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MEASUREMENT OF CHANNEL PLANFORM IN PARTS OF THE UPPER GANGA PLAINS OF UTTAR PRADESH USING REMOTE SENSING AND GIS TECHNIQUES

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Abstract

The dynamic channel planforms of river systems must be understood in order to regulate the impacts of river channels on neighbouring ecosystems. The present research used remote sensing and GIS methods to examine the morphological characteristics of channels and their changing patterns in the Ganga River and its tributaries, including the Ramganga, Kali, and Garra channels from 1975 to 2018. Earth observation data, topographic maps, and GPS field surveys were used to conduct geomorphic mapping, sinuosity changes, and large-scale river channel dynamics. The river's phenomenal oscillation is accentuated by its movement across four decades. To assess the meandering of the river, the sinuosity of the river channels was calculated. The length of the channel varies from 55.1 to 58.9 with a sinuosity (SSI) of 1.02 to 1.11 for Ganga, 27.3-32.4 (SSI: 1-1.07) for Ramganga, 57.5-64.3 (SSI: 1-1.02) for Kali, and it is 26.9-32.9 (SSI: 1-1.08) for Garra. Twenty-six cross-sections were taken into consideration to determine the pace of river movement. The results indicate that the migration of both banks of the river channels varied between 30 and 2900 m in the Ganga, 5 and 649 m in Kali, 134 and 2849 m in the Ramganga, and 25 and 805 m in the Garra. The river channels have continuously moved from their previous positions as a result of hydrological processes and the region's terrain. The aim of carrying out this particular study is to enable the authorities/stakeholders to identify the location-wise erosion and accretion-impacted regions towards implementing constructive steps for managing the river channel shifting activity. The study provides baseline data for addressing river management challenges related to river dynamics, floods, droughts, and environmental sustainability.

Keywords*:* Geomorphic mapping, Sinuosity Index, River Dynamics, Ganga Plains, Uttar Pradesh, Remote Sensing and GIS

Introduction

Running water is a dynamic geomorphic agent that erodes materials and transports them to different locations on the earth's surface. Form and processes are intertwined, and both must be examined to understand the genesis and evolution of landforms. The shape may be measured by analysing its geometric and hydrological parameters, which include discharge and flow rate. The processes may be river function, such as erosion, deposition, and transportation. Alluvial channels are dynamic and vulnerable to change, yet they change in a variety of ways and at extremely variable rates. River course change is a natural phenomenon caused mostly by bankline erosion, accretion, and downcutting. The changing behaviour of the river channel regulates channel pattern, indicating channel form adjustment with the underlying topography and human activities (Charlton, 2008; Verma et al., 2021). During turbulent flow conditions, lateral migration is invariably linked with bank erosion of the stream bed or channel wall.

The three major Himalayan rivers, the Ganga, Brahmaputra, and Indus, are the world's most sediment-loaded rivers, carrying an estimated 599, 650, and 291 Mt/year, respectively, sediments every year. It accounts for approximately 9% of the entire yearly load transported from continents to seas globally (Meybeck, 1976; Hasnain & Thayyen, 1999; Sinha and Tandon, 2014). The Ganga Plains provide the greatest examples for learning the major issues of river dynamics. The river course of Ganga has changed over time, especially in its seaward stretches before entering the Bay of Bengal (Gupta, 2012). Several scientists have studied fluvial dynamics in terms of tectonics, sedimentology, and hydrological variability (Jain and Sinha, 2004; Thakur and Aggarwal, 2012; Mukherjee and Pal, 2018; Agnihotri et al. 2020). Pati et al. (2008) analysed the western bank of the Ganga in Allahabad to detect the course shift on a spatiotemporal scale. Sarif et al. (2021) investigated the river course changes and morphometric features of the Ganga upstream and downstream of the Farakka Barrage from 1794 to 2017 using historical maps, aerial photographs, satellite imagery and geospatial techniques to understand the river dynamics. Satellite-based remote sensing and GIS tools are utilised to monitor the dynamic environmental changes in river channels. The measurement of a river's channel sinuosity is an important aspect of morphometric analysis since it indicates channel flow and morphological features (Karki and Nakagawa, 2019; Jodhani, 2023).

Accurate knowledge of the physical properties of alluvial channels through quantitative analysis is required for alluvial plain regions because they play a significant role in human subsistence. Alluvial channels have a natural propensity to deviate from a straight path, increasing their sinuosity (Mittal, et al., 2023). Over time, meanders migrate downstream and cause issues at the local level. As a result, rivers with varied patterns behave differently, as do other physical properties such as channel slope and gradient. Therefore, pattern identification might be the initial step in assessing river stability and possible threats. Fluvial processes are primarily caused by natural causes such as discharge, terrain, soils, geological structure, and anthropogenic like deforestation, channelization and construction of dams, etc. Flooding occurs regularly in the upper Ganga plains as a result of the construction of reservoirs and dams on the upper course, the alteration of channels and canals, deforestation and changing agricultural practices, and other human activities. These operations may cause differences in river processes, such as channel course shifting and river bedload destabilisation. Excavation of fertile soils, unauthorised sand and gravel mining, and change of plant cover have all been prevalent in recent days, resulting in flash floods and increased water velocity, all of which have an impact on river processes. Keeping this in mind, the study of shifting courses and fluvial processes, with a focus on the river Ganga and its tributaries running between Farrukhabad and Hardoi in Uttar Pradesh, has been undertaken as a problem for understanding river form and process. The following objectives were set: (i) explore various morphological aspects, (ii) establish geometric properties of channels and their changing pattern, and (iii) analyse the likely reasons for the changing pattern of river processes.

