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Sediment Load Concentration and Resultant Channel Planform in the Lower Gandak Plain

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ABSTRACT

Erosion, transportation and deposition by running water are closely related and these works are performed in association and not in isolation. One cannot be performed without others. These works are determined on other factors like topography, geology, structure and composition of rocks, slope, amount of water availability and its characteristics, climate etc. Huge catchment area of the Gandak River is lying in the Himalayan mountainous region. This region is receiving good amount of rainfall concentrated in four months of monsoonal period June to September (JJAS). This period has also high temperatures leading to large amount of glacial ice melt. Hence, enormous water is drained off the mountain steep slope. The Himalaya is very young and has fragile rocks and ecosystem. Anthropogenic activities in those areas are primary cause, apart from natural weathering, for generation of more and more shattered materials which are brought by running water downstream much easily. Therefore, highly sediment concentrated water brings large quantity of loads. It is deposited in suitable conditions along its paths in the plain and with flood water. It results the formation of flood plain. According to the erosion and deposition, different types of major and minor features are formed. In other words, water and sediment determine the layout of the plain appearance. In this background, it is attempted to (i) study sediment concentration in discharged water and (ii) illustrate the channel planform of the Gandak River in the plain. To achieve these aims, secondary data has been collected and analyzed. It is expected that this study will help in executing an integrated development plan for the flood affected area of Lower Gandak River Plain.

Keywords: *sediment load, channel bars, channel planform, meandering, braiding, slope/gradient and channel cutoff*

INTRODUCTION

Movement of water in the river is a dynamic factor affecting performance and function of a river. This function is again dependent upon many other factors like topography/ relief of area, geology structure and composition of rocks, slope, flowing surface water quantity, climatic conditions etc. The Himalayan southern slope receives high rainfall due to obstruction in monsoonal air movement. The monsoon months have high temperatures due to which glacial melt water is added to rainwater. Hence, enormous amount of water drains the steep slope. More rushing water has greater energy to erode and transport. Since, sedimentary rocks of the newly fold mountain are highly weathered, erosional works of the river is very high. When the slope is high, they are transported easily downwards, but decrease in the slope lead to deposition of the transported materials as carrying capacity gets reduced. Large size loads are deposited first but smaller sized loads like sand, silt and clay are further brought down with flowing water. In plains, slope is further reduced; hence, smaller particles are deposited in due course. The deposition of sediments is the cause of the formation and development of plain by the river. This process has been repeated since time immemorial and, in this way all the plains of the world have been formed. The formation of the plain is not uniform but has great differences depending upon multiple factors. That is why; the plain has several macro, meso and micro landforms. The appearance of different landforms and the pattern of channels in the plain, if seen in a panoramic view, are called planform. Thus, channel planform is the resultant of different factors in interaction with flowing water and sediment brought downstream and its deposition.

The Gandak River Plain is a part of the Gangetic Plain located at "foredeep" depression in "outfall" of the Himalaya. The origin of foredeep is associated with formation of the Himalaya (Kumar et al., 2007, Kent and Muttoni, 2008). The deposits of alluvium in the plain have great bearing on neotectonics in the recent Holocene period (Srivastava et al., 2015). Gradient of the Gandak plain is about 0.57 meter/km in northern part while in southern part, it has come down to less than 0.17 meter/km (GFCC, 2004; Prasad and Rishideo, 2021[a]). The geomorphic characteristics of the Gandak Plain are determined by the pedogenesis and sediment deposits (Mohindra et al., 1992; Srivastava et al., 1994). Basically, Pedogenesis is a soil forming process and it is governed by many factors like the rocks from which it is formed; relief and topography; past and prevailing climatic conditions including organic contents and duration through which it is under the formation. Scheffers, May and Kelletat (2015) clearly explain river meandering and according to them, "Debris of different sizes (from silt to boulders) transported by flowing water in the area are real tools of erosion and are responsible for the incision of valleys" (Scheffers et al., 2015)

Varying amount of water in the river is a dynamic force with which many alternations are brought. Changes cause the planform to vary with time and space in the affected areas. In other words, changes in natural or anthropogenic factors affect the flow which brings change in the planform either in terms of pattern or sinuosity or braiding index (Knighton, 1984). Changes in meander, shifting of bend, channel movement etc. are controlled by water discharge and accompanied sediment loads and their sedimentation. Large quantity of flowing water in short duration in the Gandak due to torrential rain and high snowmelt brings flood in low lying flat plain. The flood is also associated with channel change because of avulsion and lateral cut-offs in the Gangetic Plain (Geddes, 1960; Sinha, 2004, 2005; Jain et al., 2012). The flooding process is continuing since time immemorial, but the intensity and frequency of floods as well as carried sediment have substantial increased since mid of the last century (Valdiya, 1985; Gopal et al., 2002; Kale, 2005; Singh, 2009; Patnayak and Narayanan, 2010). Sinha et al. (2014) have studied about the threshold and planform dynamics in the Kosi River and found that the Kosi River is prone to avulsion (Hossain at al. 2013, Prasad and Rishideo 2021[b]). The avulsions are also observed with the Gandak River as well.

OBJECTIVES, DATA AND METHOD

Objectives

The main objectives of this study are to (i) study sediment concentration in discharged water and (ii) illustrate the channel planform of the Gandak River in the plain.

Data Source and Methodology

To achieve the objectives mentioned above, secondary data has been used and analyzed. The sediment concentration data is collected by the Gandak Project Authority. Sample water is collected at 9:00am from river at three sites – Triveni, Dumariaghat and Lalganj. Collected water is analyzed, sediment concentration is assessed and total quantity is calculated based on discharging water. The average discharge, sediment load and its concentration are computed for ten-days, month and year. The record of the same was kept in register but now everything is digitally stored. During monsoon season, when discharge is rising rapidly, water sample collection frequency is increased to hourly or even at half hourly also to reflect the increasing discharge and peak occurrence. Hence, the sediment concentration data was collected from GFCC where record is also kept. Month-wise concentration of sediment is analyzed.

IRS LISS III Satellite Imagery of 29th October 2009 has been used to delineate three reaches of the Lower Gandak Plain and overall planform description of the river. Different spots of the channel reaches are identified to describe meso level channel planform features from Google Earth Image were snapped on 15th October 2021. The satellite imageries were used for the year 1976, 1996 and 2016, at an interval of 20-years and river course was traced. To see the changes over the selected duration in their panoramic view, they are superimposed.

