



Spatiotemporal Migration of the River Ganga in Middle Ganga Plane: Application of Remote Sensing and GIS Technique

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Abstract

The process of channel migration becomes crucial to a populace living in or near the floodplain or to government organizations involved in planning or upholding the infrastructure within or nearby the floodplains. Spatiotemporal migration of the River Ganga in the Middle Ganga Plain for about forty years (1972–2018) was measured using Landsat images, coupled with extensive ground checks. Assessment of satellite images of 1972, 1990, 2000, 2010, and 2018 reveals the Ganga River migrated within its valley, demonstrating significant changes in the channel geometry on a decadal scale. Heavy rains promote the enhancement of the sediment load in the channel triggering a further increase in the sinuosity index. However, the overall sinuous nature of the Ganga River channel is mainly fault-controlled. The variable lateral migration of the channel seems related to heavy rains and reactivation of chute channels within the river valleys. The lateral movement of the river is one of the critical factor responsible for the failure of the older floodplain (bank) within the valley by the undercutting process.

Keywords Riverbank migration · River Ganga · Channel migration · Remote sensing

Introduction

The river migration across floodplains and the sporadic erosion of River Valley Terrace Surface are a natural process (Leopold et al. 1964; Yang 1971; Singh et al. 1999; Randle 2006; Pati et al. 2008; Chakraborty and Mukhopadhyay 2015). Channel shift is a common phenomenon in meandering and braided river systems on Earth's surface. In general, channel shift is mainly the river movement back and across its valley over a period of time (Chakraborty and Mukhopadhyay 2015). River migration concerning space and time is a manifestation of a river to its anthropogenic and natural activities.

Such changes may include 2D changes (e.g., adjustments in channel planform) along with specific 1D change (e.g., changes in depth, width, and thalweg length) in the

river morphology (Wallick et al. 2006; Ahmed et al. 2018). However, if the channels incised as it is the case with most of the rivers of the central Ganga Plain, they can migrate inside their valleys only. The process of channel migration becomes crucial to a populace living in or near the floodplain or to government organizations involved in planning or upholding the infrastructure within or nearby the floodplains. Fluvial architecture and channel pattern are sensitive indicators of river migration and can accommodate in response to changing sediment load, hydrology, and active tectonics (Goswami et al. 1999; Schumm et al. 2000; Pati et al. 2008; Shukla et al. 2012; Singh 2015; Singh et al. 2016, 2017; Kanhaiya et al. 2019). Lateral shifting of river banks implies an asymmetric position of the channel in the river valley. The river responds to changes in the sediment–water discharge (Yang et al. 1999; Schumm et al. 2000; Thakur et al. 2012). The river migration occurs due to the change in the river width, sinuosity, braiding characteristics, etc. (Parua 2002). The river migration causes a considerable amount of riverbank erosion, inundation, and movement of the population living close to the riverbank. The River Ganga is the trunk river of the Indo-Gangetic Foreland Basin. After making confluence with the Yamuna

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River at Allahabad, it becomes the axial river of the basin. It is flowing incised into its river valley, which is carved within the Upland Terrace Surface (T_2 surface) of the Ganga Plain (Singh 1996; Shukla et al. 2001; Srivastava and Shukla 2009; Shukla et al. 2012; Jayaswal et al. 2016). Several studies on the spatiotemporal reallocation of riverbank have been carried out for many rivers like the Ganga River (Srivastava and Singh 1999; Swamee et al. 2003; Pati et al. 2008; Thakur et al. 2012; Chakraborty and Mukhopadhyay, 2015; Debnath et al. 2017; Bhowmik et al. 2018; Ahmed et al. 2018), River Varuna (Prakash et al. 2016), River Majuli (Mani et al. 2003), Brahmaputra River (Kotoky et al. 2005), River Tummel, Scotland (Winterbottom and Gilvear 2000), River Indus (Harbor et al. 1994), River Bhagirathi-Hugli (Pal et al. 2016).

The traditional perspective to collect data about the migration of rivers has been ground-based investigations that are extravagant, time-consuming, and complicated. Remote sensing data provide a synoptic view and the opportunity of studying the dynamic characteristic of rivers using temporal remote sensing data. With consideration of all the previous studies, the present work focuses on the channel morphology variations of the Ganga River in the Middle Ganga Plain, using morphological and cross-sectional approach. The current work is focused on determining the migration behavior of the River Ganga, within the Valley in Middle Ganga Plain (between Allahabad and Buxar), by analyzing 46 years of satellite imagery. The River Ganga flows in the SE direction following the general slope of the Gangetic Plain, which is densely populated and highly cultivated (Fig. 1). Therefore, a small change in river flow direction affects these populated areas. The study of channel dynamics and flow patterns of the Ganga River will be a positive approach to minimize the effect of such changes.

Ganga River and the Study Area

The Ganga River, which is the axial river of the Ganga Plain, originates from Gangotri glacier (Gomukh in Himalaya) and flows for about 2500 km, ultimately debouches into the Bay of Bengal forming the largest Ganga–Brahmaputra delta on the shelf and Bengal Fan in the deep sea. The Ganga River carried a large sediment load throughout the Quaternary period and deposited over the foreland basin to form the northern Gangetic Plains. The Ganga Plain evolution has taken place under the changing setting of extra- and intra-basinal tectonics and climate (Shukla et al. 2001; Shukla and Bora 2003; Tandon et al. 2006).

The River Ganga has been divided into seven reaches based on morphology and channel characteristics (Singh

and Singh 1992; Singh 1996; Shukla et al. 2012). The sectors designated as 0: Gaumukh to Haridwar; I: Haridwar to Garhmuktesar; II: Garhmuktesar to Allahabad; III: Allahabad to Buxar; IV: Buxar to Barh; V: Barh to Farraka; and VI: Farraka to the Bay of Bengal (Fig. 2a), (Singh and Singh 1992; Singh 1996, 2001; Singh et al. 1996).

The Ganga Plain is divided into six geomorphic units on the regional scale (Singh 1996; Shukla et al. 2001) such as MP (Marginal Plain Upland Surface), T_2 (Upland Terrace Surface), F (Megafan Surface), PF (Piedmont Fan Surface), T_1 (River Valley Terrace Surface), and T_0 (Active Flood Plain Surface) (Fig. 3).

For the present study, the GRV sector III (Singh 2007), which is from Allahabad to Buxar, has been chosen because of frequent changes in channel characteristics and flow patterns of the Ganga River (Fig. 2a). The Ganga River course near Allahabad is controlled by Allahabad fault (Fig. 2b), while near Varanasi, it is restricted by Chunar–Saidpur fault (Swamme et al. 2003; Shukla and Raju 2008; Shukla 2013). From Allahabad to Chunar, the River Ganga flows in southeast direction, and the valley is bounded by the Craton (Vindhyan Supergroup) in the south. From Chunar to Saidpur, it turns toward NE direction, and then, it further follows the natural gradient to ENE from Saidpur to Buxar with the development of paired floodplains. This GRV III sector has a humid subtropical climate, characterized by the cold winter season and the monsoon season (June–September) when it receives the maximum rainfall of 70–80% of the total annual rainfall (Singh et al. 2007). The Ganga River shows substantial seasonal variation in sediment–water discharge, and it is at maximum during the in-monsoon season when all the channel characteristics are changed (Pati et al. 2008) as compared to the dry season in May.