Description of the Study Area

The river Ganga and its tributaries, namely the Ramganga, the Kali and the Garra, are draining through this study area. The river Ganga originates at a height of 3892 meters from the Gangotri glacier in the Himalayas and flows 2525 km through vast alluvial plains. It Develops one of the biggest delta systems in the world and finally debouches into the Bay of Bengal. The river Ganga gains its name at Devprayag in the Uttaranchal Himalaya, where the Bhagirathi and Alaknanda river meets to form the main channel of this river. The total drainage area is more than a million square kilometres, and it supports nearly 40% of India's total population. Physiographically, the river plains are divided into three categories, namely, Upper, Central and Lower plains, covering various states, i.e. Uttarakhand, Uttar Pradesh, Bihar, Jharkhand and West Bengal.

The study area is a part of the Upper Ganga Plains located between Farrukhabad, Kannuaj and Hardoi region of Uttar Pradesh (UP) State in India. This region is bounded by the districts of Badaun, Shahjahanpur in the north; Kheri, Sitapur in the East; Kanpur Dehat, Kanpur Nagar, Unnao, Lucknow in the South; and Auraiya, Etawah, Manipuri in the West. It lies between latitudes 27°01' - 27°18' N and longitudes 79°38' - 80°00' E covering an area of about 1121 sq. km (Figure 1). In the present study region, the river Ganga is the trunk stream flowing with a stretch of 60 km in length and varying distance from 2 to 5 km in width. The Ramganga, Garra and Kali rivers are the three main tributaries of the river Ganga passing through the study area. The tributary Ramganga joins the Ganga at a distance of 10 km north of Kannauj and the Ganga-Garra confluence is located further 10 km downstream. The river Ramganga originally emanates from Doodhatoli ranges in Uttarakhand at a height of 3600 m. It flows through the Corbett National Park of Uttarakhand and it descends upon the plains near Ramnagar of Nainital district. Bijnor, Moradabad, Bareilly, Badaun, Shahjahanpur and Hardoi cities of Uttar Pradesh are situated on its banks. The river Garra is another tributary of the river Ganga and it originates from the Nandhaur range in Nainital District of Uttarakhand, Kaumon Himalaya. It flows through the three districts of Uttar Pradesh namely Pilibhit, Shahjahanpur and Hardoi. The total length of the river from its origin to the merging point at Hardoi is about 200 km. In the present study, the river Garra flows about 30 km in length and varies from a width of 0.5 to 1 km. It merges with the river Ganga more than 12 km distance to the Kannauj area. Another important tributary of the river Ganga is the Kali River originated in the Doon valley of Uttarakhand and passes through the Saharanpur, Muzaffarnagar and Bagpat districts of Uttar Pradesh. In the present study, the river Kali flows through the districts of Kannauj and Hardoi and it merges with the river Ganga after flowing about 60 km distance.

