: silty and clayey facies This lithofacies is developed near the top of bar sequence. It is characterized by 5- to 20-cm thick climbing ripple lamination in silt and parallel laminations in silty clay with mud lenses. Climbing ripple lamination is produced by the migration of small ripples when much sediment is available in suspension.

Fig. 3 Litholog showing facies of the river bank deposits



Facies 3: aeolian rooted sandy facies During summer, aeolian processes dominate over fluvial ones and may form sand dunes in pockets on top surface of the channel bar deposits. Dunes are 1.5–4 m in length and 0.5–1.0 m in height. It is characterized by 20- to 50-cm thick solitary planar cross-bedding. This facies is made up of well-sorted fine sand and silt.

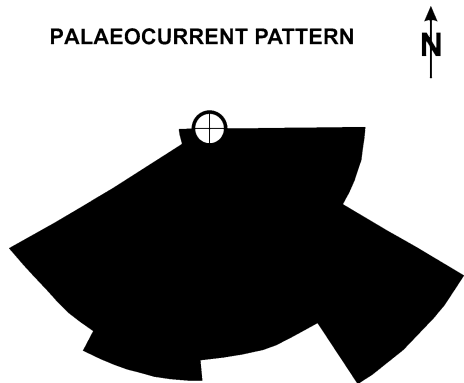
The sandy unit showing planar cross-bedding, trough cross-bedding, and ripple lamination makes the major portion and is present in the lower to middle part of the channel bar deposits. Silt and clay unit, showing climbing ripple lamination and laminated mud, constitutes minor portion and is present above the sandy facies. Aeolian sandy facies, if present, makes the negligible percentage of the channel bar deposits.

The facies of the river bank deposits are sandy, silty, and clayey (Fig. 3). The sandy facies is prominent in the lower and middle part. This 120- to 200-cm thick unit is devoid of sedimentary structures, only faint low-angle discordances are visible at some places. The sandy unit is underlain by 20- to 40-cm thick silty unit. The upper most part is 40- to 50-cm thick clayey unit. The facies of the river bank deposits are laterally persistent, only thickness and percentage of different litho units may vary from place to place.

4.1 Palaeocurrent pattern

The channel bar deposits consist of large scale cross-bedding, formed in response to prevalent flow direction by the migration of large bed forms. The palaeocurrent was analysed to determine the direction of palaeo-flow of the river and also the movement of bed forms. Statistical parameters such as vector mean (θ_v) indicate that the average current direction is

Fig. 4 Rose diagram showing Palaeocurrent pattern



168°. Vector strength or vector magnitude ($L\%$) also known as consistency ratio, the measure of dispersion or consistency of the current direction is 81, and variance (S^2), the quantitative estimate of palaeocurrent variability is 1,343. The palaeocurrent pattern (Rose diagram) as measured from planar and trough cross-bedding in the channel bar deposits shows distinct bimodality (Fig. 4). It indicates that there are two main directions for the movement of bed forms and the flow of water in the channel. Palaeocurrent pattern (vector mean) suggests a general southward flow. High vector magnitude values indicate the presence of persistent unidirectional current.

4.2 Granulometric analysis

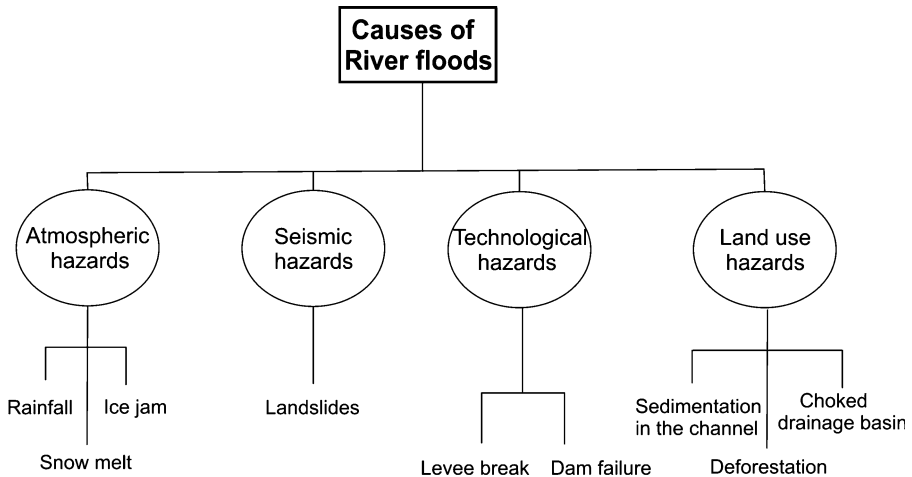
The granulometric parameters indicate that the sediment size is 2.4 and 2.28 ϕ for lateral and braid bar deposits, respectively. The sediments are fine sand, and its size varies between 2 and 3 ϕ for different sandy facies of the channel bar deposits. The sediment size in the river bank deposits varies from 2.3 to 3.5 ϕ for sandy units. The river bank sediments are made up of fine sand. Sand is a non-cohesive granular material with low degree of compaction and has a capacity for sliding, removal, and scouring. Finer sediment (clay) has resistance against sliding, removal, and scouring action.

