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ANALYSIS OF SEDIMENT LOAD AND ITS CONCENTRATION IN THE LOWER GANDAK FLOOD PLAIN, NORTH BIHAR

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ABSTRACT

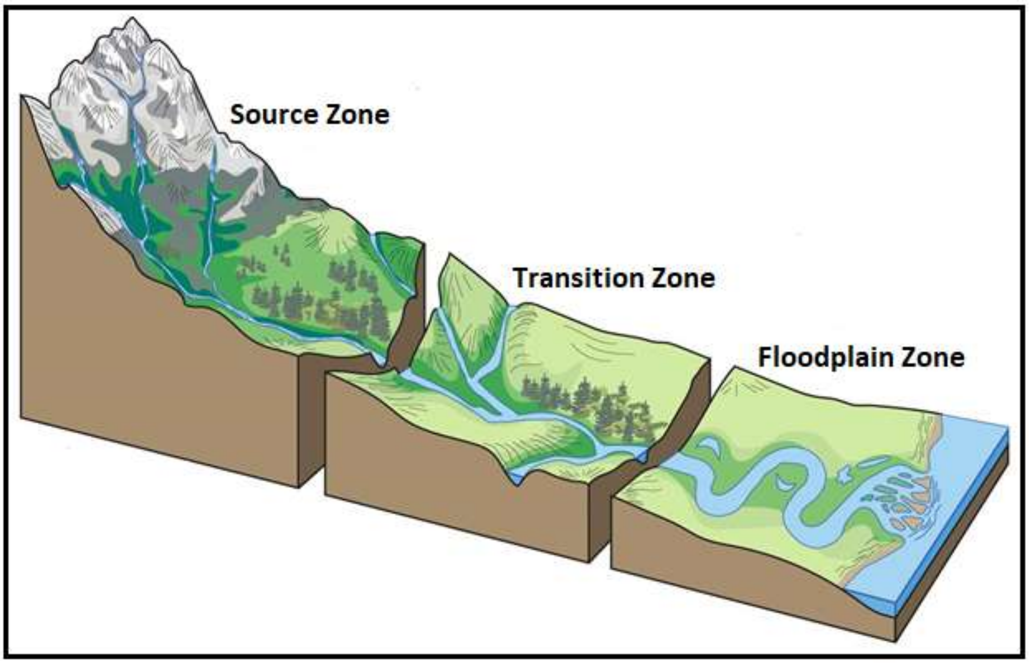
Erosion, transportation and deposition by running water are closely related and these works are performed in association and not in isolation. One cannot be performed without the other. The efficiency of these river works is determined by other factors like topography, geology, structure and composition of rocks, slope, and 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 mostly 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. Human activities in those areas are the cause of 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 containing – sand, silt and clay. It is deposited in suitable conditions along its paths. It is the result of flood plain formation. 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 the discharge and sediment characteristics of the Gandak River, (ii) analyze the relationship between discharge and transported sediment and (iii) illustrate the concentration of sediment in the flowing channel. To achieve these aims, secondary data has been analyzed. It is expected that this study will help in executing an integrated development plan for the flood affected area of the Gandak River as sediment yield in the plain is the big culprit for flooding and channel shift.

Keywords: *River Discharge, Rating Curve, Sediment Concentration, Lower Gandak Flood Plain, Aggradation and Degradation.*

INTRODUCTION

The discharge of any river is the excess amount of water left-out by evaporation, percolation, surface storage, and its retention by vegetative cover and human uses after receiving through precipitation and snowmelt. The Gandak River basin receives very heavy rainfall during monsoon season from June to September (JJAS). This period is also associated with high temperature causing addition of more water from glacial ice melt in its basin. JJAS, a period of four months contribute more than four-fifth of annual rainfall. According to GFCC (2004), 85 percent rainfall is occurring from June to October (JJASO). The rainfall distribution over the entire Gandak basin has wide departures. The average annual rainfall in Nepal mountainous territory has 203 cm while that of the lower plain in India is receiving only 110 cm. In suitable hydro-meteorological synoptic condition, the maximum rainfall in a period of 24-hours has been recorded substantially very high (GFCC 2004). Due to this, it is quite clear that the higher intensity of rainfall in shorter duration on the precipitous Himalayan slope is a big challenge for the people in the Indian plain. It is this type of high discharge of the river which brings enormous changes in the plain. A generalized schematic presentation of a river course is given in Figure 1 which clearly speaks a lot about its action by visualization.

Figure 1: An Idealized Diagrammatic Presentation of a River Course



Based on: https://www.nps.gov/subjects/geology/fluvial-landforms.htm (Last accessed on 14 October 2021)

The power of the flowing water is determined by its quantity and velocity, slope of the flow, geology of the area, porosity and permeability of rocks in river basin, vegetative cover, land use and land cover changes, water retention capacity and overall human interaction with the fragile ecosystem. Based on these factors, the velocity of water carries available sediment load to its capacity. Whenever, the sediment is greater than the carrying capacity, they are dropped down. The river loads and water discharges are responsible for making great changes in the course of the river in general and in the plain in particular. Flooding is the process through which plains are formed as well as channel paths are determined. The aggradation and degradation processes by the flowing water create numerous micro-morphology in the plain. Important among them are bars and shoals, refill and pools, channel cutoff cliff, which are causing the channels to bend or braid or creating of cutoff lakes and even channel shifting. Therefore, the discharge and associated sediments are the causes for variety of changes in the plain.