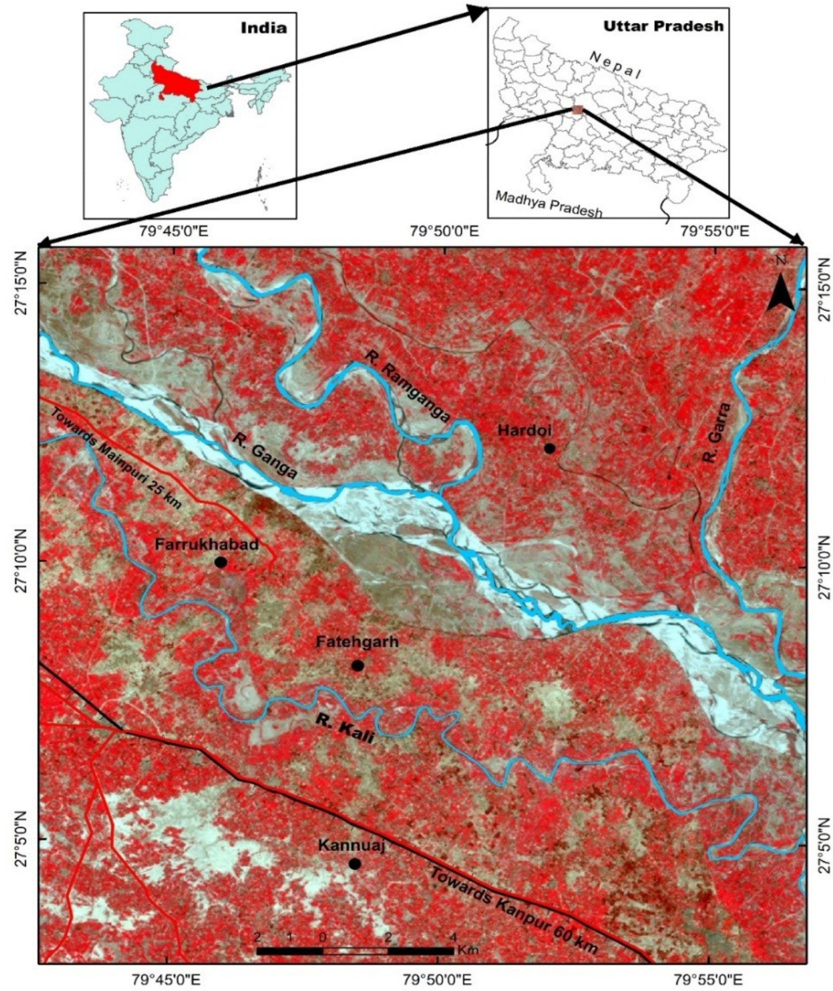

Figure 1. Location of the study area

Climatic variables such as temperature and rainfall play an important role in studying the environmental behaviour of a particular region. The study area is characterized by a sub-tropical humid type of climate. The lowest temperature is 8°C recorded in the month of January and the maximum temperature reaches up to 41°C in the month of May (IMD 2018). The dry winds called *Loo*, which blow at a greater speed, causing heat-related stress and sometimes leading to death. The area receives more than 95% of total rainfall during the southwest monsoon season (June to September). The average annual rainfall received by the study area is 881 mm.

Quaternary alluvium is divided into two types of alluvium i.e. older alluvium and newer alluvium. The major portion of the study area is occupied by older alluvium (Bhagar) of middle to upper Pleistocene age. Newer alluvium (Khadar) is restricted to the paleo bank of the river represented by terraces consisting of fine to medium-grained, gray, micaceous, unconsolidated sand with grey silt and clay sediments. Lithologically, the surface is characterized by sand flats and elongated mounds. The silty clayey surface hosts a number of paleochannels and oxbow lakes and supports multiple crops.

The region supports nearly 0.9 million population, with a major portion of rural accounting for 77%. The advantage of fertile plains, along with the water accessibility from the Ganga and its tributaries, is the density of the study area is 900 persons per sq. km (Census 2011). The literacy rate is 69.6% of which female are 55.2% and male are 57.5%.

Materials and Methods

The Survey of India topo maps numbered 54 M/11, M/12, M/15, and M/16 on a 1:50,000 scale was utilized to prepare a base map for the study region. LANDSAT satellite data MSS, TM, ETM+ and Sentinel-2 for the years 1975, 1988, 2002, and 2018, respectively, was used for the purpose of research. The date of acquisition of the datasets during the month of November 21-29 for all the years. The digital elevation map of the study area is generated from the Shuttle Radar Topography Mission (SRTM) DEM. The image data is geo-rectified with WGS-1984-UTM (Zone 44) projection. Image enhancement techniques have been applied to enhance the image quality for a better understanding of feature extraction. The colour composite technique has been applied to creating false colour composite (FCC) maps (Figure 1). The base map and satellite data were utilised to analyse the historical river channel changing of the Ganga and its tributaries, including the Ramganga, Garra, and Kali. ERDAS Imagine 14 and ArcGIS 10.5 software were used to analyse digital images and conduct statistical analyses. In addition, a GPS field survey was carried out to identify distinct landforms and landscape characteristics.

The river channels were delineated through on-screen digitization using a base map (1975) and satellite data (1988, 2002, and 2018) to calculate various sinuosity indexes in a GIS environment. The topographic sinuosity index (TSI), hydraulic sinuosity index (HSI) and standard sinuosity index (SSI) were calculated by using the following formulae (Muller, 1968).

$$HSI = \text{Percent equivalent of } CI\text{-}VI/\ CI\text{-}1$$
$$TSI = \text{Percent equivalent of } VI\text{-}1/CI\text{-}1$$
$$SSI = CL/VL$$

Where CL is the channel length, VL is the valley length along the stream, CI (channel index) is the ratio of CL to Areal distance, and VI (valley index) is the ratio of VL to Areal distance.

Further, the river courses have been categorized as straight (SSI =1.0), sinuous (SSI =1.0-1.5) and meandering (SSI > 1.5).

We have also investigated the river course changes of the river Ganga and its tributaries the Ramganga, the Kali and the Garra rivers. The spectral band (B4) micro meter (μm) was utilised to delineate the river bankline since it is suited for water detection. The shifting courses of the river channels were studied during a forty-three-year period from 1975 to 2018. Based on the basemap (1975), 26 fixed cross-sections were chosen. The 2018 image was used as a reference to determine the current location of the Ganga and its tributaries. To better comprehend the river's morphological variations, cross-sections of uneven distances were chosen at several sites along the river's flow from north to south. These cross-section locations were chosen based on the visual assessment of temporal satellite images and significant morphological changes in the river. All cross-sections were labelled with alphabetical letters ranging from A to Z. The cross-sections were labelled A-J for the Ganga, K-O for Kali, P-T for the Ramganga, and U-Z for the Garra. Positive numbers indicate a right-side shift, while negative values suggest a left-side shift from the baseline year. The distance between the left and right banks of the river channel, as well as the direction of migration of the river bank line throughout the research period, were estimated at all cross-sections.