Study area

Formation of Indian plain and different geomorphological features are the product of water and sediment brought from the Himalayan mountainous catchment, little description of that area needs to be explained here. The Himalayan catchment of the Gandak River constitutes 38680 km^2 (GFCC 2004). It lays between the Tsampo River basin in north and the Ganga River in south. Its eastern boundary extends to the Kosi basin and to the west it is bounded by the Ghaghara plain. The Gandak River originates from an altitude of 7620 meter (CWPRS 2012) from north of Dhaulagiri close to Nepal-Tibet boundary. The latitude of the origin is 29°18'N and 83°58'E longitude. It is well known fact that the Himalaya has evolved from the Tethyan sediment. Therefore, its geology is affecting the plain formation in India.

Himalaya is a 'live mountain' with active tectonics. Himalaya is fundamentally fragile and triggering factors such as rainfall and earthquakes make the mountains highly vulnerable to landslides and other mass-wasting processes (Prasad 2010, Prasad and Dorji 2011). The Gandak or Kali Gandaki forms the deepest gorge of the world (Carosi et al. 2014) surrounded by more than eight thousand meter high peaks of Dhaulagiri and Annapurna. A generalized picture in terms of schematic cross-section of the Himalaya from the Ganga River in south to the Trans-Himalaya in north is shown in Figure 1. Though, this figure does not reveal the vertical exaggeration, but still it has its own importance in highlighting the changing altitudinal sequences. Hence, greater slope caused greater erosion and transportation in association with heavy rainfall/and snowmelt.

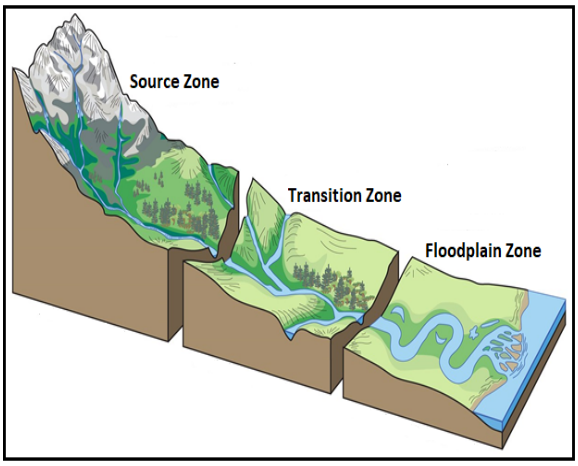

Figure 1: Three-Dimensional Diagrammatic Cross Section of the Himalaya
Based on: https://www.nps.gov/subjects/geology/fluvial-landforms.htm

It is a fact that the Himalayan slope is very precipitous and huge amount of sediment is generated due to rushing water along steep slope. Since the Himalaya is still rising, the stress is created and rocks are under constant crushing effect. It causes further fragility and human encroachment in the area in terms road/dam/reservoir construction as well as change in any form of land use is causing further sediment generation. Bhandari (NA) very categorically stated, "Indiscriminate construction activity compounds the problem that concerns not only 45 million people in the Himalaya and nearly seven times as many in the plain." A three-dimensional diagrammatic cross section of the Himalaya along with brief description is shown in Figure 1. It is quite obvious that the amount of water in far upper catchment is very low, but towards downside, it keeps on increasing by confluences of several tributaries. Even small quantity of water performs higher erosion and transportation due to high slope.

The Lower Gandak Plain extends between 25º21'23"N to 27º26'54"N latitudes and 83º49'00''E to 85º15'52"E longitudes. The area under study is lying primarily in the Indian Territory covering two districts of Uttar Pradesh – Maharajganj and Kushinagar; and eight districts of Bihar – West Champaran, East Champaran, Gopalganj, Siwan, Saran, Vaishali and Muzaffarpur. Together, it is 7620 km^2 out of which 968 km^2 is in UP and 6652 km^2 is in Bihar (Figure 2).

The details of the area falling in the Lower Gandak Plain as well outside the Gandak catchment are presented in Table 1. This table is self-explanatory but it is important to mention that district lying at the down-most end of plain have lower share of area like Begusarai and Samastipur. It is dependent on the position and location of the districts and extension of its catchment.

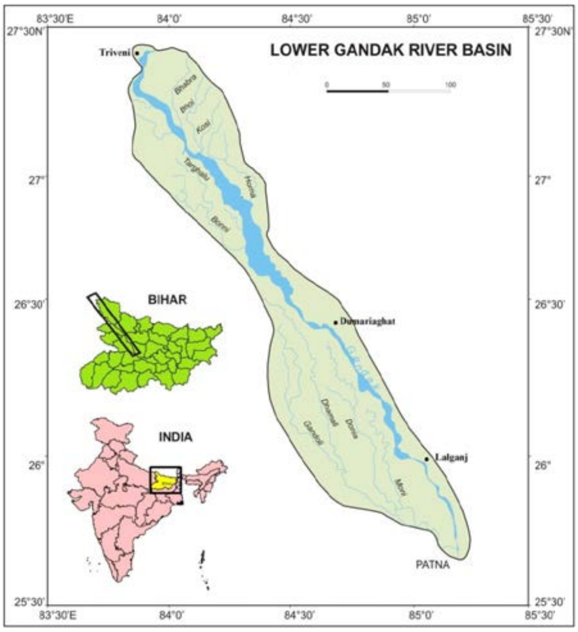

Figure 2: Location of Study Area

Source: Prepared by authors based on Plate 11 & 12: Soil and Land Use Survey of India (SLUSI) Atlas (1988)

Table 1: District-wise Distribution of Lower Gandak Catchment Area

State	Districts	Total area of the district (km^2)	Catchment area in district (km^2)	% of catchment area in district	Catchment % in district.
U.P.	Maharajgunj	2951	400	13.55	05.25
	Kushinagar	2874	568	19.76	07.45
	Total	5825	968	16.62	12.70
Bihar	W. Champaran	4250	2100	49.41	27.56
	E. Champaran	4155	1150	27.68	15.09
	Muzaffarpur	3123	600	19.21	07.87
	Vaishali	1995	1200	60.15	15.75
	Samastipur	2579	300	11.63	03.94
	Begusarai	1889	250	13.23	03.28
	Saran	2624	650	24.77	08.53
	Gopalganj	2009	402	20.00	05.28
	Total	22624	6652	29.40	87.30
Grand Total		28449	7620	26.78	100.00

Source: GFCC (2004)

There is drastic change in slope when the Gandak River debouches in the plain near Triveni at India-Nepal border. Deposition of sediments is prominently observed. Lateral erosion becomes more, valley widening is resulted. Sediment deposition in the valley/river bed exhibits braiding pattern. Further downstream, meandering is also observed. Several big tributaries of Gandak River are running more or less parallel to the Gandak and confluence with it later. Some of these tributaries are originating from the foothills and some of them start their journey from plain itself after collecting surface flow from smaller streams. Tributaries of the Gandak River are presented in Table 2.