CWPRS (2012) investigates the morphology of the Gandak River in the plain with the help of remote sensing satellite data for different periods and topographical sheets published by Survey of India. The Gandak River has high suspended sediment, low slope, lower carrying capacity, frequent flooding and hyper-avulsive behavior (Sinha and Friend, 1994; Sinha, 2009). The study on the avulsion of the Kosi River has very well analyzed by Geddes (1960), Gole and Chitale (1966), Das (1968), Wells and Dorr (1987, Gohain and Prakash (1992), Prasad (2000, 2002 and 2008). This river has shifted for a cross-sectional distance of 115 km in a span of about 214 years starting from 1736 to 1950 of documented history. Though the migratory tendency is still continuing, but most of the time it is confined within the two embankments. The same tendency is also observed with respect to the Gandak River.

OBJECTIVES, DATA AND METHODS

Objectives

The main objectives of this study are to (i) study the discharge and sediment characteristics of the Gandak River, (ii) analyze the relationship between discharge and transported sediment and (iii) illustrate the concentration of sediment in the flowing water.

Data and Methods

To achieve the above mentioned objectives, data has been collected from secondary sources. Primarily sediment carried with discharge by the Gandak River has been utilized in this paper. It is collected from the office of Ganga Flood Control Commission, Patna. There are three sites – Triveni, Dumariaghat and Lalganj – of which data has been used. At these sites gauge and discharge of river were measured. Sample discharge of water was collected from river at about 9 am daily. Different grades of coarse, medium and fine sediment were assessed per liter. Based on discharge, quantity of sediment was computed on daily basis. Day-wise analyzed data was maintained in a register and now it has been stored in computer. Ten-days, monthly and annual mean sediment were computed and record of the same was maintained. When discharge was rising and flood-like situation was occurring, the frequency of water collection for analysis was increased to hourly and sometimes to half-hourly as well for better analysis.

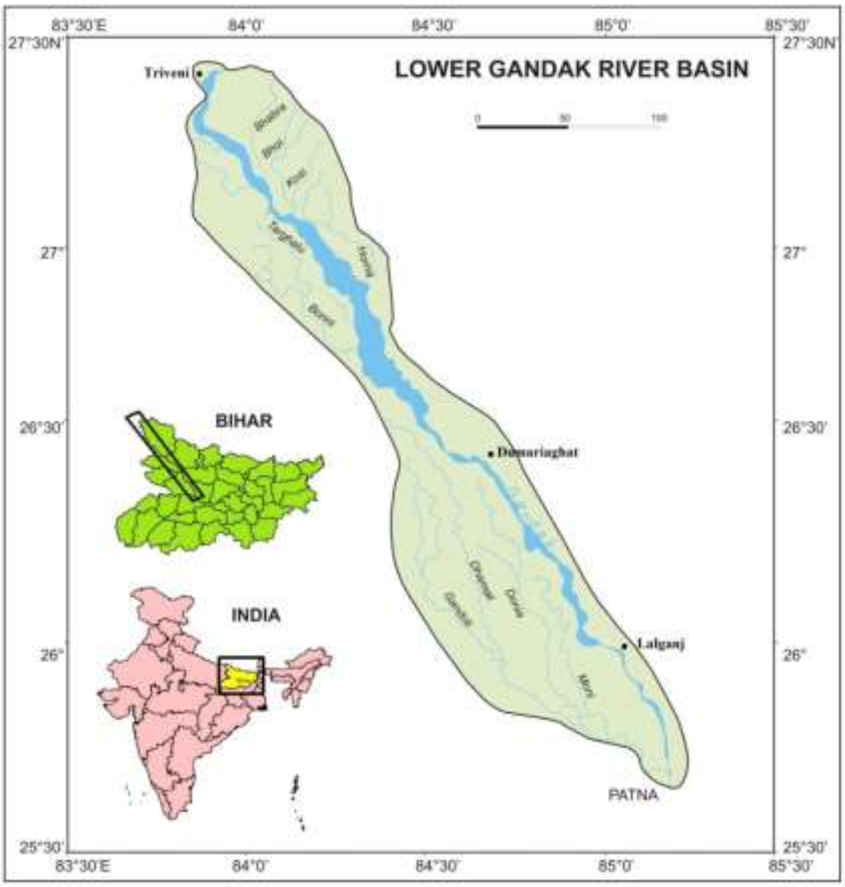
Based on above data, annual silt load quantity for 1986-1999 was collected and analyzed by graphical presentation and a comparison has been made to see the variations among them. Based on quantity of sediment found at Triveni, Dumariaghat and Lalganj, aggradation and degradation tendency of the Gandak River is ascertained by getting the difference between successive quantities of sediment.

The monthly average silt concentration per liter of discharged river water for 1986-1999 has been analyzed for all three sites mentioned above. Out of total silt concentration, percentage for coarse, medium and fine sediment has been computed and presented graphically. Month-wise total sediment concentration was shown graphically and very well corroborate the relationship discharge.