Results and Discussion

Mapping of Fluvial Landforms

The research region has a variety of fluvial landforms, including alluvial plains, abandoned channels, oxbow lakes, sandbars, meander scars, paleochannels, active channels, islands, and floodplains (Figure 2). These geomorphic features were mapped using satellite data by adopting visual interpretation techniques in a GIS environment. To evaluate landform characteristics, we carried out extensive fieldwork and employed high-resolution Google Earth images. Geologic influences such as tectonic history, lithology, structure, and denudation, as well as river flow and sediment transport mechanisms, can all influence valley formation and landform morphology (Goodbred, 2003). Alluvial channels are susceptible to change of pattern and shifting in their position as the alluvium or sediment load is eroded, transported and deposited.

Alluvial plain: This geomorphic unit occupies around 810 square kilometres, accounting for 73% of the overall area. These plains have flat or level slopes and are surrounded by flat-lying regions such as flood plains and water bodies. The alluvial plain is considered the most fertile terrain, and it provides a variety of economic and livelihood activities for the inhabitants.

Flood plain: It is distinguished by the presence of many oxbow lakes, abandoned channels, mender scars, and sparse plant cover. Flood plains form on both sides of river channels when the river overflows its banks during flooding. The Ganga floodplain is substantially larger than the other streams that run through the study region. A wide flood plain is observed between the Fatehgarh and Kannauj regions. Sediment and mud are deposited on the floodplain at regular intervals, making the soil rich and suitable for agricultural activity.

Paleochannels: Paleochannels have been noticed as stretch, lobate, or sinuous alluvial landforms spanning around 22.4 square kilometres. These are plotted using variable geometry, breadth, and orientation, demonstrating the river's fluctuating migratory distances from the present path. These geomorphic features are found in groups and contain high moisture in low-lying locations, making them useful for reconstructing an area's morphological past. They are made up of fine to extremely fine grey to yellowish-brown clay, with sand and silt mixed together. During drier periods, these paleochannels, which are potential aquifers for groundwater, might be profitably utilised.

Active channel: This geomorphic unit has constant water flow throughout the year. The rivers Ganga, Garra, Ramganga, and Kali flow through the region of approximately 20.4 sq. km. All rivers are sinuous in character. Sand deposition is easily distinguished by its light tone and smooth texture.

Sand Bars and Islands: These accretion features of the alluvial channel are typically associated with the meandering channel. The channel bars located near the point where rivers join the plain are characterised by coarser deposits, whereas the point bars found downstream are produced with clay and silt. Islands are inner morphological features of a river channel that might impact the river's shape and dynamics. Sand bars and islands occupy approximately 15.5 and 5.5 square kilometres of the study area, respectively.

Meander scar: Scars are the remnants of meandering active channels made of sand and silt that formed during the formation of the oxbow lake. When the oxbow lake entirely fills with sediments, it forms meander scars. They disconnect from the current channel and eventually become a distinct feature.

Ox-bow lakes: These are recognised as independent, but during floods, they became joined to the main river channel.

Abandoned channel: These are linked to the shifting channel of the Ramganga and Garra rivers. The channels are distinguished by their dry bed.

Sinuosity Analysis

The most important indications in hydrologic geometry are the pattern and size of meanders in river channels. Engineers and geoscientists can use it to build bridges or dams. Table 1 shows the findings of sinuosity indices for the Ganga, Ramganga, Garra, and Kali River systems. From 1975 to 2018, the channel index of Ganga ranged between 1.26 and 1.38. Similarly, the valley index varies from 1.2 to 1.29. It represents how the river spreads in its valley and forms bars inside its meander path. The SSI indicates a sinuous (<1.05) to braided river pattern (>1.11), while the HSI shows an alternating increasing and reducing pattern, and the TSI shows a declining and growing pattern. The Ramganga River is the Ganga's right bank tributary, and its merger point varies from year to year. As a result, the confluence point is also changing. The high CI (1.79) and SSI (1.07) indicate that the river is sinuous, although the HSI is less impacted than the TSI. The Garra river channel is influenced by terrain, with HSI ranging from 2.13 (1988) to 27.31 (2002). TSI ranges from 72.68 to 97.86, demonstrating a significant impact on terrain. The CI of the river Kali, a left-bank Ganga tributary, fluctuated from 1.76 (1972) to 1.99 (2018). The high measurements for VI-1.97 (2018), TSI-97.86 (1988), and SSI-1.08 (2002) indicate sinuous. The investigation found that the Ganga and its tributaries belong to the sinuous channel (1 to 1.11) group, which represents the river's mature stage. Alluvial channels regularly change their pattern in response to the rate of water discharge and sediment load. The sinuosity values range from 1.0 (straight) to 3.0 (Brice and Blodgett, 1978). The HSI is relatively low in the studied area, indicating that the valley is at the constriction stage. The high TSI value affects sinuosity, indicating that the research region is dominated by topography, whereas deposited material from flood plains reduces HSI.