Table 2: Tributaries of the Lower Gandak River System

S. No.	River	Direction	Origin	Outfall at	River Condition
1.	Bhabsa	L	16 km east of Triveni	Patkhauli	Live channel
2.	Harha	L	5 km south east of Bagaha	Balna	Live channel
3.	Mahi	R	Village BalnaMasrakh	Hajipur	Live channel
4.	Gandaki	R	Village Karnia	Sitalpur	Dried up/silted up
5.	Ghogri	R	Near Ramkola Factory	Bishambharpur	Dried up/silted up
6.	Kakara	R	Near Bajahia	2 km u/s of Sonepur bridge	Dried up/silted up

L= Left Bank Tributaries and R= Right Bank Tributaries (GFCC 2004)

The materials available in the Gandak plain can very well be grouped into three – upper, middle and lower. The upper plain primarily made up of Siwalik conglomerates, sandstones and clays. The middle plain is formed by lignites, sandstones and clays whereas the lower is made up of grey and purplish sandstones (GFCC 2004) along with fine silt and clays. In terms of soil availability, Terai soil in the upper, calcarious alluvial in the middle and alluvial soil in the lower plain are abundantly found. From Valmikinagar Barrage to its confluence with the Ganga River at Hajipur near Patna, Gandak runs for a distance of 260 km. The change in height is 59.8 meters. It gives a gradient of 0.23 meter/km (Table 3). In upper reach of the river, slope is substantially high (0.57 meter/km) while in lower reach, it is low (less than 0.17 meter/km). It is also to mention that just in a river distance of 12 km, slope has reduced to almost half to 0.3 meter/km from 0.57 meter/km. In fact, it happens to almost all rivers of the world. When the river debouches into the plain slope is generally high, but further downward, it reduces rapidly.

Table 3: Slope along the Gandak River between Different Segments

SI. No.	River Segments	Segment length (km)	Height difference (meter)	Average bed slope	Bed materials
1	Valmikinagar to Patharwa Head works	12	6.8	0.57 meter/km	Shingle and sand
2	Patharwa H/W to Chhitauni Rly. Station	28	8.5	0.30 meter/km	Average size 0.21 mm
3	Chhitauni Rly. Station to Dumariaghat	122	28,0	0.23 meter/km	N.A.
4	Dumariaghat to Hajipur	91	15.5	0.17 meter/km.	N.A.
5	Hajipuar to confluence with Ganga	7	1.0	≤0.17 meter/km	N.A.
Valmikinagar to Confluence with Ganga		260	59.8	0.23 meter/km	--

N. A. = Grain size of bed material not available
Source: Ganga Flood Control Commission, Patna, 2004

RESULTS AND DISCUSSION

River Morphology

River morphology is description of channel shapes and its appearance. Both shape and appearance changes because of dynamic factors of the river. It is primarily determined by discharge and associated basin characteristics mainly as geology, land use, slope and climate. Therefore, morphology of a channel is the function of various factors. The structure and composition of bed and bank are important as discharge is carried through this path in a concentrated manner. The way discharge is altering its path, water flowing through its channel or overtopping during flood time, determines the appearance. The available water and carried sediment load characteristics also sculptures the area. Erosion and deposition by channel during bankful discharge as well as in lean season gives different appearance. In time immemorial days, rivers were quite natural, but now, anthropogenic imprints are visible. Because of human interference in the catchment area of a river, its morphology has also changed which we termed anthropogenic factors. Changes in land use creates huge amount of sediment and the same is easily available for the river to carry. Hence, it is also impacting the morphology of the river.

A generalized schematic diagram given in Figure 3 is vividly expressing that channel form changes with erosion and deposition. It is a regular feature in the plain by all rivers of the world. Initially, the channel is single thread straight but due to lateral erosion, it keeps on enlarging itself. When it is wide enough, sediment is deposited in the channel and water moving path is divided and subdivided and multiple channels are visible across two banks of river (Figure 3). Meandering is common to most of the rivers and it is said, “Snakes and river never run straight”. With lateral erosion, meander also keeps on increasing and at slip-off (outside of the bend), there is erosion while at point bar (inside of the bend), deposition is pronounced.

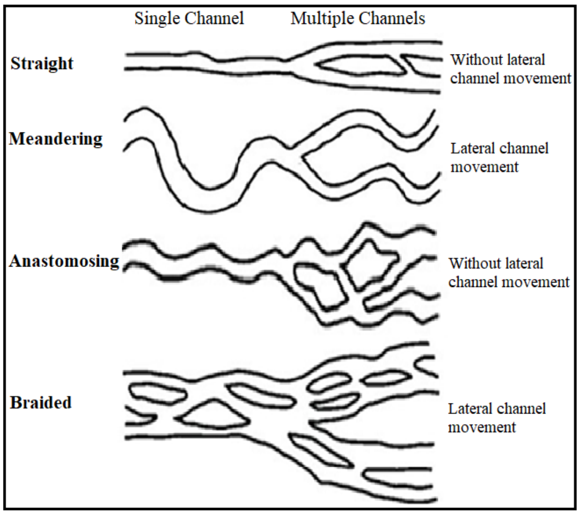

Figure 3: Changes in Channel Form: Lateral Erosion and Deposition
Source: Modified after Misiura and Czechowski (2015)

Anastomosing pattern of the channel is termed when two or more than two channels exist across a river. Meandering or braiding pattern channels can be termed as anastomosing (Makaske, 2001). Braiding pattern is the characteristics of river in the plain when it carries large sediment loads in its flowing water. At different segments of the Gandak River also exhibits all these characteristics.

Sinuosity and Braided Indexes

Thalweg length (L_t, along the deepest bed of channel) is divided by straight length (L_r) of a channel segment to get meander ratio or sinuosity index. Thalweg is also termed as the navigable deeper middle path of a channel. It is expressed as:

Sinuosity Index (SI) = L_t/L_r

Braiding index can be calculated by getting length of all bars in a segment of the channel reach. It is multiplied by two ($2B_l$) and is divided by the straight length of the channel segment (L_r). It is expressed by:

Braided Index (BI) = $2B_l/L_r$

When sinuosity index is:

Less than 1.1: Straight Channel
1.1 to 1.5: Sinuous Channel
More than 1.15: Meandering Channel
2.0 to 4.0: Moderately Braided Channel
4.0 to 5.0: Highly Braided Channel
More than 5.0: Intensely Braided Channel

The steps and method for calculating Sinuosity Index (SI) and Braided Index (BI) is shown in Figure 4.