STUDY AREA

The study area is lying in the Indian territorial plain below Triveni (Nepal). It is characterized by relatively flat plain. The gradient in the upper part of the plain is more while coming down the plain, the slope keeps on reducing progressively. The surficial geology of this area is very new because of flood deposited sediments every year. In another words, it is on make every year. Several smaller tributaries originating from the foothills region are running almost parallel for shorter distances and, finally, meet the river. Many of them are local seasonal streams and carry water only during raining season. This river originates from an altitude of 7620 meter (GFCC 2004) in Tibet near its boundary with Nepal. The larger part of its catchment area is lying in Tibet and Nepal covering 38980 km^2 while in India, it is only 7620 km$^{2.}$ It makes total catchment (mountainous plus plain) area equivalent to 46300 km^2. If we compare the upper and lower catchment, it is 84.19 percent (mountainous) and 16.46 percent (plain), respectively. Over an area of about 6500 km^2 in the upper catchment, glaciers are occupying. The major tributaries of the Gandak in the mountainous region are seven in number known as “sapt-Gandaki” (ICIMOD 2017). They are “Trisuli, Budhigandaki, Daraudi, Marsyangdi, Madi, Setigandaki and Kaligandaki”. The area is considered to be formed by seven streams (NCAER 1964). The total length of the Gandak River is 640 km out of which 380 km in Tibet and Nepal and remaining 260 km is in India. The study area is shown in Figure 2. Its extension is from 25º21’23”N to 27º26’54”N latitude and 83º49’00’’E to 85º15’52”E. longitude. The study area is elongated from northwesterly to southeasterly direction.

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)

RESULTS AND DISCUSSION

The Gandak River Sediment Load

Sediments in rivers are solid and dissolved products of weathering and erosion performed by running water. Depending upon the ability of the river water, the solid particles are transported. The sediments available in the river are the product of the running water processes. They are produced by the action of water through which it runs over. They are fragmented materials originating from weathering and denudation of rocks and finally disintegrated by fluvial processes. The solid sediments are transported in various forms by bed load, saltation load, suspended load and dissolved load. Depending upon the carrying capacity of the channel, loads are on run or are deposited. The carrying capacity is affected by the amount of water, nature of bed as well as its gradient, roughness and shear stress. Change in any one of the component leads to change in the capacity of the water to erode and transport the loads/ materials. The weathering process is also a determining factor in making the load available to river or helping the river to erode the surface much easily.

Sediment Characteristics

The Gandak River brings enormous amount of water and silt (GFCC, 2004). This river basin is a part of the Ganga River system. The Ganga River brings a large amount of sediments from the upstream Himalayan region, deposit a part of this in the alluvial plains. In the same way, the Gandak River also does the same. Significant amount of sediments are deposited in their journey downward depending upon the discharge velocity and its carrying capacity. The Gandak River exhibits meandering tendency and in the process it has shifted about 4 to 5 km westward during the last 50 years of 20th century (GFCC 2004). This trend of westerly movement is still going on. It is substantiated by the attack of the channel on the western bank and embankment. Meandering and channel shift are attributed to the high charge sediment coming along the river with discharge. The causes of excess silt are mainly recognized as deforestation and, unscientific cultivation on Himalayan steep slopes. Deforestation and felling of trees for timber or firewood also have a significant role in clearing the land. Apart from these reasons, frequent landslides during monsoon, road and building construction and overall human economic activities also contribute considerably to the silt charge in the river.

The problem of silt is the biggest in managing the flood in the Indian plain. Majorly, the silt is excessively generated from the mountainous slope; their solution and management also lay at the source soils. It could be minimized by proper and judicious land management, change in cropping practices and smaller silt-trapping reservoirs construction on tributaries of the Gandak River and overall control on human activities. Since the silt generating source region is lying on the foreign soils, a better relation between two countries and cooperation towards solving the problem needs to be dealt very intrinsically.

Channel Load Particle Size

Sediment loads carried by river channels are of different types. When the river is in mountainous region, even the cobbles and gravels are transported very easily with increased discharge, but the same is not the case in the rivers while running through the lower slopes. Due to reduced velocity of the running water in the plain, the silt and clay are more prominent and found abundantly. All are depending on the slope, discharge and the nature of the river bed.

The sediment transport in a river channel is direct function of the water flow. Water flow itself is dependent upon several factors. Primarily, the channel loads are grouped into three – smaller particles, transported in suspended form; bigger sized sediment which are rolled down along the bed (bed loads) and the intermediaries in size transported through saltation. The grain size is presented in millimeter and each subsequent downward is half the size of the immediate upper one or in reverse way, it can be said that the size of each upper one in Table 1 is double the size of the immediate lower one. It is said to be a geometrical grain size with a constant ratio of 1:2 ratio. Therefore, this scale is considered to be well suited to describe the size of the sediment. The millimeter scale of Wentworth is converted to micrometer as well as in phi scale.