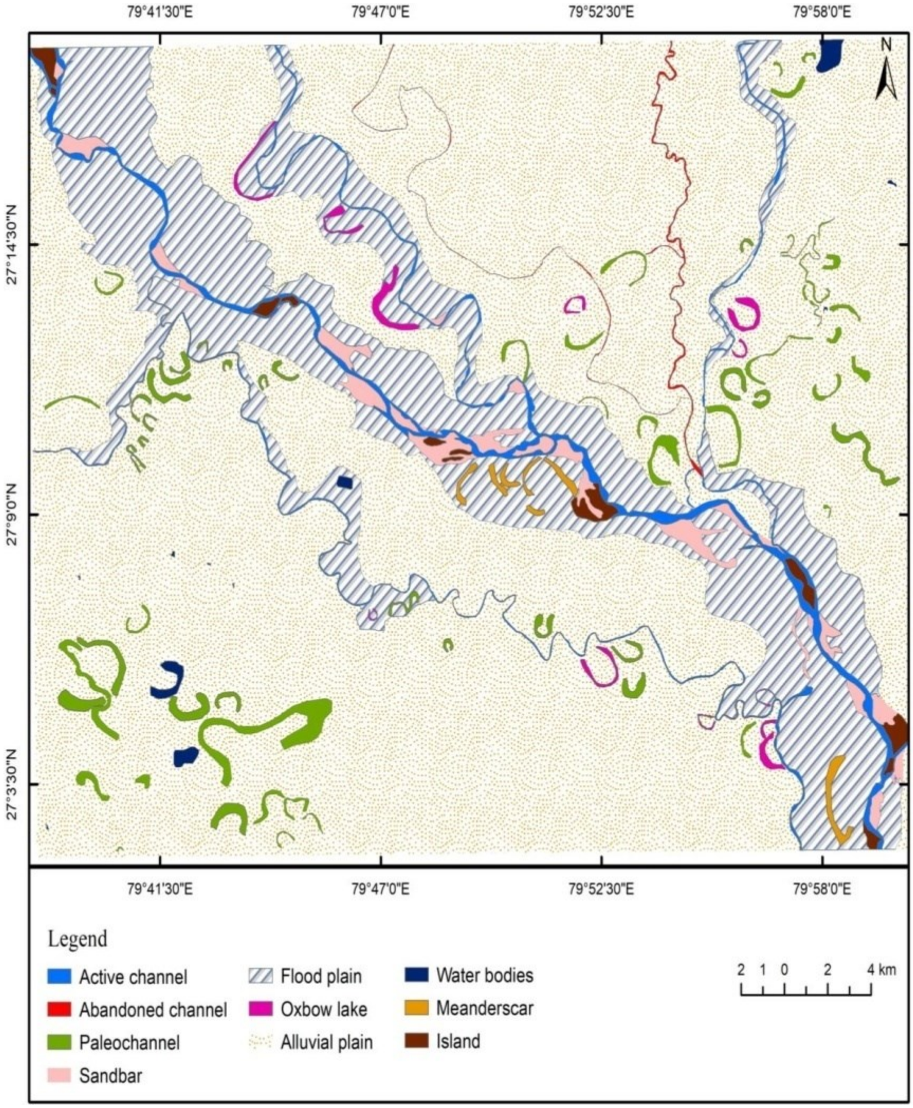

Figure 2. Fluvial landforms identified in the study area

Table 1: Sinuosity index of river channels of the study area.

River	Year	CL	VL	AL	CI	VI	HSI (%)	TSI (%)	SSI
Ganga	1975	55.11	53.68	41.6	1.32	1.29	10.58	89.41	1.02
	1988	58.89	52.82	42.48	1.38	1.24	36.98	63.01	1.11
	2002	56.89	55.47	44.75	1.27	1.23	11.69	88.3	1.02
	2018	58.37	55.66	46.15	1.26	1.2	22.17	77.82	1.04
Ramganga	1975	27.31	27.07	15.92	1.71	1.7	2.1	97.89	1.00
	1988	28.51	27.03	15.92	1.79	1.69	11.75	88.24	1.05
	2002	29	26.94	17.84	1.62	1.51	18.45	81.54	1.07
	2018	32.45	28.87	18.25	1.77	1.58	25.21	74.78	1.00
Kali	1975	57.48	56.97	32.18	1.78	1.77	2.01	97.98	1.00
	1988	60.7	60.17	37.67	1.61	1.59	2.3	97.69	1.00
	2002	62.49	61.02	31.65	1.97	1.92	4.76	95.23	1.02
	2018	64.36	63.66	32.26	1.99	1.97	2.18	97.87	1.01
Garra	1975	32.91	31.41	23.07	1.42	1.36	15.24	84.75	1.04
	1988	29.28	29.13	22.25	1.31	1.3	2.13	97.86	1.00
	2002	25.67	23.69	18.42	1.39	1.28	27.31	72.68	1.08
	2018	26.92	26.61	19.38	1.38	1.37	4.11	95.88	1.01