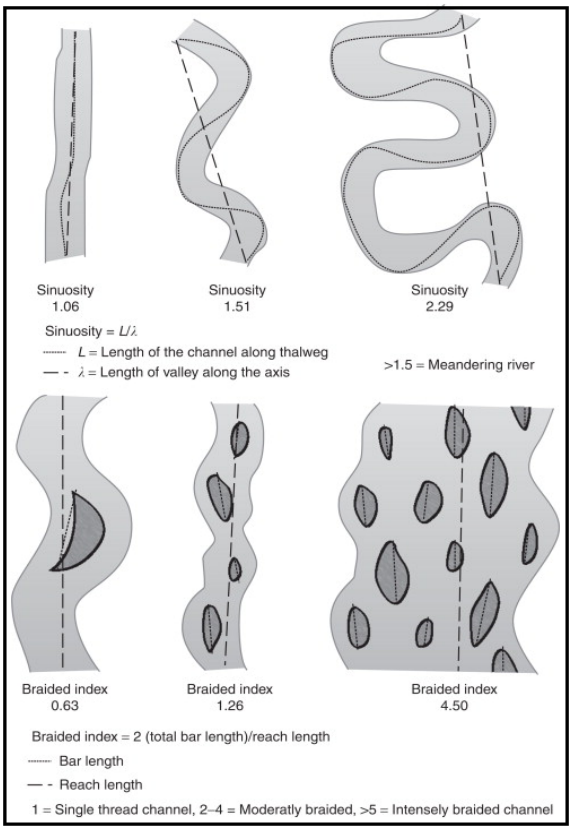

Figure 4: Calculation of Sinuosity and Braided Indexes
Source: Fuller, Reid and Brierley 2013

Sediment Concentration with River Water

Monthly average sediment concentration for a long duration is collected from Central Water Commission (CWC) for three sites Triveni, Dumariaghat and Lalganj along the Gandak River. The same is presented in Table 4. From this table it is quite evident that there is very high variation in the concentration of sediments. During lean season (January and February) in terms of water flow in the river is very low while in high discharge days (June to September) it is very high. It is quite evident that the sediment concentration in the upper reach (Triveni) is less in comparison to lower reach (Lalganj) particularly when discharge is relatively lower (September to June). Though the rise in discharge is observed from the month of May but sediment concentration is higher at Trveni when flood like situation is arising and it is continuing till October. It is explained by the fact that smaller sized sediment is higher when slope is even less and discharge is not swift. But when discharge is higher during monsoon days, upper reach (Triveni-higher slope) produces more sediment, but when the water reaches downstream, slope is reduced substantially, sediment is lower in the flowing water. A comparative month-wise concentration of sediment over years can very well be seen from Figure 5.

Table 4: Average Monthly Sediment Concentration

Month	Average Sediment Load in gm/litre discharged water		
	Triveni	Dumariaghat	Lalganj
January	0.091	0.360	0.514
February	0.069	0.254	0.355
March	0.136	0.236	0.319
April	0.142	0.321	0.445
May	0.266	0.357	0.484
June	0.862	0.741	0.927
July	2.428	1.764	2.144
August	2.102	1.812	2.268
September	1.898	1.861	1.987
October	0.760	1.084	1.637
November	0.366	0.608	1.097
December	0.154	0.475	0.710

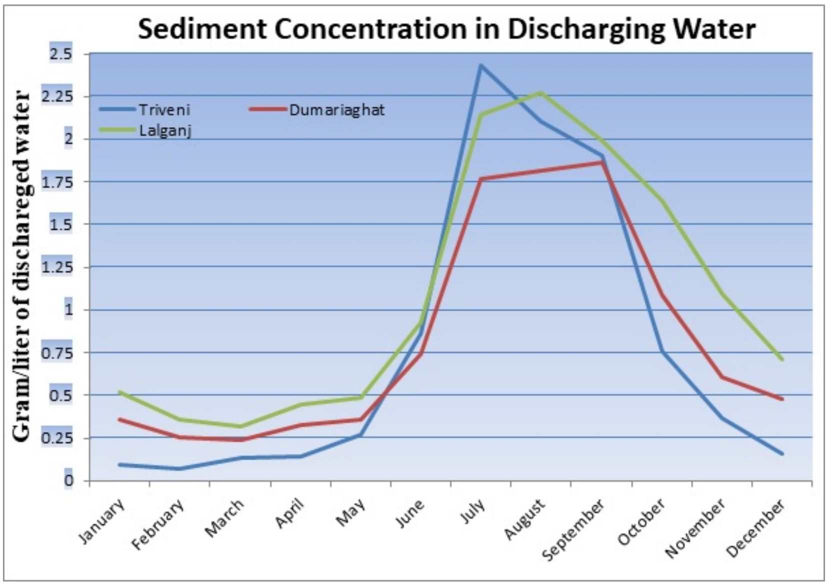

Figure 5: Monthly Sediment Concentration at Three Sites

Total Sediment Generation

Based on daily sediment concentration data collection and discharge computation, total sediment generated at three sites – Triveni, Dumariaghat and Lalganj have been computed by Gandak Project Authority and the same is collected from CWC, Patna. The total sediment carried by running water at these sites is presented in Table 5 for the period 1986-87 to 1998-99. This table shows excessive sediment load during 1988-89 particularly at Lalganj. Out of three sites, it is 95.8 percent sediment generation is observed at Lalganj. It seems impossible. The concerned authorities were consulted but no satisfactory answer was provided to this issue. With marginal variations, there is well aligned figures are there for all sites except 1988-89.

Table 5: Silt Load and Generation at Selected Sites along the Gandak River

Years	**Triveni**	**Dumariaghat**	**Lalganj**	**Total of All Sites**	**Triveni**	**Dumariaghat**	**Lalganj**	**All Sites**
	Quantity of Annual Sediment Load in '000 Tonnes				Percentage Contribution of Sectors			
1986-87	87,893	66,099	72,939	2,26,931	38.73	29.13	32.14	100
1987-88	1,34,117	52,806	1,79,482	3,66,405	36.6	14.41	48.98	100
1988-89	*1,32,293*	*59,119*	*43,68,648*	*45,60,061*	*2.9*	*1.3*	*95.8*	*100*
1989-90	1,34,765	36,853	55,469	2,27,087	59.35	16.23	24.43	100
1990-91	85,423	23,509	55,196	1,64,128	52.05	14.32	33.63	100
1991-92	52,444	46,778	39,297	1,38,519	37.86	33.77	28.37	100
1992-93	51,157	18,624	26,146	95,927	53.33	19.41	27.26	100
1993-94	1,28,996	31,202	44,601	2,04,799	62.99	15.24	21.78	100
1994-95	32,179	33,148	60,659	1,25,987	25.54	26.31	48.15	100
1995-96	1,13,561	40,673	35,211	1,89,445	59.94	21.47	18.59	100
1996-97	43,773	40,960	13,631	98,364	44.5	41.64	13.86	100
1997-98	19,549	12,329	20,028	51,906	37.66	23.75	38.58	100
1998-99	14,676	22,291	59,521	96,488	15.21	23.1	61.69	100
1986-1999	10,30,826	4,84,391	50,30,828	65,46,047	15.75	7.4	76.85	100
Average	79,294	37,261	3,86,987	5,03,542				
Except 1988-89	8,98,533	4,25,272	6,62,180	19,85,986	45.25	21.41	33.34	100
Average	74,878	35,439	55,182	1,65,491				

Note: Figures for 1988-89 are bold and underlined: unbelievably high at Lalganj.
Source: Based on Ganga Flood Control Commission (GFCC), Patna, 2004

Sediment yield is the function various factors but discharge is always a dynamic force. It was tried to corroborate rainfall of recorded stations nearby Lalganj, but there was no excessive rainfall during that year. If average sediment quantity and percentage is calculated for the said period it comes to more than 75 percent at Lalganj while for both sites Triveni and Dumariaghat together is less than 25 percent. If just one year of dubious data is removed, percentage for Lalganj comes down to one-third of three sites and seems to be in alignment. The same is computed at the end of Table 5. A diagrammatic presentation of the same is presented through Figure 6.