Methodology and Data Used

The thalweg lines or river centerline were digitized from the oldest datasets (1972) along the center of the active river channel for straight reaches and along the eroded bank, for meandering channel. For the year (2018), centerline of the river has been digitized from OLI imagery and validated with selected field checks. The succeeding centerlines of the river were overlaid, and their migration behavior from the base year (1972) was calculated. The migration of the river was measured with the migration polygons method. The migration rates of the river are then calculated by using the following method (Giardino and Lee 2011).

$$\text{Migration rate (Rm)} = (A/L)/y$$

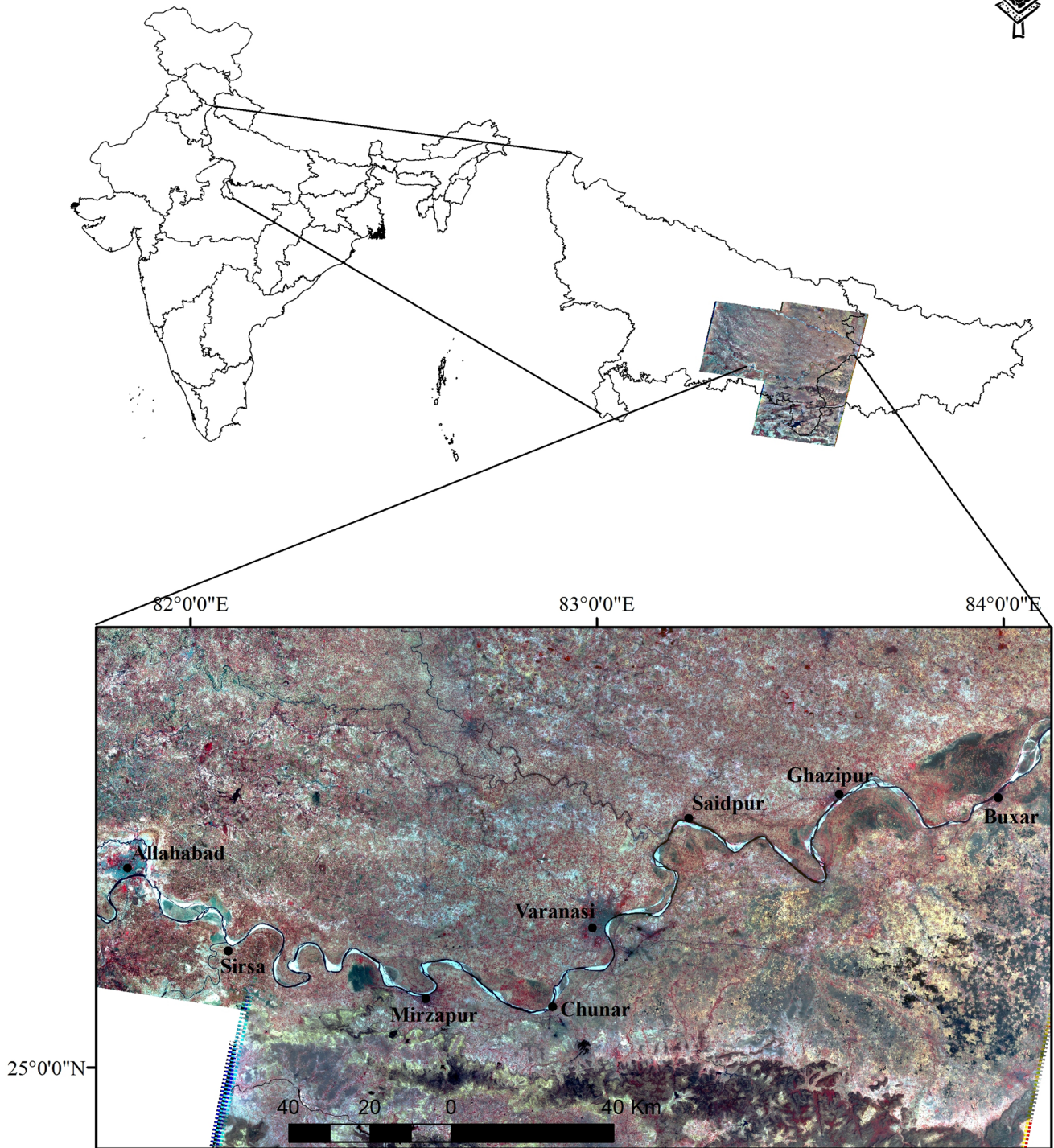


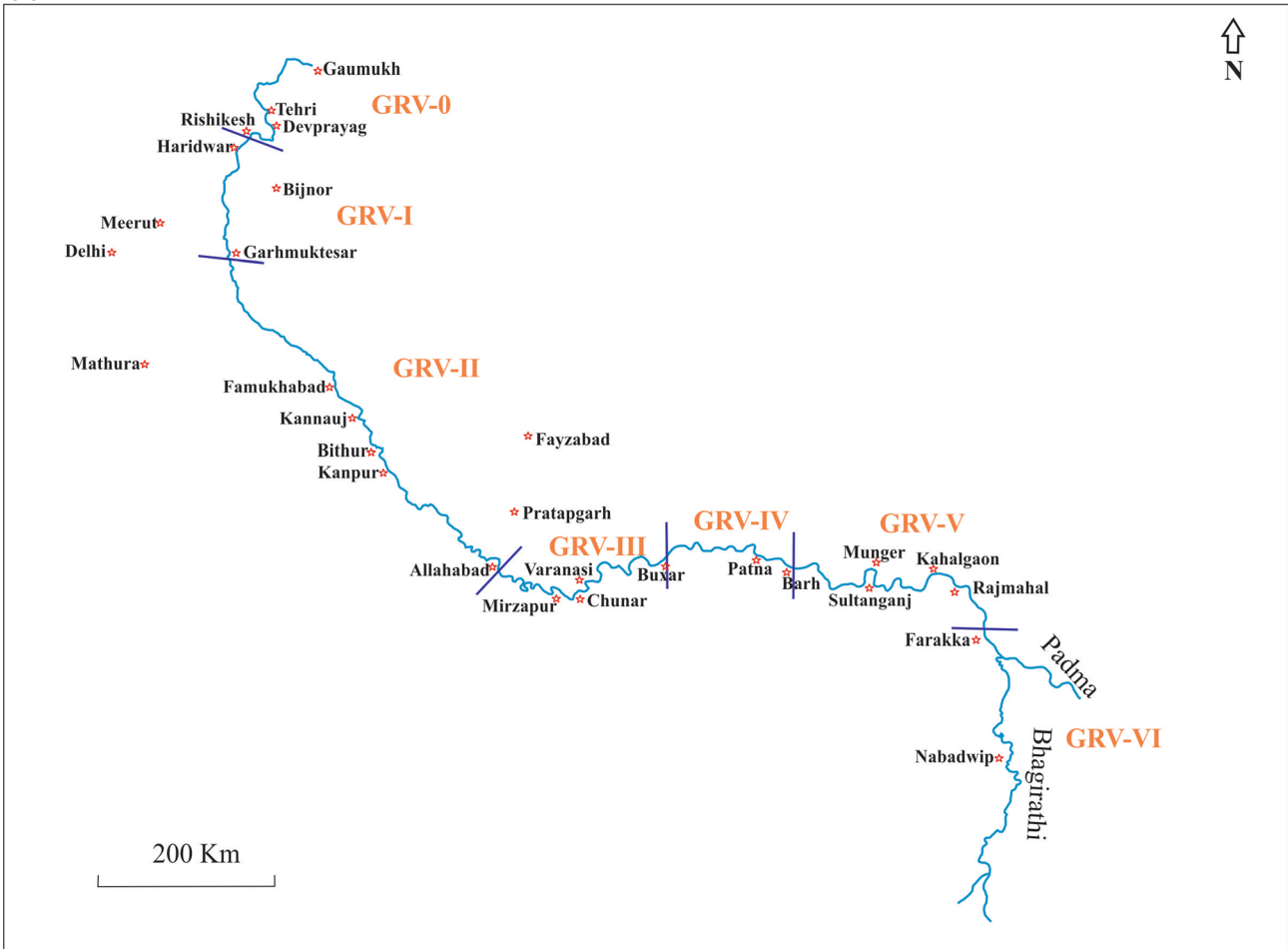
Fig. 1 Figure showing location of the study area, Landsat images of path/row (142/43, 142/42, and 143/42) band combination are 432

where L = length of centerline, A = polygon area, and y = time interval.