(Note: CL- the length of the channel in the stream, VL- the valley length along a stream, CI- (Channel Index) = CL/ Air, an index of total sinuosity, both hydraulic and topographic, VI- (Valley Index) = VL/ Air, an index of total topographic sinuosity, TSI- topographic sinuosity index, HSI- hydraulic sinuosity index and SSI- standard sinuosity index)

River Dynamics

River Dynamics of the Ganga Reach: The width of the river channel in several cross-sections (A to J) varied between 1975 and 2018. Proper channel constructing suggests that the Ganga River is gradually migrating to the north and northeast (Table 2). The river's breadth ranged from 130 m to 2200 m in 1975 and 150 m to 680 m in 2018. The maximum and minimum shifts of erosion were -1891.8 m (A) and -30.6 (H) on the right bank, and -2506.6 m (A) and -576.5 m (E) on the left bank. Deposition shift rates were 1722.9 m (J) and 30.7 m (C) on the right bank, and 2888.5 m (J) and 41.7 m (C) on the left. Overall, eight migration erosional sites (05-right bank and 03-left bank) and twelve depositional shift sites (05-right bank and 07-left bank) were found (Figure 3). At cross-section A, both banks experienced significant erosion of -1891.8 m and -2506.6 m towards the south-west. The large-scale deposition shift occurred on the right bank of the channel, between 1722.9 m and 2888.5 m at cross-section J towards the north. Following the cross-section F, the river divides into two branches and eventually unites in the channel around H. Between F and H, erosion and depositional processes dominate (Figure 3). There is a significant difference in river width between these two places. Industrial plants, notably those producing glass, have been developed in this region for business purposes. Sand mining operations are affecting the Ganga River and its tributaries. These unauthorised and illegal operations take place in the villages of Behta Ballu, Samchipur Tarai, Raipur Chihatpur, Katri Sota, Sinoli, and Katri Naampur. During the research period, the river course moved significantly on the right bank, and channel migration occurred mostly in the south-west direction. In 1975, the river channel between cross-sections I and J was separated into two branches, however, it is still running as a single channel in 2018.

Figure 3 a) Meandering of river Ganga b) River islands c & d) Severe erosion occurred at left and right bank of the river Ganga e) Thick alluvium deposits (terrace) f) River depositional process.

Table 2: Width of river and its bankline at various cross-sections during 1975-2018.

River	Cross-Section	River Width (m)		Right Bank (m)	Left Bank (m)	Direction of Migration
		1975	2018			
Ganga	A	130	680	-1891.8	-2506.6	South-west
	B	150	190	906.8	865.8	North-east
	C	150	180	30.7	41.7	Southward
	D	150	200	699.1	656.5	North
	E	340	180	-747.5	-576.5	South-west
	F	210	320	-681.8	-848.1	South-west
	G	2200	150	-159.4	1932.9	North
	H	920	270	-30.6	588	North
	I	320	410	1035.2	957.1	North
	J	1540	260	1722.9	2888.5	North
Kali	K	170	40	-68.4	89.6	North
	L	170	110	5	170.1	North
	M	280	50	-66.9	34.5	North
	N	210	50	539.5	645.7	North
	O	190	100	28.1	164	North
Ramganga	P	180	70	160	235.9	North-east
	Q	160	100	-1209.5	-1153.3	South-west
	R	340	50	-134.1	154.7	North
	S	300	50	-653.8	-404.1	South-west
	T	290	60	-2848.9	-2609.5	South-west
Garra	U	190	100	56.0	150	North-east
	V	200	90	-25.6	93.8	North-east
	W	170	70	-390.1	-288.2	South-west
	X	160	20	-66.1	73.8	North
	Y	150	30	-805.7	-612.8	South-west
	Z	160	-	-	-	-

(Note: Positive values indicate the right-side shift and negative values show a left-side shift from the base year)

River Dynamics of the Kali Reach: The channel width of Kali reach ranged from 170 m to 280 m in 1975 and 40 m to 110 m in 2018. At cross-section N, there is a massive migration lead to deposition of 539.5 m on the right bank and 645.7 m on the left bank of the river channel heading north. This is the location where the greatest amount of shifting occurs. Only K (68.4 m) and M (66.9 m) on the right bank showed erosion, while the remaining locations were identified as depositional sites. Both bank lines of the Kali River contain the highest number of positive values, indicating a northward movement.