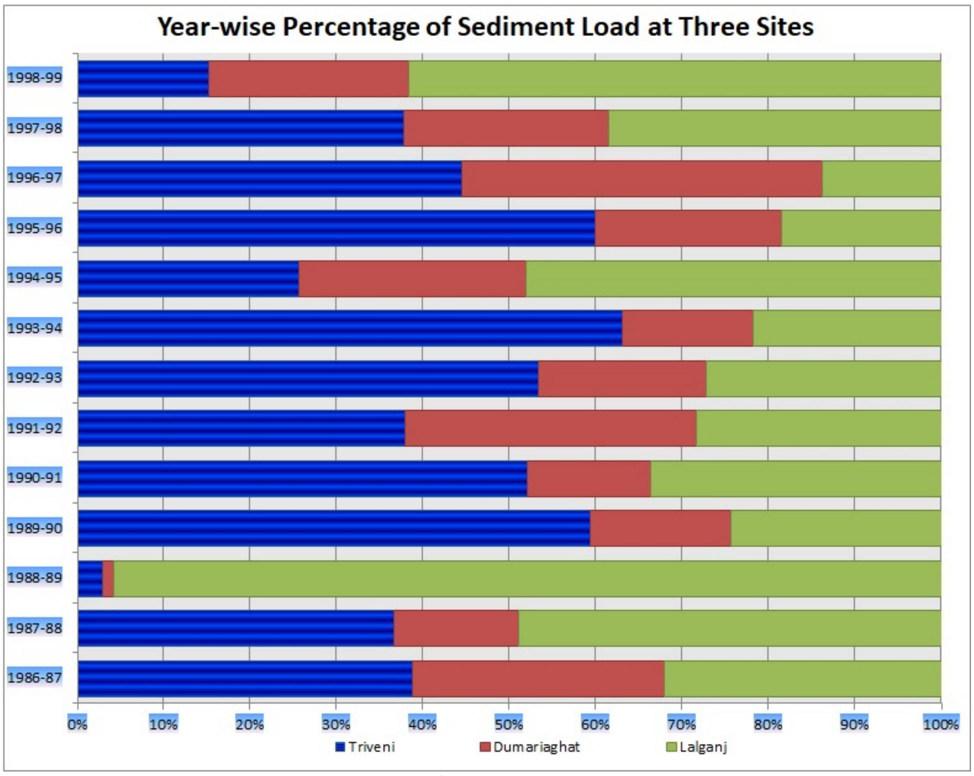

Figure 6: Distribution of Sediment Load among three Sites

Planform of the Gandak River

Numerous studies have been attempted to study morphology of the Gandak River. The most important among them is by the Ganga Flood Control Commission (GFCC, 2004). The Gandak River is surveyed along several cross-sections every year after monsoon season, preferably during January-February. The same data is supplied to the Central Water and Power Research Station (CWPRS) is located at Khadakwasla near Pune. It is a research station where the River Gandak (along with many rivers of India) has been simulated. It is a model in which different components of river morphology are incorporated, which is a replica of the river. Different levels of discharges of water are released and the changes coming due to change in discharge is recorded and monitored very minutely. In this way, CWPRS used to advise the Gandak Project Authority about the actions to be taken by them before the coming monsoon months. The Technical Report No. 5015 which was published in November 2012 by the Central Water Commission (CWC), Government of India is comprehensive and elaborative study on Morphological Studies of River Gandak. Apart from GFCC, many of the academicians have also studied about the morphology of the Gandak River (Fuller, 2013)

Planform of a river is the appearance of channels but at a point of time. The flow of river water and associated sediment load is said to be in a quasi-equilibrium state. Quasi-equilibrium is a slow process into which changes are taking place slowly. For example, when flowing water and its sediment is always said to be compensated and maintain a balance. In this process, increasing discharge lead to picking up of sediments and increasing erosion while decreasing discharge will lead to dropping of its loads and lowering in erosion. Therefore, this quasi-equilibrium state gives an appearance of the channel at any given point of time preferably termed as planform of the river/channel.

Channel Planform Reaches

The channel planform is the visible channels of a river at a point of time seen in the area. The Gandak River in the plain could be divided into three reaches based on the imageries of 29th October 2009. They are:

a. Reach I: Valmikinagar to Gautam Buddha Setu
b. Reach II: Gautam Buddha Setu to Dumariaghat Bridge
c. Reach III: Dumariaghat Bridge to Confluence with Ganga

Reach-wise Channel Characteristics in the Plain

Table 6 has been compiled on the basis of data generated from Google Map on 30th November 2018. The mid-river length is the measurement taken almost through the center of the river starting from Valmikinagar Barrage. Pool length or thalweg length represents the measurement along the deepest channel from Valmikinagar to its confluence with the Ganga River. Since river has meanders at certain sections, thalweg length is greater than straight mid-river length. Straight length is a crow-fly distance from points separating reaches. Right and left bank lengths are distance measured along the respective banks.

Table 6: Reach-wise Channel Characteristics: The Gandak River in the Plain

Reaches	Mid-River Length	Length along the Deepest Bed	Straight Length	Channel Sinuosity Index	Right Bank Length	Left Bank Length
Reach I	70.21	76.37	60.75	1.26	76.32	90.11
Reach II	96.52	108.22	88.58	1.22	119.67	111.08
Reach III	103.55	107.65	91.23	1.18	109.24	103.45
All Reaches	270.28	292.24	240.56	1.22	305.23	304.64

Source: Computed by authors based on Google Map Image on 30 November 2018.

Channel Sinuosity Index is a dimensionless value which is arrived at by dividing length of a stream by straight length between two points – upper and lower of the same channel. The length of a stream is the measurement along the deepest bed of the channel. It is called thalweg of the channel. The straight length is measured between dividing/separating points/margins of the reaches.