Table 1: Diameter of Grain Size Classification as Proposed by Wentworth

Diameter of Grain Size			Wentworth Size Class	
Millimeter	Micrometer	Phi Scale	Nomenclature	Categories
4096 to 256		-12.0 to -8.0	Boulder	Gravel
256 to 64		-8.0 to -6.0	Cobble	
64 to 4		-6.0 to 2.0	Pebble	
4 to 2		-2.0 to -1.0	Granule	
2 to 1	2000 to 1000	-1.0 to 0.0	Very coarse sand	Sand
1.0 to 0.50	1000 to 500	0.0 to 1.0	Coarse sand	
0.50 to 0.25	500 to 250	1.0 to 2.0	Medium sand	
0.25 to 0.125	250 to 125	2.0 to 3.0	Fine sand	
0.125 to 0.0625	125 to 63	3.0 to 4.0	Very fine sand	
0.0625 to 0.031	63 to 31	4.0 to 5.0	Coarse silt	Silt
0.031 to 0.0156	31 to 15.6	5.0 to 6.0	Medium silt	
0.0156 to 0.0078	15.6 to 7.8	6.0 to 7.0	Fine silt	
0.0078 to 0.0039	7.8 to 3.9	7.0 to 8.0	Very fine silt	
0.0039 to 0.00006	3.9 to 0.06	8.0 to 14.0	Clay	Mud

Source: Based on Wentworth (1922)

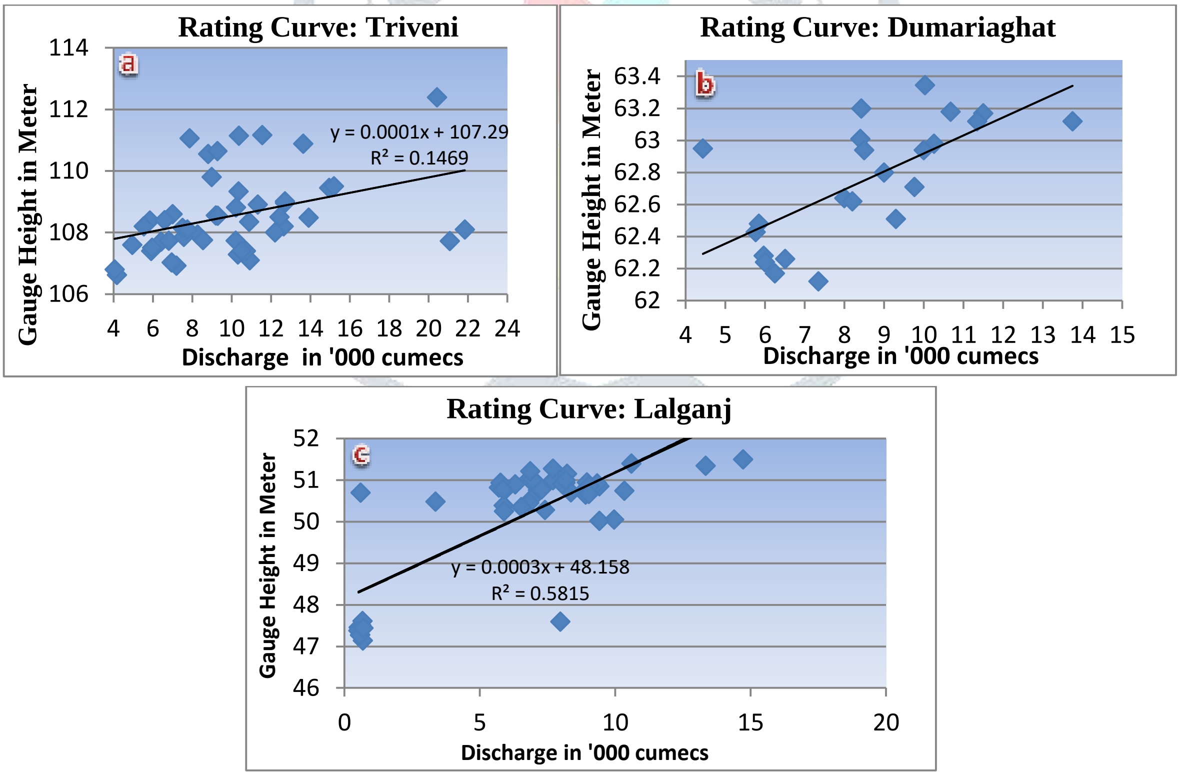
Table 1 shows the classification of particle size classified by Wentworth. According to this classification, the biggest size of boulder is greater than 256 mm in diameter, while the smallest sized-sediment – clay has a diameter of about 0.00006 mm. The sediments transported by river channel in the plain are grouped into three classes – coarse, medium and fine.

The sediments found in the Gandak River are classified into coarse, medium and fine representing sand, silt and clay. From Table 1, it is obvious that the sand is further divided into five categories based on its size. The sand varies from 2.00 mm (the largest) to 0.0625 mm (the smallest) diameter. In the same way, silt is divided into four groups varying from 0.0625 mm (the largest) to 0.0039 mm (the smallest) diameter. The clay is the smallest particles found in the flowing water of the channel and its diameter is less than 0.0039 mm. All these are carried by river discharge in association other factors. With increase in the water level (stage of river), amount of water in the river increases. Hence, the relationship between water level and discharge is analysed by rating curve below.