The river migration was determined, for the years 1972, 1990, 2000, 2010, and 2018, based on the demarcation of a

series of transects perpendicular to the channel and computing the distance between the intersection points and the channel bank (Leopold 1964; Gurnell et al. 1994; Giardino and Lee 2011). In this process, transects were drawn at an

(a)



(b)

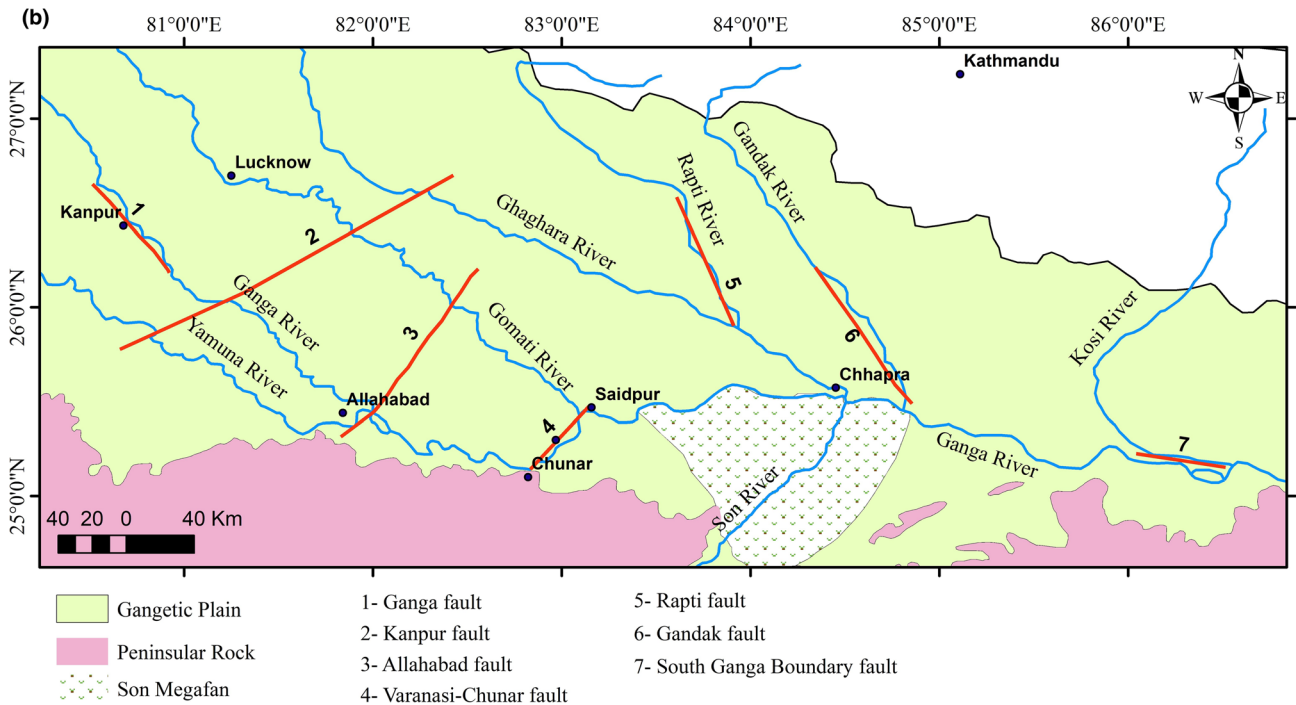


Fig. 2 a Schematic map showing the Ganga River and divisions of Ganga River valley into seven sectors (modified after Singh et al. 2007). **b** Diagram showing structural controls on the flow of major rivers in the central Gangetic plain (after Swamme et al. 2003)

interval of 30 km for each individual location to reduce the prejudice of choosing the migration points. The mathematical formula is as follows Giardino and Lee (2011):

$$\text{Migration distance (Dm)} = T_1 - T_2$$

here, T_1 and T_2 are the concerned investigation years of successive river migration.

The overlay maps of river bank migration are prepared (Fig. 4) over time phase from 1972 to 2018 to get the overall scenario of the erosion and deposition patterns within the valley of the River Ganga in Middle Ganga Plain (Allahabad and Buxar). The investigation of river bank migration was carried out from different Landsat imageries in the Arc GIS platform. GIS software, ArcInfo-10, was used to estimate the riverbank migration in the study area of the Ganga River.

Landsat images (data) have become as necessary tools to understand of changes in the Earth's surface triggered by natural disasters, climate, and anthropogenic change. In this study, orthorectified images of Landsat sensors MSS

(Multi-Spectral Scanner) for the year 1972, TM (Thematic Mapper) for the year 1990, ETM + (Enhanced Thematic Mapper Plus) for the year 2000–2010, and OLI (Operational Land Imager) for year 2018 are used for the analysis (Table 1). The Ganga River banks in the study area were manually digitized (visual interpretation) for different temporal span, viz. 1972, 1990, 2000, 2010, and 2018 at the scale of 1:50,000. The digitization errors like overshoot, under-shoot, etc., are eliminated through topology in Arc GIS.

The SI (sinuosity index) is defined as the ratio between the length of the meander belt axis to the channel length (Leopold et al. 1964; Mueller 1968; Singh et al. 2019).

Results and Interpretation

Assessment of satellite images (data) of 1972, 1990, 2000, 2010, and 2018 reveals that the Ganga River migrated within its valley, demonstrating significant changes in the channel geometry on a decadal scale (Fig. 4). The remote sensing data of years 1972–2018 are preferred because, during this interval, the monsoonal rainfall was decreased, influencing the river characteristics and migration (Singh et al. 2019). The River Ganga in Middle Ganga Plain (Allahabad and Buxar) (Singh et al. 2019) is divided into