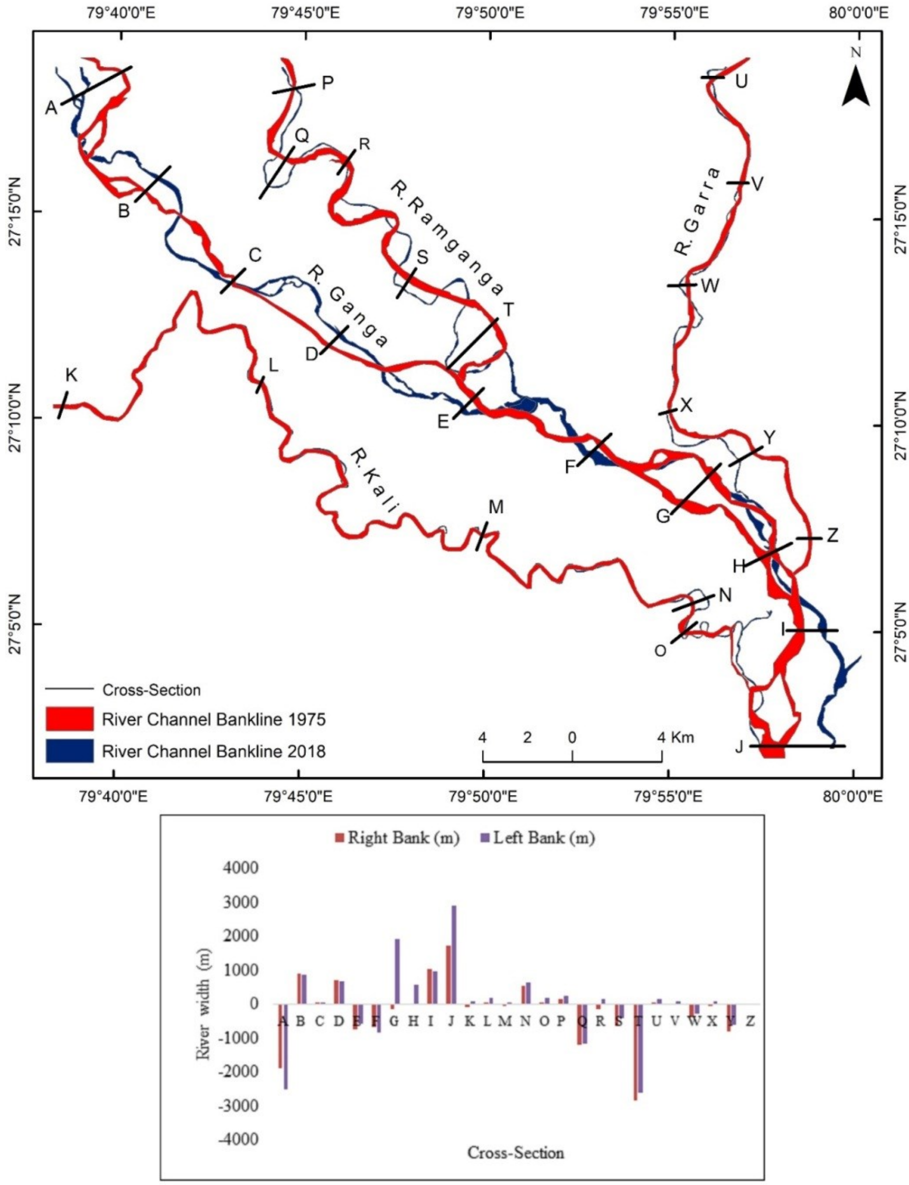

Figure 4. Channel position of the river Ganga and its tributaries in the study area.

River Dynamics of the Ramganga Reach: In cross-sections from P to T, the river bank line was shifted to the left, primarily in the south-west direction. In 1975, the maximum river width was reported at R (340 m), while the minimum was at Q (160 m). In 2018, the river's breadth ranged from 50 to 100 metres. During the research period, erosion was the most common occurrence, followed by deposition. The right and left banks have shifted maximums at T, which are -2848.9 m and -2609.5, respectively. The river's path was altered to the southwest. Accretion is greater at P on the left bank at 235.9 m and 160 m on the right bank. Overall, this river runs in a meandering manner, as seen in Figure 4.