Rating Curve of the Gandak River

Rating curve of a river/channel is presentation of the relationship between stage (water datum level) and corresponding discharge of the flowing water. Generally, every stream channel is unique and different in its own. Stage-discharge relation is the outcome of the stream cross bed-profile materials, shape-size-geometry and bed roughness of the channel. Rating curve of two sites of the same stream may be different if the parameters are changing. Therefore, rating curve is unique to a particular site for a particular stage of water flow. It is generally developed after rigorous accurate data collection of stage and discharge and then a relationship is established between them. The rating curve for three sites Triveni, Dumariaghat and Lalganj are plotted for peak discharges collected for 1956 to 2002 (GFCC, 2004) and presented in Figure 3

Figure 3: Rating Curve of the Gandak River at Triveni, Dumariaghat and Lalganj

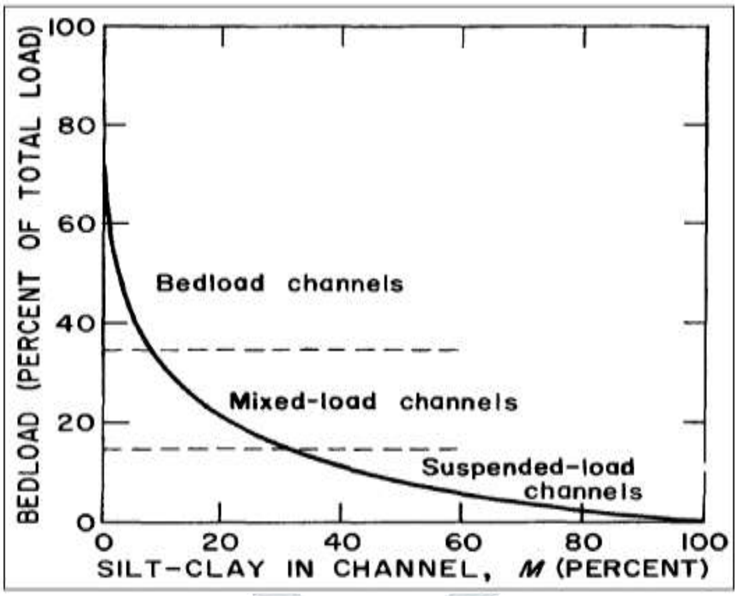


Peak discharge is a single highest figure taken from a calendar year for a particular site. Sometimes, it is observed that many discharge figures are bigger in other years than the value taken as the highest for some particular years. But it is constrained by definition of the peak as it has to be taken only one highest discharge from a calendar year and not the other higher figures from other years. In order of their location along the Gandak, Triveni is in the uppermost part, while, Lalganj is the lowermost part, before meeting with the Ganga. Dumariaghat falls in between. At Triveni, the rating curve is almost straight with higher stage. Observed stage is less than 107 meter (above mean sea level (amsl)) to more than 112 meter amsl – a difference of about 6 meter. Almost similar shape of rating curve is observed at Dumariaght but very less change in stage. It is about 62.1 meter amsl to 63.4 meter amsl – a difference of only 1.3 meter. At Dumariaghat, river is very wide with braiding pattern of channels with longer cross section, where the water level is not reaching higher. At Lalganj, river bank is narrower, water is more, water level (stage) becomes higher and the rating curve becomes curvi-linear. It means, at lower stage, the flow of water is lower, but increase in stage lead to greater increase in discharge.

Relationship between Bed Load with Mixed and Suspended Load

The transport of sediment in the river channel is dependent upon the channel energy and the size of the sediment. It is quite natural that the bigger sized sediments could be transported when the channel energy is very high. The channel energy is again determined by the slope of the bed, roughness and resistance of the channel, volume of water and the available sediment characteristics. It is obvious that the fine-grained sediments could easily be transported by the channel, even if, the discharge is less or slope is less, but the same is not so in case of relatively bigger sized sediments. Schumn (1963) has done a good study to establish the relation between the bedload and the silt-clay size in the channel (Figure 4). He has also tried to work out the classification of alluvial channel and the associated sediment and has presented very good schematic tabular information about the type of channel stability and accompanied characteristics of sediment (Table 2).

Figure 4: Relationship between Bedload With Mixed and Suspended Load



Source: Schumn (1963)

From Figure 4 it is clear that the bedload is very low as it needs higher energy to transport and it is confined to less than 15 percent (Table 2). With reduction in the size of the sediment, lesser energy is needed to remove/transport. Therefore, the quantum of sediment under smaller size is increased. In other words, it can be stated that the size of the sediment and the quantity to be transported has negative correlation. It means, the increase in the sediment size causes the quantity of the transported sediment to reduce, "if other given conditions remain constant". But when the size of the sediment is reduced, there is increase in transported quantity with the same statement, "if other given conditions remain constant".