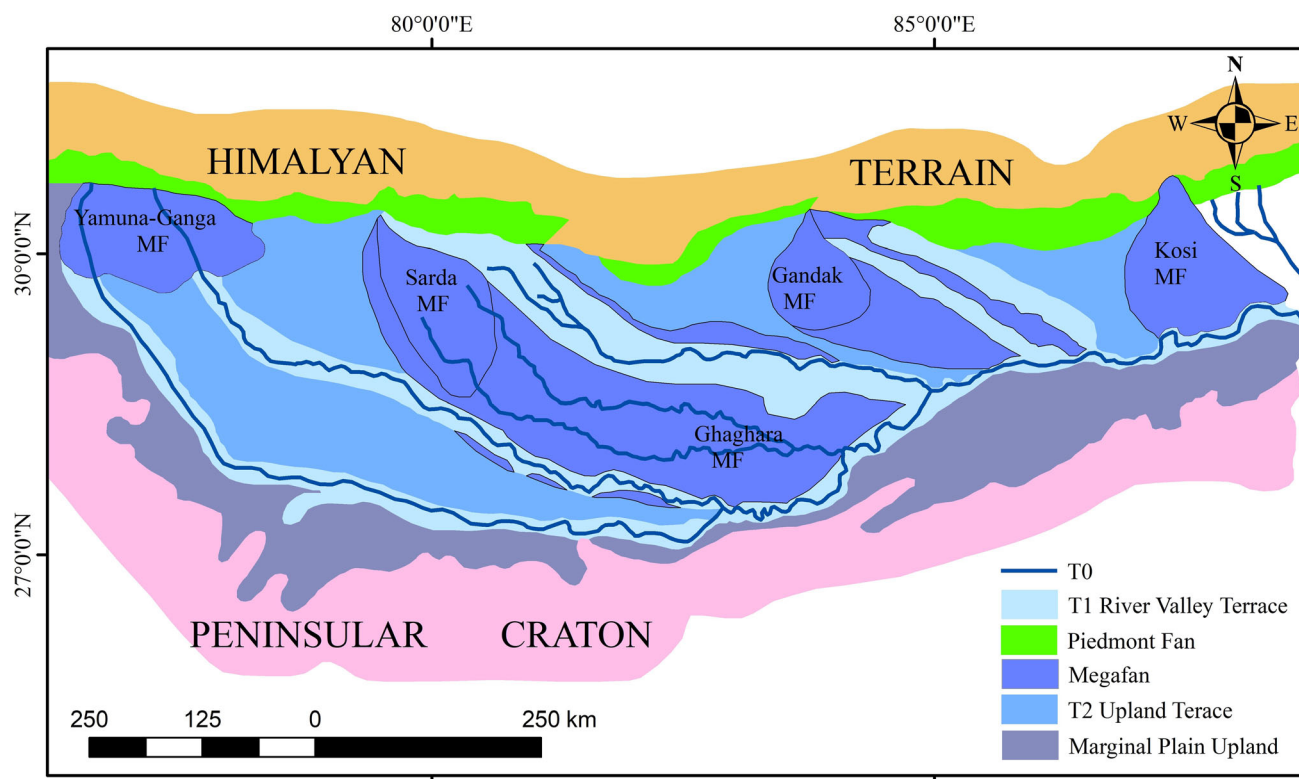


Fig. 3 Geomorphic map of the Ganga Plain showing regional geomorphic surfaces (Modified after Singh 1996; Shukla et al. 2001)

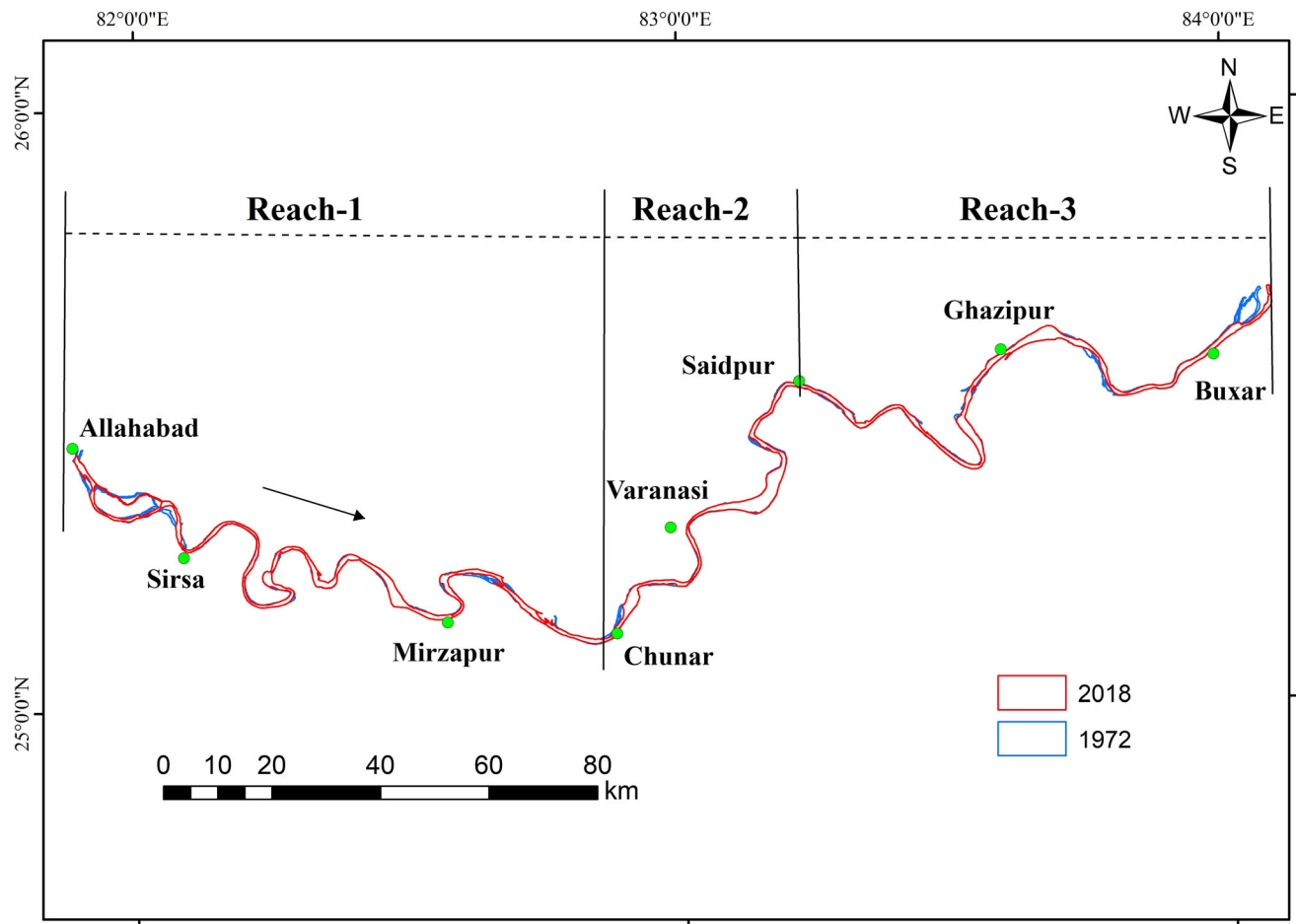


Fig. 4 Reach-wise division and Historical (1972–2018) positions of the Ganga River

three reaches based on valley width, floodplain–channel–bar characteristics. The three reaches are (a) Allahabad to Chunar reach, (b) Chunar to Saidpur reach, and (c) Saidpur to Buxar reach.

(a) Allahabad to Chunar Reach

The River Ganga receives the cratonic influx of sediment from the River Yamuna. Between Allahabad and Chunar, the general flow direction of the Ganga River is southeast. After the confluence of the Yamuna River at Allahabad, the Ganga River is showing a braided channel pattern. Pati et al. (2008) observed neotectonic activity in the River Ganga course near the Allahabad district. The different geomorphic features of migration as meandering scars, paleochannels, abandoned meandering channels, meander cutoffs, etc., are noticed in this reach within the valley of the Ganga River. In the Allahabad to Chunar reach, the active channel width varies from 1700 to 221 m (Table 2). Within this reach, the Ganga River channel shows sinuosity, ranging from 1.33 to 1.37 (Table 3). The increased

shift of channel belt near Allahabad on the right bank in 2018 is 4.93 km (Table 4). While the maximum change observed in mid-channel is 2.26 km near Allahabad in 2018 (Table 4). The maximum migration rate of the Ganga River is calculated as 0.09 km/year between 2010 and 2018 (Table 5). Some locations lateral shift of the Ganga River calculated in terms of distance and direction given in Fig. 5. It is probably related to the confluence of the Yamuna with Ganga near Allahabad and the control exerted by the Allahabad fault. Because of the confluence of two major river systems, the sediment–water budget suddenly increases, which induces mid-channel bar formation causing diversion of the second-order channels and hence the channel migration. From Allahabad to Chunar, the River Ganga flows in southeast direction with maximum active floodplain and channel migration in the northern side, while the southern side is bound by the Craton represented by rocks of the Vindhyan Supergroup not allowing any further shift.