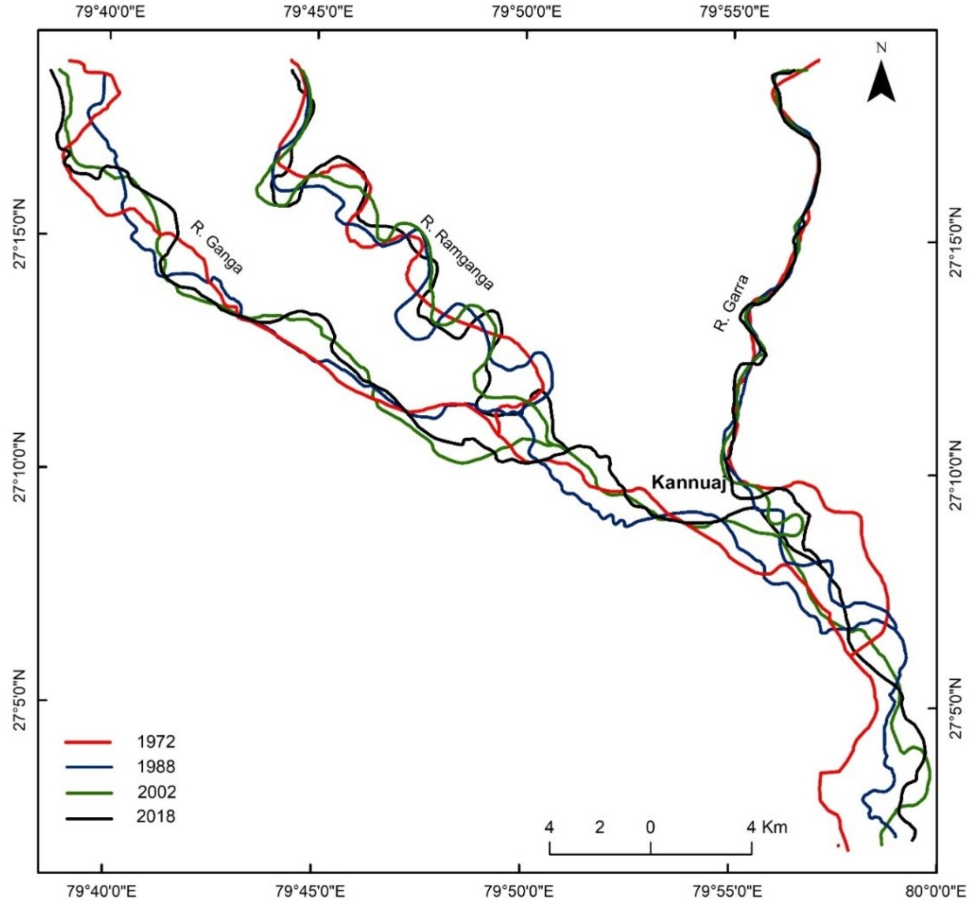

Figure 5. Change of confluence of river channels Ganga-Ramganga and Ganga-Garra.

River Dynamics of the Garra Reach: The width of the river channel in U-Z cross-sections ranged from 150 m to 200 m in 1975 and 20 m to 100 m in 2018. The Garra's channel positions suggest a progressive migration northward and northeastward. The maximum and minimum shift of channel erosion was -805.7 m (Y) and -25.6 m (V) on the right bank, and -612.8 m (Y) and -288.2 m (W) on the left bank. The deposition was only seen in the right bank 56 m at U. The left bank had a maximum of 150 m (U) and a minimum of 73.8 m at the cross-section X. After this point, the region is prone to active floods, which may result in channel relocation. Overall, this reach had a considerable number of erosional sites. In 1975, the river channel was combined with the Ganga at 1500 metres south of the Z cross-section, then at 1830 metres south of the Y in 2018. The change occurred at the confluence site between Y and Z, which is connected to local channel shifting at the confluence point caused by silt and water discharge variations in the active river channel (Figure 5). The river's course reveals lateral bank erosion. Between 1975 and 2018, all cross-sections preserved the U-right bank line relocated to the left side of the river. Maximum migration occurred at the Y cross-section, which measured -805.71 m and -612.82 m along its right and left bank lines, respectively, in the south-west direction. The river channel width at the cross-section Z was 160 m in 1975, but it has not reached this point in 2018 since it merged with the Ganga above this cross-section.

Conclusions

Alluvial rivers are characterised by channel erosion and accretion. Variations in water flow and sediment discharge rate cause the river channel to shift location. Channel shifting is primarily determined by a variety of hydrological and morphological features, including erosion, deposition, and discharge. Alluvial rivers meander naturally and are characterised by lateral erosion. It produces a shifting pattern throughout time. The present study examines the river channel movement and sinuosity of the Ganga and its tributaries, the Ramganga, Kali, and Garra rivers, from 1975 to 2018. Alluvial plains are occupied nearly 75% of the total area. River sinuosity index varies between 1.00 and 1.11 in the study area indicating sinuous to braided pattern. The Ganga River migrated as little as 30 m and as far as 2900 m at various cross-sections. Maximum and minimum changes were noted at different cross-sections of other river channels as follows: 5 to 649 m for Kali, 134 to 2849 m for Ramganga, and 25 to 805 m for Garra. The river channels have continuously moved from their previous positions as a result of hydrological processes and the region's terrain. Erosion was widespread along the Ganga and its tributaries. Except for the Kali River, all channels are constantly changing as they go from north to southeast. River channel movement or migration is caused by dynamic physical processes such as water and sediment movement over time. Aside from natural causes, manmade influences also contribute to changes in the river's location. Several significant activities were noted in the study area, including unauthorised farming, illicit sand mining, and the building of artificial dams to control river flow. When combined with river flow data, high-resolution satellite data collected at regular intervals during the monsoon and non-monsoon seasons might be very helpful in accurately determining river dynamics. The shifting location or movement of river channels across time and geography is crucial for resolving management issues. Time-sequential images from different times, as well as GIS assistance for mapping and measuring channel position, can be employed in a variety of geographic regions, notably in fluvial environments. It has been demonstrated that GIS techniques, together with fieldwork, play a vital role in fluvial morphology and riverbank erosion studies.

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