Table 2: Classification of Alluvial Channels

Mode of sediment transport	Channel sediment in %	Proportion of total sediment load		Channel stability		
		Suspended load %	Bedload %	Stable (graded stream)	Depositing (excess load)	Eroding (deficiency of load)

Suspended load	30-100	85-100	0-15	Stable suspended load channel, width-depth ratio less than 7; sinuosity greater than 2.1; gradient relatively gentle.	Depositing suspended load channel, major deposition on banks cause narrowing of channel; streambed deposition minor.	Eroding suspended-load channel, streambed erosion predominant; channel widening minor.
Mixed load	8-30	65-85	15-35	Stable mixed-load channel, width-depth ratio between 7-25; sinuosity between 2.1-1.5; gradient moderate.	Depositing mixed-load channel, initial major deposition on banks followed by streambed deposition.	Eroding mixed-load channel, initial streambed erosion followed by channel widening.
Bedload	0-8	30-65	35-70	Stable bedload channel, width-depth ratio greater than 25; sinuosity less than 1.5; gradient relatively steep.	Depositing bedload channel, stream bed deposition and island formation.	Eroding bedload channel, little streambed erosion; channel widening predominant.

Source: After Schumn (1963)

Silt Observations

There are three sites for monitoring the silt carried by the Gandak River. They are Triveni, Dumariaghat and Lalganj. These sites are commissioned by the Central Water Commission and data is collected and analysed. The feedback is given to the Gandak Project officials as well as to the Central Water and Power Research Station (CWPRS) for further study under simulation condition at Khadakwasla near Pune. The overall monitoring is of Ganga Flood Control Commission (GFCC). The river silt analysis is based on the data available for three above mentioned sites as well as datum level survey data are utilized here. The silt load data collected from the GFCC for three sites, namely, Triveni, Dumariaghat and Lalganj is presented in Table 3. The figures given here are in thousand tonnes indicating the quantity of sediment carried by the running water of the Gandak River on an annual basis for the given period from 1986 to 1999. Based on the total sediment of three sites, the percentage is calculated for each year for each of these three sites.

Table 3: Silt Load and their Concentration at Selected Sites along the Gandak River

Years	Triveni	Dumaria ghat	Lalganj	Total of All Sites	Triveni	Dumaria ghat	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				

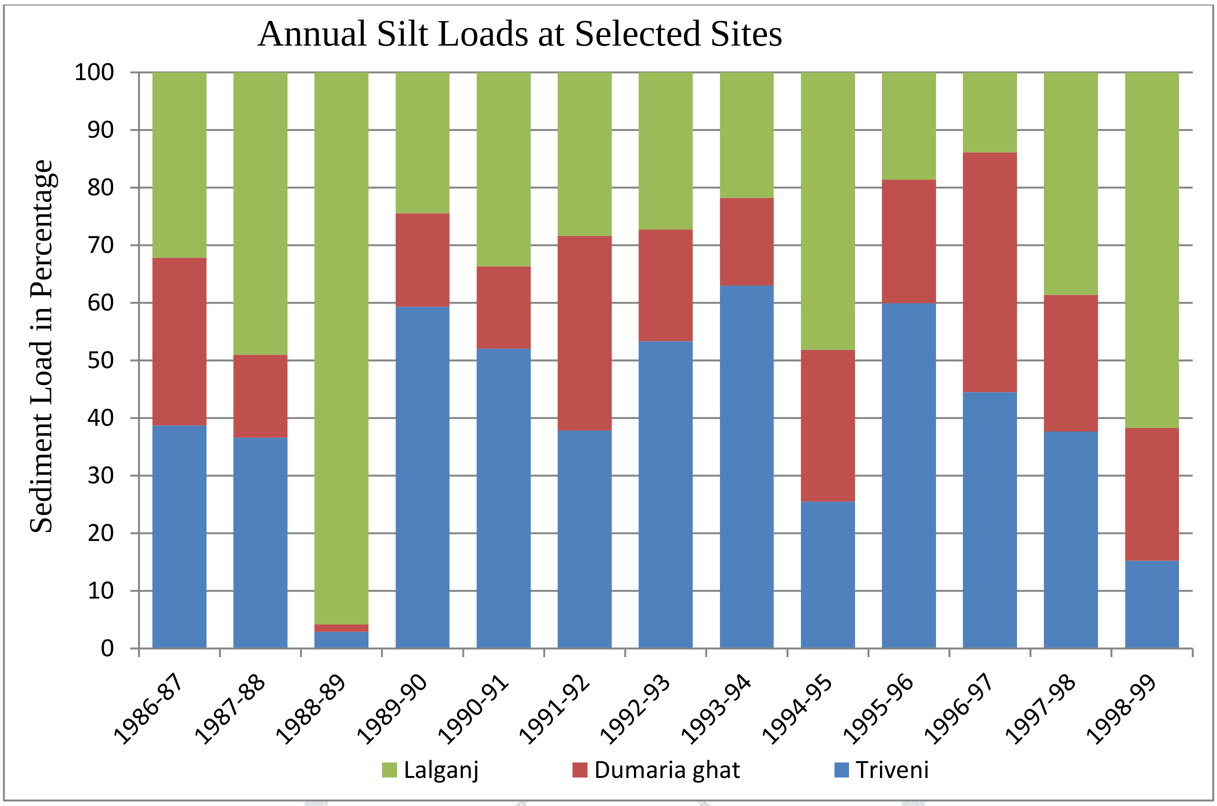
Note: Figures for 1988-89 are bold and underlined: unbelievably high at Lalganj.
Source: Based on Ganga Flood Control Commission (GFCC), Patna, 2004