Table 1 Description of Landsat data used in the study area

Data type	Satellite sensor	Date of Acquisition	Path/row	Spatial resolution (m)	Source
Remote sensing images	Landsat-MSS	November 10, 1972	153/42	79	Earth Explore (https://earthexplorer.usgs.gov/)
		November 10, 1972	152/42	79	Earth Explore (https://earthexplorer.usgs.gov/)
	Landsat-TM	November 17, 1990	143/42	30	Earth Explore (https://earthexplorer.usgs.gov/)
		November 10, 1990	142/43	30	Earth Explore (https://earthexplorer.usgs.gov/)
		November 10, 1990	142/42	30	Earth Explore (https://earthexplorer.usgs.gov/)
	Landsat-ETM +	December 15, 2000	142/43	30	Earth Explore (https://earthexplorer.usgs.gov/)
		December 15, 2000	142/42	30	Earth Explore (https://earthexplorer.usgs.gov/)
		November 20, 2000	143/42	30	Earth Explore (https://earthexplorer.usgs.gov/)
	Landsat-ETM +	November 25, 2010	142/43	30	Earth Explore (https://earthexplorer.usgs.gov/)
		November 25, 2010	142/42	30	Earth Explore (https://earthexplorer.usgs.gov/)
		December 18, 2010	143/42	30	Earth Explore (https://earthexplorer.usgs.gov/)
	Landsat-OLI	November 7, 2018	142/43	30	Earth Explore (https://earthexplorer.usgs.gov/)
		November 7, 2018	142/42	30	Earth Explore (https://earthexplorer.usgs.gov/)
November 14, 2018		143/42	30	Earth Explore (https://earthexplorer.usgs.gov/)	

Table 2 Temporal change in the Ganga River width in different reaches (maximum, minimum, mean)

River reaches	Width (m)	Years				
		1972	1990	2000	2010	2018
Allahabad–Chunar	Max	1012.00	1149.00	1711.00	858.00	1106.00
	Min	256.00	398.00	508.00	221.00	449.00
	Mean	590.30	691.30	886.00	475.80	750.90
Chunar–Saidpur	Max	716.00	822.00	815.00	728.00	725.00
	Min	496.00	512.00	418.00	401.00	543.00
	Mean	628.00	715.67	677.67	603.33	644.67
Saidpur–Buxar	Max	1006.00	1469.00	997.00	883.00	1440.00
	Min	486.00	455.00	359.00	270.00	52.00
	Mean	670.89	854.22	498.56	473.44	739.22

(b) Chunar to Saidpur Reach

From Chunar to Saidpur, the River Ganga flows in a northeast direction carving a straight and narrow valley. However, in this reach, the Ganga River is having marked sinuosity and is characterized by distorted meanders. The

main channel also shows the development of small-sized mid-channel bars. The Ganga River shifts from one margin of the valley to another.

In the reach between Chunar and Saidpur, the average maximum and minimum channel widths vary from 822 to 401 m, respectively (Table 2). The River Ganga is confined

Table 3 Temporal change (1972 and 2018) in sinuosity index of the Ganga River between Allahabad and Buxar (Modified after Singh et al. 2019)

River reaches	Valley length (km)	Channel length (km)					Sinuosity index				
		2018	2010	2000	1990	1972	2018	2010	2000	1990	1972
Allahabad–Chunar	129.53	173.47	180.67	176.98	178.69	176	1.33	1.39	1.36	1.37	1.35
Chunar–Saidpur	82.58	76.33	83.41	82.67	82.84	84.13	0.92	1.01	1.00	1.00	1.01
Saidpur–Buxar	97.48	130.52	125.7	125.47	124.8	126.3	1.33	1.29	1.28	1.28	1.29

Table 4 Migration of the Ganga River in different reach (base year is 1972)

River reaches			Years			
			1990	2000	2010	2018
Allahabad–Chunar	Left bank	Max	1.06	1.53	1.7	1.08
		Min	0.04	0.01	0.01	0.02
		Mean	0.23	0.44	0.24	0.32
	Right bank	Max	1.07	1.42	4.41	4.93
		Min	0.01	0.02	0.01	0.30
		Mean	0.37	0.52	0.80	1.13
	Mid channel	Max	1.06	1.47	2.21	2.26
		Min	0.01	0.02	0.03	0.25
		Mean	0.24	0.47	0.51	0.67
Chunar–Saidpur	Left bank	Max	0.09	0.14	0.15	0.31
		Min	0.01	0.01	0.05	0.08
		Mean	0.05	0.05	0.11	0.16
	Right bank	Max	0.09	0.07	0.14	0.35
		Min	0.01	0.03	0.04	0.06
		Mean	0.06	0.05	0.10	0.34
	Mid channel	Max	0.05	0.04	0.04	0.15
		Min	0.01	0.01	0.02	0.01
		Mean	0.04	0.03	0.03	0.09
Saidpur–Buxar	Left bank	Max	0.85	0.73	0.68	2.64
		Min	0.04	0.01	0.01	0.03
		Mean	0.26	0.29	0.27	0.90
	Right bank	Max	0.36	0.37	0.53	13.00
		Min	0.01	0.01	0.07	0.48
		Mean	0.21	0.14	0.24	3.74
	Mid channel	Max	0.54	0.52	0.75	11.78
		Min	0.02	0.01	0.03	0.06
		Mean	0.18	0.20	0.24	2.98

and incised between the valley walls (Shukla et al. 2012; Singh et al. 2019). There is a minimum shift of 0.01 km (Table 4) observed in mid-channel near Varanasi, possibly due to the entrenched flow of the river along the Chunar–Varanasi fault (Swamee et al. 2003; Singh et al. 2019). The shift of the left and right bank of the river is given in Table 4, which is not much. The maximum migration rate

of the Ganga River is calculated as 0.12 km/year between 2010 and 2018 (Table 5). Lateral shift of the Ganga River was calculated in terms of distance and direction given in Fig. 5. In this reach, the river is flowing along the fault has caused rivers to incise. Because of the deep incision of 10–15 m, the valleys are narrow and lateral migration of the Ganga River is restricted (Shukla et al. 2012; Singh

Table 5 The migration rates of the Ganga River calculated by using the Giardino and Lee 2011 method, and taking 1972 as the base year

Year	Channel polygon area (A) (Sq km)			Channel length (km) (L)			A/L			T	Migration rate (km/year)		
	Reach-1	Reach-2	Reach-3	Reach-1	Reach-2	Reach-3	Reach-1	Reach-2	Reach-3		Reach-1	Reach-2	Reach-3
1990	116.06	58.21	118.92	178.69	82.84	124.8	0.65	0.70	0.95	8	0.08	0.09	0.12
2000	125.64	50.05	74.02	176.98	82.67	125.47	0.71	0.61	0.59	10	0.07	0.06	0.06
2010	66.80	31.98	58.65	180.67	83.41	125.7	0.37	0.38	0.47	10	0.04	0.04	0.05
2018	121.24	74.81	105.17	173.47	76.33	130.52	0.70	0.98	0.81	8	0.09	0.12	0.10

et al. 2019). The fault has forced the Ganga River to flow NE against the general slope of the Ganga Plain, which is to SE.