This index establishes the relationship between ratio of channel length and shortest distance between two points. It reflects the characteristics of a channel behavior in terms of morphology, hydrology and sedimentology of the area through which it passes. If the ratio/index is 1.0 to 1.05, the channel is supposed to be straight course. It means, the thalweg is equal to or near equal to the straight length of the channel. If ratio/index falls between 1.05-1.5, it is considered to be sinuous course. The index with greater value of 1.5 indicates meandering course (Leopold et al, 1964). The index is quantifying how much course of a channel deviates from the shortest possible length. All three reaches mentioned here has more or less similar index ranging from 1.18 to 1.26. According to Leopold, the Gandak River in the plain is representing a sinuous channel pattern.

Reach I: Upper Gandak Plain

Reach I starts from Valmikinagar barrage in north and it continues till Gautam Buddha Setu (Figure 7). This barrage is at the boundary between two countries, and it falls partly in India and partly in Nepal. Its length is about 70 km downstream to the barrage. In between the two limits of this reach, there is a railway bridge known as Bagaha-Chhitauni Rail Bridge. From Valmikinagar to railway-bridge, river is flowing in the shape of a banana. In north, it is flowing from north-east to south-west direction for about 40 km. Thereafter, a sharp turn is observed and it flows from north-west to south-east direction for a distance about 30 km when railway-bridge comes. At both ends, river is narrow because of barrage in the north to railway-bridge in the south (in center of the reach). In the first half-stretch, river displays a braiding tendency. Many channels are appearing across river when one observes through cross sections. But still the breading is confined in relatively smaller width of the river.

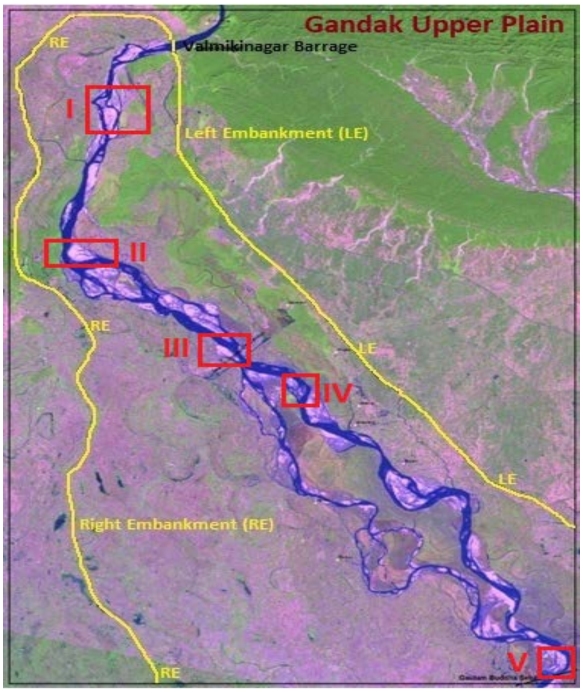

Plate 7: Reach I: Upper Gandak Plain

Source: IRS LISS III Imagery Dated 29th October 2009

After Bagaha-Chhitauni Railway Bridge, river occupies wider space laterally with many channels running parallel. River is exhibiting anastomosing channel pattern. Anastomosing pattern is called when two or more than two interconnected channels appear and they enclose the flood basin (Makaske 2001). It constitutes multi-channels rivers in the alluvial plain. It happens largely due to relatively low energy as slope is reduced drastically, water is spread over wider channels with multi-divergence and convergence. Reduction in the channel energy causes river to flow through numerous channels. Both near railway-bridge as well as at Gautam Buddha Setu, river is narrow exhibiting single across the banks but in between the two limits, it is interlacing with huge sized stabilized islands/bars among them. Numerous twists and turns along with channels are common affair.

The two embankments – right and left – are shown on the satellite imagery. Close up view of five spots are identified (shown in Figure 7) and images from the Google Earth (dated 15th October 2021) are snapped for better presentation which is given in Figure 8.

Part I of Figure 8 clearly shows typical diverging tendency of debouching river in the plain. Northern part is about 10 km downstream to Valmikinagar Barrage. River is flowing in southerly direction but with multiple channels. Large channel bars are obviously visible. Channels are deep water with dark colour. To the right bank, embankment is clearly visible. To the left side bank, many channel paths are observed. Part II has substantial changes in terms of channel divergence. Though, multiple channels are there, but for substantial distances, prominent single channel is visible. In the central part of channel segment, channels are making a knot by getting merged together. Further eastward, it gets diverged into several channels again. To the eastern segment of Part II, channels are joining together to form a united channel. Widespread channel bars within river banks as well as outside are observed. These bars are deposited during bankfull discharge and flood duration. The north-south direction of the river is changed to west-east direction.

Figure 8: The Gandak River Channels at Selected Spots
Source: Google Earth Images dated 15 October 2021

At stretch III, river is running in northwest to southeast direction. Prominent single channel is visible but other minor channels are quite distinct. Meander and braiding with lesser intensity are obvious. Sand and silt dominated channel bars are there. To the right bank, stable higher deposits are seen. To the right bank, shallower depressions like features are observed. In this stretch, channels are deeper and stability is more in comparison to other two reaches discussed above. Part IV falls further downstream and exhibits wider and stable channels with bar formation. In fact, bar formation is observed all through the Gandak channels starting from debouching into plain in northwest to confluence with the Ganges in the southeast. Channels are wider, water is shallower and banks are stabilized. Further southward section is denoted by Part V where the channels are stable. Bars are wider, multiple channels are visible but prominently two relatively shallower channels are apparent.

Reach II: Middle Gandak Plain

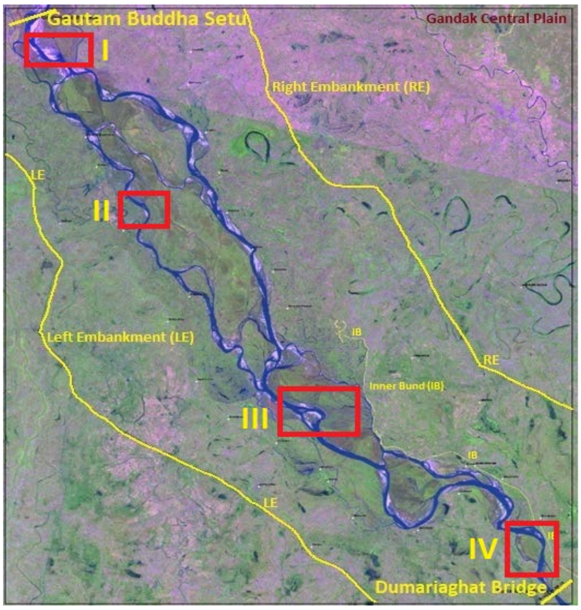

Figure 9: Reach II: Middle Gandak Plain
Source: IRS LISS III Imagery Dated 29th October 2009

Middle Gandak Plain (Reach II) starts from Gautam Buddha Setu, in northwest to Dumariaghat Road Bridge in southeast (Figure 9). Its extension is about 96 km. It is also exhibiting an anastomosing character. It is like more or less a mirror image of second half of Reach I (Bagaha-Chhitauni Rail Bridge to Gautam Buddha Setu). This character is observed till 60 percent of length of this reach. It is approximately 58 km from Setu, nearby Khairathwan village on right bank. From here to the downstream, river becomes a single one except a narrow channel still flowing to north-east direction. After running for about 18 km, rejoins near Gausia village but after that narrower channel becomes a prominent one like the first in south. Both of prominent channels finally join near Salempur (right bank) and Sangrampur (left bank). Thereafter, a single prominent channel continues till Reach II end.