5 Natural hazards

River-born natural hazards are classified into two types: (a) flooding and (b) lateral erosion.

5.1 Flooding

It is the most widespread of all the natural hazards. Floods have a very high impact upon homeless, moderate in terms of injuries, and low loss of life in comparison with other natural hazards (Foster 2000). The main reasons of flooding in this area are high snow melt, and mass movement in the upper reaches and poor drainage, blockade, and high rain fall in the catchments area, and dam/levee failure (Fig. 5). The river valley is narrowed by constructing artificial levees to provide the land for settlements for continuously increasing population. When discharge exceeds the capacity of the channel, flooding occurs on adjacent areas and can have destructive effects. It originates in two ways: a—logging and spreading of water due to heavy rains and b—breaking of levee due to rise of water level in



Modified from Foster (2000)

Fig. 5 Causes of flooding

the river channel. At Turtipar, gauge site located between Barhaj and Gothani, flood has occurred for 56 times in 1983, 1988, and 1996 (Dhar and Nandargi 1998) due to heavy rainfall in the catchment. The levee failure is the main reason of flooding in this area.

5.2 Lateral erosion

The analysis of the lateral erosion by Ghaghara River is of both social and scientific interest. It originates because of its alluvium content made up of sand, silt, and clay in different proportions. The (sand and silt) sediments are non-cohesive and unconsolidated, so they can undergo weathering, transportation, and sliding. The geomorphological, facies and granulometric analyses indicate that the lower and middle part of the channel banks and sand-bar deposits are made up of sand and silt and are prone to erosion, scouring, and mass movement, leading to lateral erosion. The abandoned channel of the river consists of sandy substrate that also initiates the lateral erosion.

It has been identified that rivers of the Ganga Plain are aligned in a preferred direction due to lineaments (Singh and Rastogi 1973; Singh et al. 1996). Rohini, Rapti, Gandak, Ghaghara, and Ganga faults in eastern Ganga Plain were identified and described by Mohindra and Parkash 1994; Singh and Singh 2005. Ghaghara is oriented in WNW–ESE to W–E direction; it means it is aligned parallel to the lineament/fault. The fractures developed during dry season in the clayey facies of the river bank deposits are parallel to the direction of the river/lineament/fault. During low-discharge period, frequency of the formation of these fractures is high. These fractures are 5–10 cm wide and 10–20 m in length (Fig. 6). With time, these fractures widen, collapse, and fall due to mass movement and enhance lateral erosion.

Ghaghara is entrenched in the channel bar deposits during the low-discharge period to maintain its hydraulic gradient. With the increase in discharge, the river overtops the channel bar and results in the sedimentation of fine grained material as over-bank deposits. The channel bar facies are underlain by over-bank facies, and this feature is laterally



Fig. 6 Fractures at the left bank of Ghaghara River near Barhaj

extensive. The capping of the fine grained material over the sandy facies attracts the population for settlement, as it can be used for cultivation too.

During high-discharge period, when sandy facies are submerged, sand becomes wet and consolidated. However, during low-discharge period, the sandy facies that makes the middle and lower part of the channel bar and river bank is exposed. The exposed non-cohesive dry sand with low degree of compaction slides due to mass movement. It moves/slides to achieve the stability, i.e. the angle of repose (sand cannot stabilize at steeper angle). Sliding and removal of sand from the river bank and bar deposits is a continuous process during low-discharge period. It results in the slumping of the upper fine grained clayey unit (Fig. 7) and causes lateral erosion. Thirty years of observations due to residence of corresponding author in the study area and local information indicate that the rate of lateral erosion is not uniform and varies between 1 and 5 m yr⁻¹. At many places, river has come very close to the settlement, and people are in continuous threat because of the lateral erosion (Fig. 8). Within a year, Kurhe Parasia village near Barhaj has disappeared due to lateral erosion.