Before making any observation about sediment analysis, it is obvious to study the collected data. With ought most care, the figures were collected and compared. It was found that the concentration of sediment and with respect to 1988-89 is unbelievably high. Out of 13 years of total sediment for three sites shown in this Table is 6,546,046 thousand tonnes, while the total of three sites in the year 1988-89, it is 4,560,061 thousand tonnes. If the percentage is calculated for just one year of 1988-89 with respect to the total of 13 years, it gives a figure of 69.66 percent. It means, one year of sediment is equal to (66.44 percent) almost two-third of the 13 years under study. This point was raised with the officials of the GFCC, but no convincible and satisfactory answer was received. The authors have no authority to challenge the data, but to interpret the same with logical thinking under the preview of the scientific understanding.

When overall percentage of sediment, for three sites over 13 years, is calculated, it comes to 15.75 percent, 7.40 percent and 76.85 percent for Triveni, Dumariaghat and Lalganj respectively. When the same is done by ignoring 1988-89, it comes to 45.24 percent, 21.41 percent and 33.34 percent for the same sites. It is well known fact that the sediment yield in the running water is determined by numerous factors and the discharge is the main cause which varies over time and water availability. For a given river, other factors are almost stationary over a period of time as drastic changes are not possible among them. Therefore, the sediment yield would increase or decrease depending upon the observed discharges. When more than one observation sites are there along the same river, the changes in the sediment yield is supposed to get reflected almost in the same manner at those sites. Both sites – Triveni and Dumariaghat are upstresm to Lalganj. Both upstream sites are showing normal sediment characteristics similar to other years even during 1988-89. Extremely excessive sediment at Lalganj denotes that extremely high discharge got generated downstream to Dumariaghat.

The distance between Dumariaghat and Lalganj is about 85 km. In such a small distance with a very small area over which, if at all, heavy downpour occurs, it might not generate that much of huge water for carrying that much amount of sediment. It also falls in a dead flat plain where given quantum of sediment generation seems next to impossible. The rainfall data was tried to correlate, if it happened so in 1988-89. The rainfall data in the surrounding rain-gauge sites did not corroborate to justify the tabulated sediment data. That is why; it was decided to go away with this year of analysis. Now, it is vivid that one year of erroneous data creates huge discrepancy. Just to make it more clear and vibrant, the same is illustrated by Figures 5. Table 3 shows that data recorded at Triveni and Dumariaghat in 1988-89 is similar to other years. Since the data is already tabulated, it is very easy to compute the percentage of the same which are shown in the last four columns of the table.

Figure 5: Annual Silt Load at Triveni, Dumariaghat and Lalganj: 1986-99



Except two years (1998-99 and 1994-95), the concentration of sediment at Triveni is always more than one-third of the total of the years under study. It is as high as 62.99 percent, 59.94 percent and 59.23 percent during 1993-94, 1995-96 and 1989-90, respectively. With respect to Dumariaghat, five years have a concentration of less than 20 percent, while only one year records more than 40 percent (41.64 percent during 1996-97). The lowest is about 14 percent in two years (14.32 percent in 1990-91 and 14.41 percent in 1987-88). At Lalganj the lowest is 13.86 percent during 1996-97, while the highest is 61.69 percent in 1998-99. It is the only year when it is more than 50 percent of 12 years under study. The overall average concentration of silt load for above mentioned 12 years is 45.23 percent, 21.41 percent and 33.34 percent for Triveni, Dumariaghat and Lalganj, respectively.

Aggradation and Degradation

The aggradational and degradational behaviour of the Gandak is conducted based on Table 3. It is also very important to mention here that the amount of sediment between two sites is continuously getting deposited and generated depending on the space and time in association of the discharge and velocity. Therefore, the aggradation and degradation tendency of the river is site based and not on space based. It is the simple subtraction of the values of silt load recorded at Triveni and Dumariaghat to ascertain the erosional and depositional tendency. Positive values after subtraction of silt load of Dumariaghat from Triveni indicate deposition while the negative one represents the load being transported further downwards. The same could be applied for Dumariaghat to Lalganj as well. It is clearly presented in Table 4.

Table 4: Aggradation/ Degradation Tendency of the Gandak in Selected Reaches
(Figures are in thousand tonnes)

Year	Triveni to Dumariaghat	Aggradation/ Degradation	Dumariaghat to Lalganj	Aggradation/ Degradation
1986-87	21794	Aggrading	-6840	Degrading
1987-88	81311	Aggrading	-126676	Degrading
1988-89	***73174***	***Aggrading***	***-4309529***	***Degrading***
1989-90	97912	Aggrading	-18616	Degrading
1990-91	61915	Aggrading	-31687	Degrading
1991-92	5667	Aggrading	7480	Aggrading

1992-93	32533	Aggrading	-7522	Degrading
1993-94	97794	Aggrading	-13398	Degrading
1994-95	-969	Degrading	-27511	Degrading
1995-96	72887	Aggrading	5462	Aggrading
1996-97	2813	Aggrading	27328	Aggrading
1997-98	7220	Aggrading	-7698	Degrading
1998-99	-7615	Degrading	-37229	Degrading