Part I of Figure 10 belongs to Middle Gandak Plain. Within middle, it is lying in upper part of the reach. Channels are wide apart separated by stable deposited old bars. The channel seems to be formed by avulsion. They are narrower in width and have large deposits of channel bars. Bars are mainly composed of sand and silt. Ripples and very narrow cutoff channels are visible. Between two large channels, vegetation grown stable old bars are also there. Part II of same figure shows very well developed meander resembling almost half-circle in shape with almost straight flowing active channel. Channel along the bend is very narrow and is about to be cutoff from the main flow and forming 'ox-bow' with dry bed. Other old smaller channels are quite apparently seen.

Figure 10: The Gandak River Channels at Selected Spots
Source: Google Earth Images dated 15 October 2021

Part III shows intense meandering of the river with narrow channel and shallower depth. Bars are confined to a narrow band. Apart from live meandering channel, older meanders are also seen. They seem to be crisscrossed by newer channels. In Southeastern part of the reach, almost complete circular meandering pattern is visible and a cutoff is about to be completed. Water is observed in both segments of channel, bending as well as the live prominent. Part IV shows stable main channel with island type bar deposits. Southern part of this segment of the reach vividly shows several smaller channels and seems to be abandoned. Translatory tendency of the river seems to be arrested by this section.

Lower Gandak Plain: Reach III

Reach III lays between Dumariaghat in the north-west to its confluence with the Ganga River in south-east. It extends for a distance of about 104 km. For most of its length, river is a bit stabilized in comparison to Reach I and Reach II. Serpentine bends are visible all through but multi-channel appearance is not that prominent. From Faizullahpur (about 18 km downstream to Dumariaghat Bridge) village on the right bank to Fatehabad (about 38 km downstream to Dumariaghat Bridge) village on the left bank, the river has bends and multi-channel existence. Beyond that and till the confluence with the Ganga, river is a single channel appearance. In this reach, river is flowing in a north-west to south-east direction (Figure 11).

Part I of Figure 12 reveals recent lateral movement of the bend of meanders. Moved channel discharges large water and previously existing channel reveals dry bed in imagery when satellite data was acquired. Different channels are obviously seen but they are also dry. Bars are also identified at several locations. Between dry earlier channel and outside of the bend (cutoff), ripples like features area identifiable. High discharge driven sediment deposition is observed. Part II is lying further downstream where river channels are quite stable. Large amount of sediment is deposited in upper reaches. River carrying capacity is reduced in lower reaches. Sediment amount is also lowered. Slope is substantially reduced. Decrease in sediment deposition, causes greater stability of the channel. Single thread channel is seen at this stretch. Intensity of braiding is substantially reduced. Bars deposits are less.

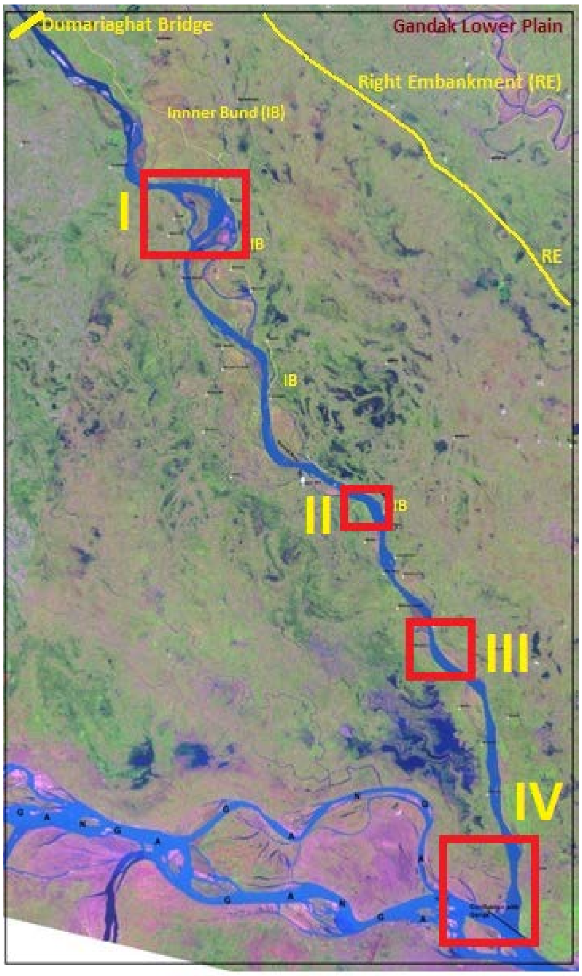

Figure 11: Reach III: Lower Gandak Plain
Source: IRS LISS III Imagery Dated 29th October 2009