6 Mitigation

Recent disaster statistics reflect an alarming trend of increasing losses from natural disasters. Land use and climate change are the primary cause of this trend. This factor increases vulnerability to natural disasters. It is argued that internal factors such as disaster-related science and policy are also responsible for the inability to stem or reverse the upward trend in disaster damage (Weichselgartner and Sendzimir 2004).

Nature creates flood and lateral erosion, and man makes it hazards. Although there is no known way to prevent flood and lateral erosion, much can be done to minimize the damage. Protection, not prevention, therefore, is the real solution. Increasing urbanization brings new challenges in reducing the threat of disaster. Yet disasters are often ignored until they strike, when the damage has been done and relief is the only response. There should be a noticeable change in policy, with more emphasis on loss reduction through mitigation, preparedness, and recovery programme.

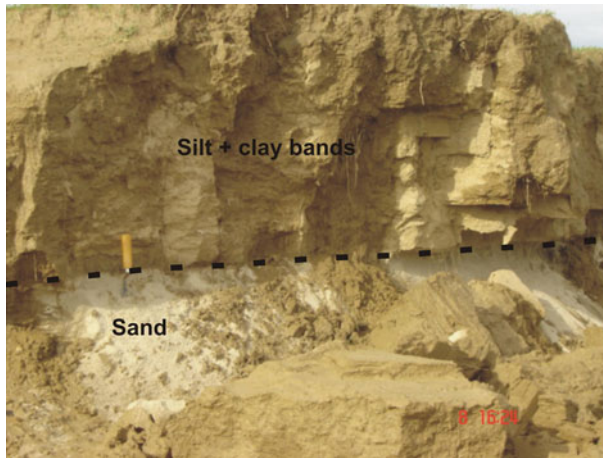


Fig. 7 Mass movement in Sandy facies near Barhaj



Fig. 8 River is approaching close to the settlement due to lateral erosion

In the study area, impact of flooding and lateral erosion can be minimized with structural and non-structural controls (Fig. 9). The structural control includes the construction of embankments, vegetation, lateral dams to control the direction of river, dumping of the boulders, sand and cement bags, and raising of villages. Plants are used for stabilizing and reducing stream banks erosion. Vegetation reduces stream-bank erosion by reducing stream flow velocity and trapping of sediments. The only way to tackle stream bank and the growing menace of flood is to control deforestation, denudation, and soil erosion and proper planning. Construction of artificial levee and dumping of boulders and sand/cement bags are very common methods for the mitigation of flooding and lateral erosion in the area (Fig. 8). Such a task must be undertaken on most urgent basis to avoid the disaster.

The non-structural factors include the forecasting, warning system, palaeocurrent and facies analysis, emergency security, delimitation of flood and lateral erosion zone, and land use planning. Further, while making the levee/embankments, palaeocurrent and fluctuation

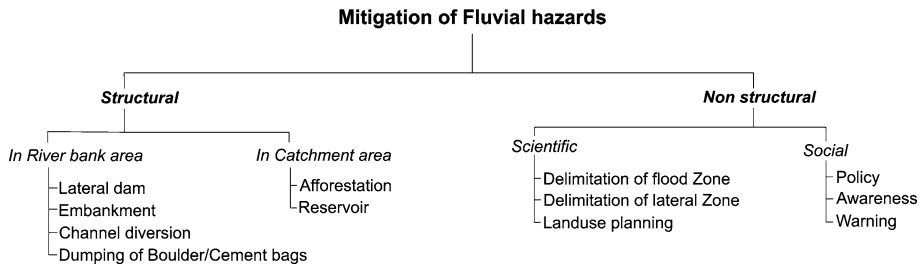


Fig. 9 Mitigation of fluvial hazard

of discharge should be taken into consideration. Policy should be made so that people do not make their settlements in the peril zone of the river. Facies, palaeocurrent, and granulometric analysis should be made prerequisite for deciding the issue of settlements.

7 Discussions and conclusions

Humans’ ecologically disruptive activities have resulted in the change of the river channel (Gregory 2006), water, sediment, and nutrient fluxes. The Ghaghara River channel is confined within wide valley (Singh et al. 2010). Part of the valley beyond the channel is used for settlement by increasing population. Giant braid bars and lateral bars in which clayey facies overlies, the sandy facies are preferred for settlement. If bank height is more and facies is clayey, lateral erosion is negligible. However, the low bank height and sandy facies exaggerate the lateral erosion.