(c) Saidpur to Buxar Reach

The flow of the River Ganga changes roughly toward eastward from Saidpur to Buxar. The average valley width in the reach varies from 4.14 to 20 km (Singh et al. 2019). The active channel is 52–1469 m (Table 2). Though currently, the river is showing the development of mid-channel bars, yet the presence of meander scars and paleochannels in the valley suggests that the Ganga River might have been meandering in the past. In this reach, the Ganga River channel sinuosity index varies from 1.28 to 1.33 (Table 3). The maximum shifts are found of the order of 2.64 km on the left bank (Table 4). It is probably related to the influence of the confluence of Gomati and Ghaghra rivers on the northern side of the River Ganga near Ghazipur. The Ganga River further changes its course toward ENE from Saidpur to Buxar with paired floodplain carved in the alluvium.

Discussion

The processes of river channel migration and its incision are signified by the complex interplay of various physical and anthropogenic elements, among which the type of bank material (soil) and autogenic behavior of the channel are the two dominating factors. The incision is mainly controlled by allogenic factors, including climate, tectonics, and base level changes related to eustasy. However, being very far away from the Bay of Bengal, sea-level changes might not have much control, if any, in the incision process of the Ganga River, while the rest of the factors in combination might have been instrumental in bringing about morphometric changes in the channel properties in the recent past. The following factors seem to have controlled the Ganga River behavior between Allahabad and Buxar:

(a) Bank Soil Type

The bank soil composition controls the pace of bank disintegration and consequent channel relocation. A few studies have been done to the bank soil type on the recurrence and extent of riverbank disintegration (Hooke 1979; Madej et al. 1994; Ta et al. 2013). The soil grain texture is a fundamental physical property of soil, which demonstrates the level of coarseness or fineness of soil contingent upon the extent of grain size (sand, silt, and clay) portion (Goswami et al. 1999). It has been investigated that in the four selected sites along the Ganga River, bank soil is slightly clayey sandy silt and slightly sandy, slightly clayey silt (Fig. 6), which is non-cohesive and easily erodible by the energetic flow in the channel.

In the study area, the leading cause of Ganga River migration may be increased river erosion at meander bends due to increased flow during the monsoon period (Jain and Ahmad 1993). The lateral erosion in the Ganga River within its valley is observed along both the left and right banks, probably related to unconsolidated sandy bank material and its abrasion due to the high velocity of recurring floods (Singh et al. 2007, 2019). It is to be noted that muddy floodplains are poorly developed, maintaining stable banks of the Ganga River. Moreover, such changes occurring within the decadal-scale are ascribed to rainfall fluctuation (Bera 2017; Singh et al. 2019) and, consequently, change in sediment supply (Singh et al. 2007).

(b) Channel Shape

The shape of the river channel indicates the distribution of flow energy in the river. In the streamflow energy, more or less equally distributed if the channel is symmetrical, then maximum strength is generally at the center of the channel. On the other hand, if the channel is asymmetrical, maximum velocity tends to move from along the middle of the channel toward banks (Morisawa 1985). In the meander bends, energy is more, and hence, undercutting of the bank material increases.