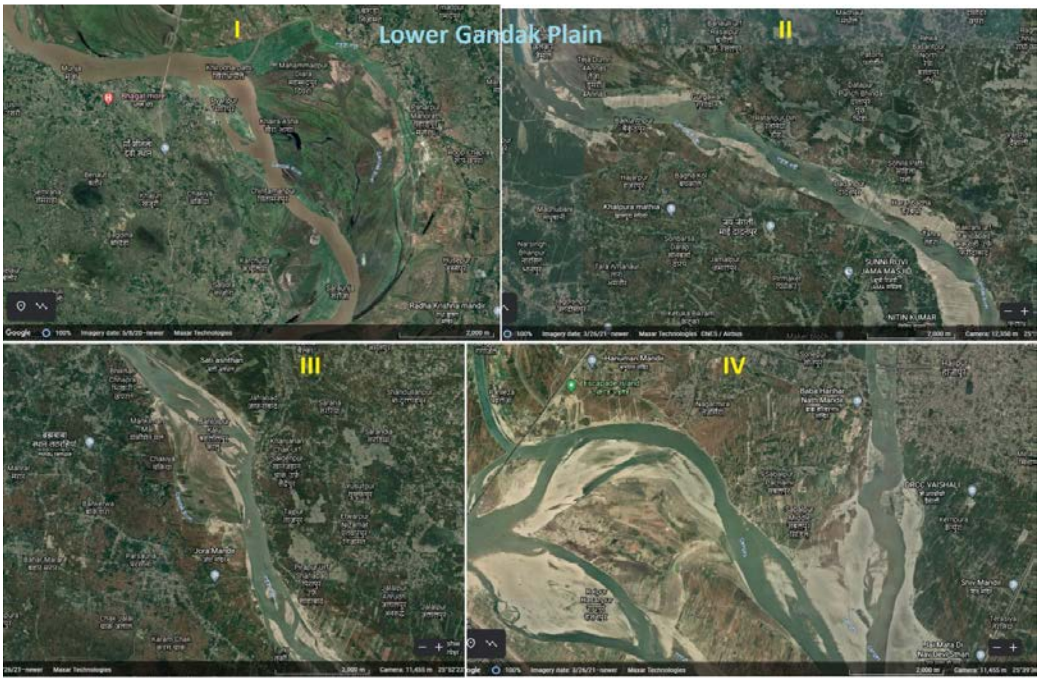

Figure 12: The Gandak River Channels at Selected Spots
Source: Google Earth Images dated 15 October 2021

Part III is the continuation of Part II when stability of the channel is more pronounced. Two knot types of features are observed where some minor channel shifting is observed. At those places, sand bars are also there. Rest of the surrounding areas shows cultivable land with vegetative cover. Minor ripples on sand bar are also there and it is vividly noted. Part IV shows end point of the Gandak River where it confluences with the Ganges at Hajipur near Patna. Before its joining, the Gandak is a single channel with greater stability here because of reduction of sediment load substantially. But before joining with the Ganga, it is very wide. During flood days, the Ganges water poses obstruction in free flow of the Gandak water. A sort of backwater effect is observed and due to this reason, two banks of Gandak are wide apart with sufficient silt deposits are observed. Hence sand bars are very large at its mouth.

Changes in Channel Planform of the Gandak

The horizontal displacement of channels for three – 1976, 1996 and 2016 – at an interval of 20-years each are superimposed and presented in Figure 13. From this figure, a comparative visualization of changes is quite obvious and vivid. It becomes very evident and vivid as to how much change has taken place from time period to another. It is quite clear that maximum planform changes are taking into the middle of the river length encompassing entire Middle Reach as well as the lower part of Upper Reach and northern part of Lower Reach. But large departures are noticed in the upper middle section of the river path. In the initial stage of the river entring into plain has relatively better stability but after a distance of about 30-35 km, channel changing courses are vividly significant. At the end, for a distance of about 40-45 km from the confluence, river is does not show significant changes in its course. After the barrage at Valmikinagar, embankments are constructed along both sides of the Gandak River. The channel in the downstream to the barrage is narrower and deeper. The water velocity is stronger and channel loads are transported downwards. Therefore, the channel chocking is not a prominent activity in the upper part for a distance of about 25-30 km. With passing distance of the river downstream, depositional tendency of the river gets enhanced and channel chocking and carving out new channel in its vicinity become a regular affair and so is the channel shifting channel planform changes.

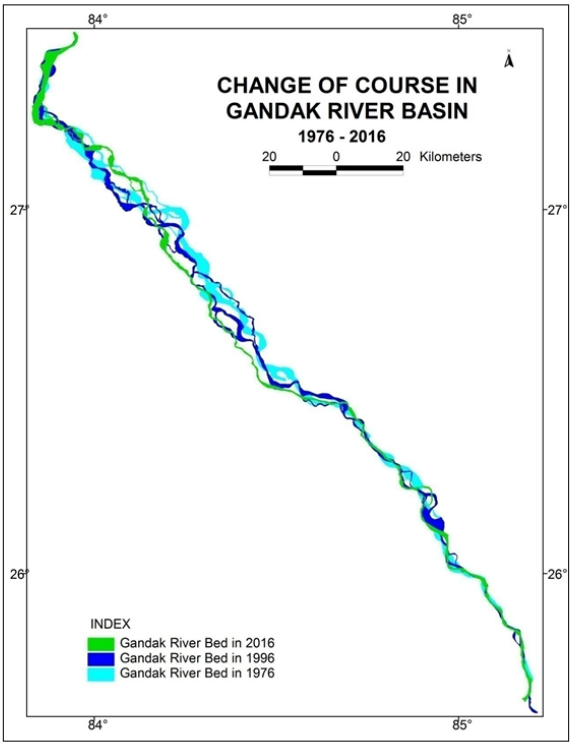

Figure 13: Superimposed Gandak River Planform: 1976, 1996 and 2016

CONCLUSION

Water is the most potent and dynamic factor in sculpturing surface landscape of the earth. When amount of water is more associated with precipitous slope like the Himalaya, action of the river is more energized. The effect of high discharge is quite obvious and pronounced. The Gandak River originates from an altitude of 7620 meter near Nepal-Tibet border north of Dhaulagiri Mountain. Almost entire Himalaya has risen from the Tethyan sediment. Its geology is new, fragile and weak susceptible to easy erosion. It is associated with high torrential rain with huge snowmelt during hot summer days. Both of situations are the cause of high velocity of accumulated water. Himalayan rocks are crushed sedimentary layers because of tectonically active zone. Therefore, they are easily eroded. Those eroded materials are easily carried down along the slope with charged water. With reduction in slope in plain areas, sediments are substantially deposited and thus deposition causes channel to move laterally. Water is also spread and channel occupies wider space. It is also a reason to deposit sediment because the carrying capacity of the water is lower very rapidly. Deposition is in the channel bed as well as in the flood plain results in meander and braiding. It happens with all rivers of the world, with varying degree of intensity. But in case of the Ganndak, it is very intense. Therefore, sediment brought by river is of great concern and it leads to channel form changes and channel migration.

The Gandak Plain is one of the densely populated pockets of the world. Annual flood or many times flooding in the same year is regular affair in the Gandak Plain. The intensity of flooding has been increasing since mid of the last century and primarily its cause is attributed to anthropogenic activities. Huge loss of crops, economy, infrastructure, transport and telecommunication and human and cattle are resulted annually. The main reason is alarming floods. Therefore, prime concern is to check the flood in the plain area. Its best suited solution is to arrest the cause. Water cannot be trapped without some ecological losses in the mountainous region after spending huge amount of money in erecting dams. But this is also not a permanent solution of flooding in the plain. Therefore, silt trapping in the source region could be one way to overcome the problem of flooding. The best method of trapping silt is the source region is by adopting nature friendly land use so that silt yield is minimized. Hence, both governments – India and Nepal – must work in close cooperation and coordination with interaction with the masses in favorable land utilization in the Himalayan catchment. Apart from that, obstruction in the water discharge should be avoided to facilitate free flow to downstream so that water is not allowed to spread in the surrounding areas.

In this way flood could be minimized, to some extent.

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