The area is characterized by sand, silt, and clay of the Quaternary period. The combination of these sediments, a low degree of compaction, scouring action, and development of fractures, makes the river to adjust their bed configurations, and so the river channel shifts laterally. In Mississippi River in Louisiana, sandy substrate compositions are considered important for the late Holocene avulsion history (Aslan et al. 2005). The fractures/lineament enhances the lateral erosion. A neotectonic terrain increases the rate of landscape change and may cause natural hazards in tropical areas (Petley 1998).

The palaeocurrent analysis tells us about the palaeo-flow direction of the river, and so the future current direction can be predicted. The Palaeocurrent pattern is bimodal; however, the river is flowing in a single general direction; it means one component of the flow is active in different directions that may be responsible for lateral erosion.

It is believed that stream bank erosion takes place during high magnitude flood conditions and some locations along a stream channel are more likely to erode than others (Geyer et al. 2003). All the river bank areas where sandy facies are prominent and/or fractures are developed between Barhaj and Gothani are prone to lateral erosion. The dominance of clayey facies and absence of fractures in the river bank areas are stable. The flooding and bank erosion occurs during high-discharge period, however, the lateral erosion operates during low-discharge period.

It is concluded that the increasing incidence of disasters is an indicator of unsustainable development. In most of the cases, man is responsible for river-born disasters. Due to increase in population, man has started living in the peril zone of the river. This makes lateral erosion a devastating hazard. The area is affected by flooding and stream-bank erosion during high-discharge period and by lateral erosion during low-discharge period.

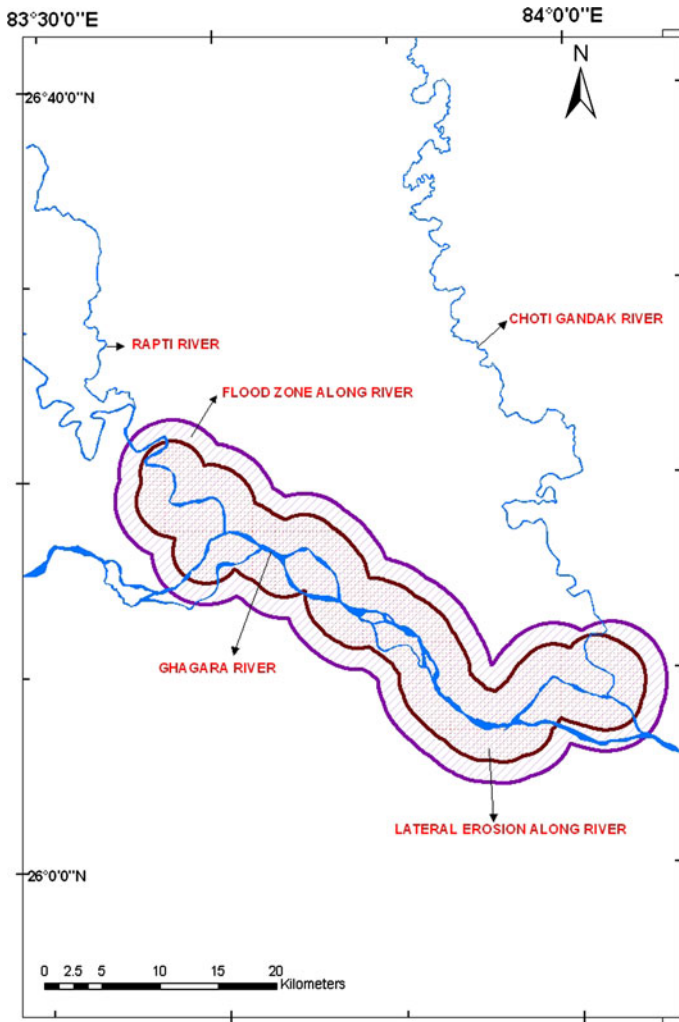


Fig. 10 Flood and lateral erosion map

The main reasons for the lateral erosion are the sandy facies, low degree of compaction, scouring, fractures, palaeocurrent, and mass movement. The settlements located at the bank of the Ghaghara River are under threat of fluvial disasters not only during high-discharge periods but also during low-discharge periods.

The trend of the river channel shifting, facies association, erosional pattern, and the river discharge should be analysed to save the society from natural hazards. Understanding of river dynamics is prerequisite for the mitigation of river-born disasters. Damage impacts can be minimized by better floodplain and river valley management, control measures for flood and lateral erosion, improved disaster preparedness and setting up of forecasting and warning system. The flood and lateral erosion zone map have been prepared (Fig. 10), as people have no idea that they are living in the danger zone of the river. There should be strong scientific management; rather, there is a need to keep people away from the peril zone of the river.

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