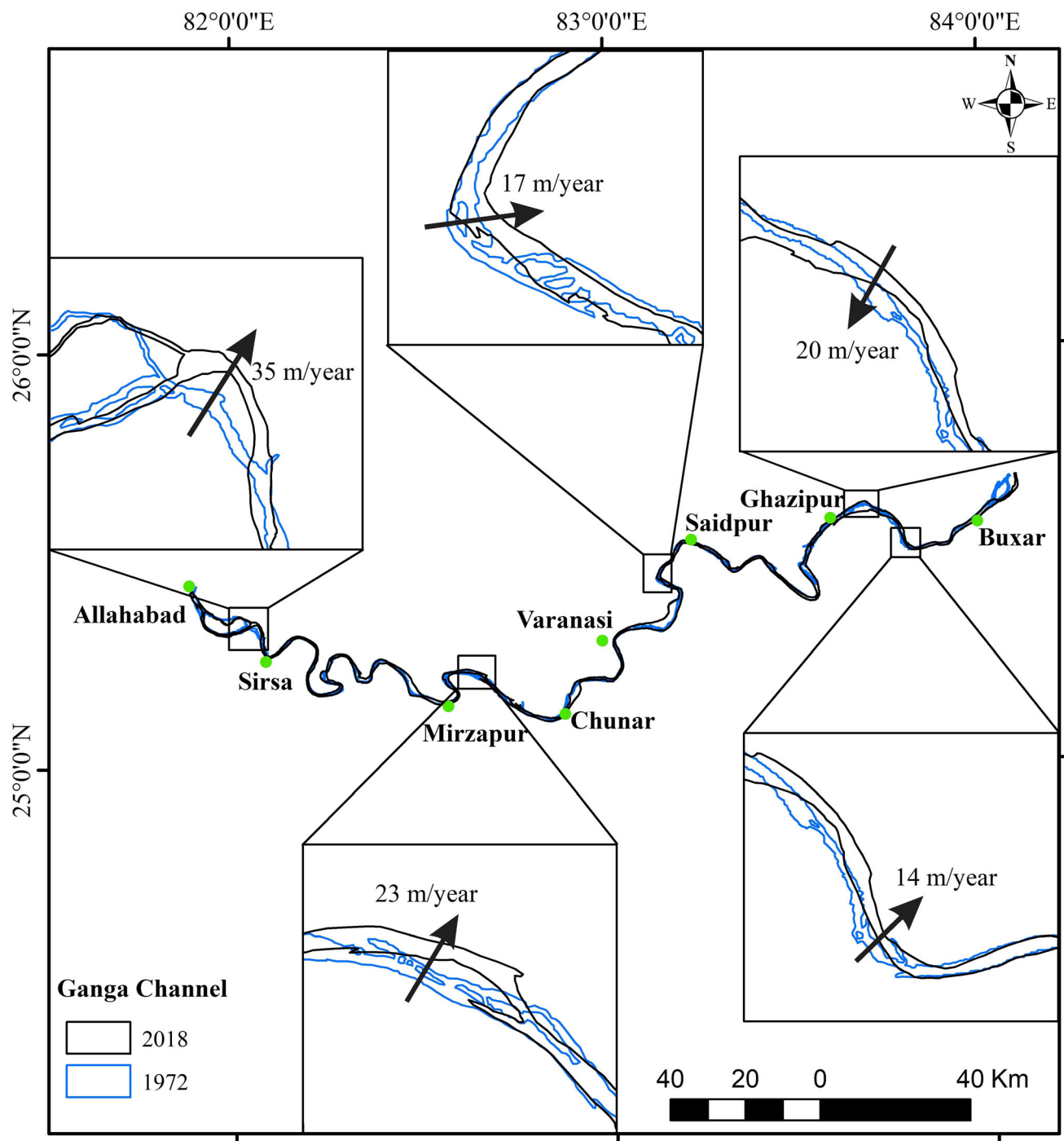


Fig. 5 The rate of channel migration in 1972–2018 in different sectors

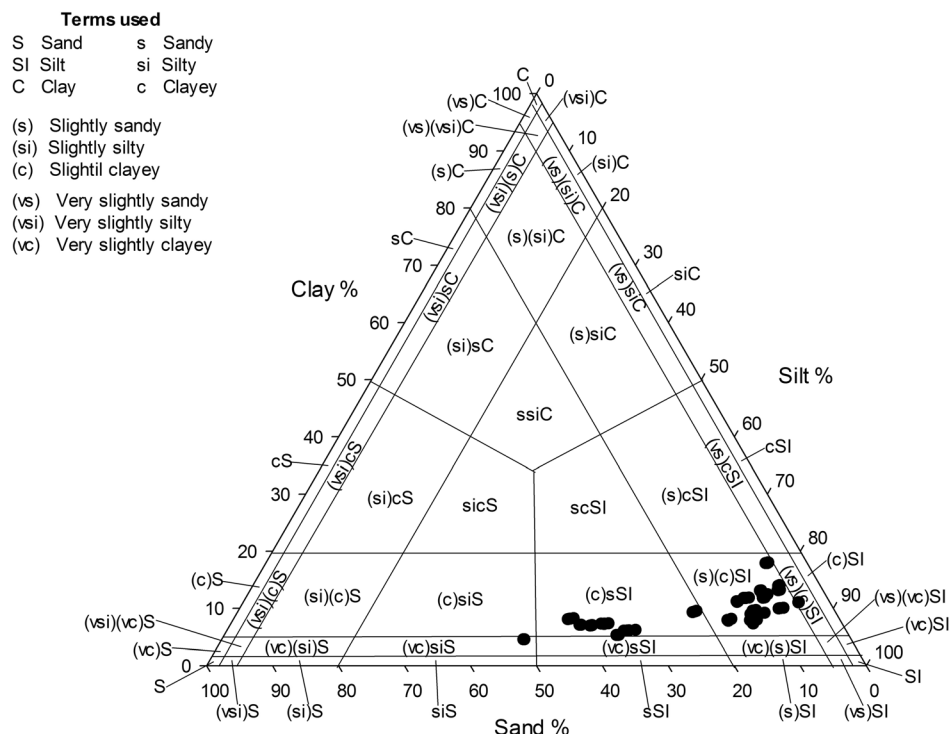
Channel morphology of the Ganga River within the studied stretch is primarily controlled by faults (Shukla and Raju 2008; Shukla et al. 2012; Shukla 2013; Singh et al. 2019). Between Allahabad and Chunar, meanders are quite well organized, while in Varanasi to Saidpur, the Ganga River shows distorted meanders and narrow valley and poorly developed muddy flood plains. During floods in monsoon months, the excess water flows through this

narrow stretch and causes massive undercutting of banks. At many places, this has been the cause of channel migration within the river valley.

(c) Neotectonics

In the studied stretch, the leading cause of Ganga River migration may be increased river erosion at meander bends

Fig. 6 Sand-silt–clay proportion in river bank material



due to increased flow during the monsoon period (Jain and Ahmad 1993). The lateral erosion in the Ganga River within its valley is observed along both the left and right banks, probably related to unconsolidated sandy bank material and its erosion due to the high velocity of recurring floods (Singh et al. 2007, 2019). Moreover, such changes occurring within the decadal-scale are ascribed to rainfall fluctuation (Bera 2017; Singh et al. 2019) and, consequently, change in sediment supply (Singh et al. 2007). However, the channel morphology of the Ganga River within the studied stretch seems to have been mainly controlled by different faults traversing studied transects. Between Allahabad and Chunar, meanders are quite well organized while in Varanasi to Saidpur, the Ganga River shows distorted meanders and narrow valley, which has been ascribed to the control of Varanasi–Chunar fault (Shukla and Raju 2008; Shukla et al. 2012). Shukla et al. (2012) have demonstrated that upheaval along a gravity fault near Varanasi has caused the Ganga River incision about 7 ka. This event is marked by raised cliff along the riverbank, reverse fault, and folds, and vertical joints present in the alluvium forming river banks.

Conclusion

1. Present work has demonstrated the utility of remote sensing and GIS platform to investigate fluvial landscape and channel behavior in decadal-scale

resolution. The presented geo-database may be useful for the preparation of a riverbank erosion risk map in the Middle Ganga Plain.

2. The present study reveals that the channel morphometry in decadal-scale controlled by the nature of rainfall, flooding, and meander characteristics. However, the overall channel behavior is tectonically controlled. Therefore, the lateral movement of the river is one of the critical factors to the failure of the older floodplain (bank) within the valley by the undercutting process.
3. Lateral migration of the channel seems related to reactivation of chute channels in meandering rivers and second-order channel in braided rivers during catastrophic floods. Both these processes are instrumental for large-scale channel shift/migration, mainly causing bank erosion.
4. Localized riverbank protection cannot provide a long-term solution to the problem of river bank migration. The hydrographic study is essential for the entire operation of positioning the dredgers and their viability.

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References

- Ahmed, I., Das, N., Debnath, J., & Bhowmik, M. (2018). Erosion induced channel migration and its impact on dwellers in the lower Gumti River, Tripura India. *Spatial Information Research*, 26(5), 537–549.
- Bera, S. (2017). Trend analysis of rainfall in Ganga Basin, India during 1901–2000. *American Journal of Climate Change*, 6, 116–131.
- Bhowmik, M., Das, C., Ahmed, I., & Debnath, J. (2018). Bank material characteristics and its impact on river bank erosion, West Tripura district, Tripura, North–East India. *Current Science*, 115(8), 1571–1576.
- Brice, J. C. (1960). Index for a description of channel braiding. *Geological Society of American Bulletin*, 71, 1833.
- Chakraborty, S., & Mukhopadhyay, S. (2015). An assessment on the nature of channel migration of river Diana of the sub-Himalayan West Bengal using field and GIS techniques. *Arabian Journal of Geosciences*, 8(8), 5649–5661.
- Debnath, J., Pan, N. D., Ahmed, I., & Bhowmik, M. (2017). Channel migration and its impact on land use/land cover using RS and GIS: A study on Khowai River of Tripura, North-East India. *The Egyptian Journal of Remote Sensing and Space Science*, 20(2), 197–210.
- Giardino, J. R., & Lee, A. A. (2011). Rates of channel migration on the Brazos River. Texas Water Development Board, pp. 1–41
- Gurnell, A. M., Downward, S. R. & Jones, R. (1994). Channel planform change on the River Dee meanders, 1876–1992. *Regulated rivers: research & management*, 9(4), 187–204.
- Goswami, U., Patgiri, A. D., & Sarma, J. N. (1999). Hydrological properties of soil from textural analysis: A case study of lower Subansiri basin, Assam. *Journal of the Indian Association of Sedimentologists*, 18(2), 261–269.
- Harbor, D. J., Schumm, S. A., & Harvey, M. D. (1994). Tectonic control of the Indus River in Sindh, Pakistan. In S. S. Schumm & B. R. Winkley (Eds.), *The variability of large Alluvial rivers* (pp. 161–176). New York: American Association of Civil Engineers Press.
- Hooke, J. M. (1979). An analysis of the processes of river bank erosion. *Journal of Hydrology*, 42, 39–62.
- Jain, S. K., & Ahmad, T. (1993). Migration behavior of River Ganga between Allahabad and Buxar using remotely sensed data. *Journal of Indian Society of Remote Sensing*, 21(1), 37–43.
- Jayaswal, V., & Shukla, U. K. (2016). *Varanasi and Ganga: Geomorphological and Archaeological Investigations at Ramnagar*. New Delhi: Aryans Books International.
- Kanhaiya, S., Singh, B. P., Singh, S., Mittal, P., & Srivastava, V. K. (2019). Morphometric analysis, bedload sediments, and weathering intensity in the Khurar River Basin, central India. *Geological Journal*, 54(1), 466–481.
- Kotoky, P., Bezbaruah, D. B. J., & Sarma, J. N. (2005). Nature of bank erosion along the Brahmaputra river channel, Assam, India. *Current Science*, 88(4), 634–640.
- Leopold, L. B., Wolman, M. G., & Miller, J. P. (1964). *Fluvial processes in geomorphology*. San Francisco, California: W. H. Freeman and Company.
- Madej, M. A., Weaver, W. E. & Hagans, D. K. (1994). Analysis of bank erosion on the Merced river, Yosemite Valley, Yosemite National Park, California, USA. *Environmental Management*, 18(2), 235–250.
- Mani, P., & Kumar, C. C. (2003). Erosion study of a part of Majuli River-Island using remote sensing data. *Journal of Indian Society of Remote Sensing*, 31(1), 12–18.
- Morisawa, M. (1985). *Rivers (Forms and processes)*. London: Longman.
- Mueller, J. R. (1968). An introduction to the hydraulic and topographic sinuosity indexes. *Ann Association of American Geography*, 58(2), 371–385.
- Pal, R., Biswas, S. S., Pramanik, M. K., & Mondal, B. (2016). Bank vulnerability and avulsion modelling of the Bhagirathi-Hugli river between Ajay and Jalangi confluences in lower Ganga Plain, India. *Model Earth System Environment*, 2, 65.
- Parua, P. K. (2002). Fluvial geomorphology of the river Ganga around Farakka. *Journal of the Institution of Engineers*, 82, 193–196.
- Pati, J. K., Lal, J., Prakash, K., & Bhusan, R. (2008). Spatio-temporal shift of Western bank of the Ganga River, Allahabad City and its Implications. *Journal of Indian Society Remote Sensing*, 36(1), 289–297.
- Prakash, K., Singh, S., & Shukla, U. K. (2016). Morphometric changes of the Varuna river basin, Varanasi district, Uttar Pradesh. *Journal Geometry*, 10(1), 48–54.
- Prakash, K., Singh, S., Mohanty, T., Chaubey, K., & Singh, C. K. (2017a). Morphometric assessment of Gomati river basin, Middle Ganga Plain, Uttar Pradesh, North India. *Spatial Information Research*, 25, 449–458.
- Prakash, K., Mohanty, T., Pati, J. K., Singh, S., & Chaubey, K. (2017b). Morphotectonics of the Jamini River basin, Bundelkhand Craton, Central India: using remote sensing and GIS technique. *Applied Water Science*, 7, 3767–3782.
- Prakash, K., Chaubey, K., Singh, S., Mohanty, T., & Singh, C. K. (2017c). Morphometric analysis of the Satna River basin. *Central India. Indian Journal of Geomorphology*, 22(1), 41–60.
- Randle, T. J. (2006). Channel migration model for meandering river. In Proceeding of the eighth federal interagency sedimentation Conference (8thFISC), pp. 241–248
- Schumm, S. A., Dumont, J. F., & Holbrook, J. M. (2000). *Active tectonics and alluvial rivers*. Cambridge: Cambridge University Press.
- Shukla, U. K. (2009). Sedimentation model of gravel-dominated alluvial piedmont fan, Ganga plain, India. *International Journal of Earth Science*, 98, 443–459.
- Shukla, U. K. (2013). Varanasi and the Ganga River: A Geological Perspective. In V. Jayaswal (Ed.), *Varanasi Myths and scientific studies* (pp. 100–113). New Delhi: Aryan books international.
- Shukla, U. K., & Raju, N. J. (2008). Migration of the Ganga river and its implications on hydrogeological potential of Varanasi area, U.P, India. *Journal of Earth System Science*, 117, 489–498.
- Shukla, U. K., Singh, S. M., & Sharma, S. (2001). A model of alluvial megafan sedimentation: Ganga Megafan. *Sedimentary Geology*, 144, 243–262.
- Shukla, U. K., Srivastava, P., & Singh, I. B. (2012). Migration of the Ganga river and development of cliffs in the Varanasi region, India during the late Quaternary: Role of active tectonics. *Geomorphology*, 171–172, 101–113.
- Singh, C. K. (2015). Middle Ganga plain: May be on the verge of seismic shock. *Journal of Geological Society of India*, 85, 511–513.
- Singh, I. B., Ansari, A. A., Chandel, R. S., & Mishra, A. (1996). Neotectonic control on drainage system in Gangetic Plain, Uttar Pradesh. *Journal of Geological Society of India*, 47, 599–609.
- Singh, I. B., Singh, M. (1992). The Ganga river valley: Alluvial valley in active foreland basin (abstract): 29th International Geological Congress, Kyoto, Japan, Abstracts, II-5-6:406
- Singh, I. B., Srivastava, P., Sharma, S., Sharma, M., Singh, D. S., Rajagopalan, G., et al. (1999). Upland interfluvial (Doab) deposition: Alternative model to muddy over-bank deposits. *Facies*, 40, 197–210.
- Singh, M., Singh, I. B., & Müller, G. (2007). Sediment characteristics and transportation dynamics of the Ganga River. *Geomorphology*, 86, 144–175.

- Singh, S. (2017). GIS based geomorphology and sedimentological investigation of the Ganga River between Allahabad and Buxar (Ph.D. thesis). Banaras Hindu University, Varanasi, India. <https://hdl.handle.net/10603/229204>
- Singh, A. K., Jaiswal, M. K., Pattanaik, J. K. & Dev, M. (2016). Luminescence chronology of alluvial fan in North Bengal, India: Implications to tectonics and climate. *Geochronometria*, 43(1), 102–112.
- Singh, A. K., Pattanaik, J. K. & Jaiswal, M. K. (2017). Late Quaternary evolution of Tista River terraces in Darjeeling-Sikkim-Tibet wedge: Implications to climate and tectonics. *Quaternary International*, 443, 132–142.
- Singh, S., Prakash, K., & Shukla, U. K. (2019). Decadal scale geomorphic changes and tributary confluences within the Ganga River valley in Varanasi region, Ganga Plain, India. *Quaternary International*, 507, 124–133.
- Singh, I. B. (1996). Geological evolution of Ganga plain—An overview. *Journal of Palaeontological Society of India*, 41, 99–137.
- Srivastava, A., & Singh, R. P. (1999). Surface manifestation over a subsurface ridge. *International Journal of Remote Sensing*, 20, 3461–3466.
- Srivastava, S. U. K. (2009). Quaternary evolution of the Ganga river system: New Quartz Ages And A Review Of Luminescence Chronology. *Himalayan Geology*, 30, 85–94.
- Swamee, P. K., Parkash, B., Thomas, J. V., & Singh, S. (2003). Changes in channel pattern of river Ganga between Mustafabad and Rajmahal, Gangetic plains since 18th century. *International Journal of Sedimentary Research*, 18(3), 219–231.
- Ta, W., Jia, X. & Wang, H. (2013). Channel deposition induced by bank erosion in response to decreased flows in the sand-banked reach of the upstream Yellow river. *Catena*, 105, 62–68.
- Tandon, S.K., Gibling, M.R., Sinha, R., Singh, V., Ghazanfari, P., Dasgupta, A., Jain, M. & Jain, V. (2006). Alluvial valleys of the Gangetic Plains, India: causes and timing of incision. In: *Incised Valleys in Time and Space*. SEPM Special Publication 85:15–35
- Thakur, P. K., Laha, C., & Aggarwal, S. P. (2012). River bank erosion hazard study of river Ganga, upstream of Farakka barrage using remote sensing and GIS. *Nat Hazard*, 61, 967–987.
- Wallick, J. R., Lancaster, S. T., & Bolte, J. P. (2006). Determination of bank erodibility for natural and anthropogenic bank materials using a model of lateral migration and observed erosion along the Willamette River, Oregon, USA. *River Research and Applications*, 22(6), 631–649.
- Winterbottom, J. S., & Gilvear, J. D. (2000). A GIS-based approach to mapping probabilities of river bank erosion: regulated River Tummel, Scotland. *Regulation Rivers Research Magazine*, 16(2), 127–140.
- Yang, C. T. (1971). On river meanders. *Journal Hydrology*, 13, 231–253.
- Yang, X., Damen, M. C. J., & Van Zuidam, R. A. (1999). Satellite remote sensing and GIS for the analysis of channel migration changes in the active Yellow River Delta, China. *International Journal Applied Earth Observation Geoinformatics*, 1, 146–157.

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