Monthly Average Silt Load

In monsoonal region, rainfall is distributed in a rhythmic manner with a large concentration during four months of rainy season. As discussed above, silt concentration is directly proportional to the available water flowing from a river. It is directly and positively related to discharge in the river. The silt load is progressively increasing with increasing discharge. Very low discharge is observed during February and March every year. After March, the increased discharge is associated with snow melt from glaciers in the higher altitudinal zone of the Himalayas. Later on, water in the river increases due to monsoonal rain and snow melt together. The concentration of silt load is also in congruence with the rainfall behaviour in the catchment area of the river. The following paragraphs deal with the monthly average silt load of the Gandak River at three sites – Triveni, Dumariaghat and Lalganj.

Monthly Average Silt Load at Triveni

There is a direct relationship between discharge and sediment yield. The lean season has less concentration of sediment as shown in second column of Table 5 for the site – Triveni. It is less than a gram of sediment per liter of flowing water in January (0.091 gram) and February (0.069 gram), while it increases to more than two grams of sediment per liter of flowing water in July (2.428 gram) and August (2.102 gram). In fact, it shows the relationship between rainfall-snow melt and increased water with the sediment yield.

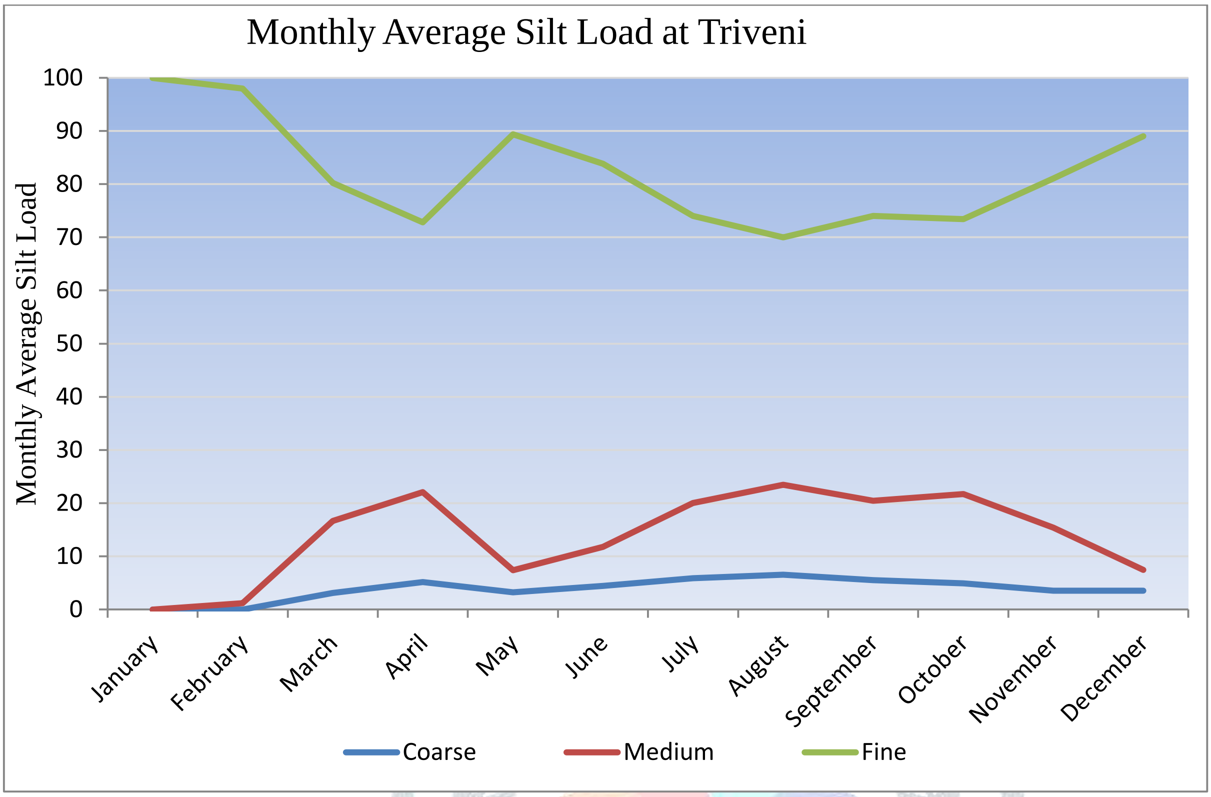
Table 5: Monthly Average Silt Data for Gandak River at Triveni

Month	Average of total sediment load (gm/liter)	Graded percentage of sediment to total		
		Coarse (%)	Medium (%)	Fine (%)
January	0.091	0.00	0.00	100.00
February	0.069	0.00	1.20	98.00
March	0.136	3.10	16.65	80.25
April	0.142	5.15	22.05	72.80
May	0.266	3.25	7.35	89.40
June	0.862	4.40	11.75	83.85
July	2.428	5.90	20.05	74.05
August	2.102	6.55	23.45	70.00
September	1.898	5.50	20.45	74.05
October	0.760	4.90	21.70	73.40
November	0.366	3.50	15.40	81.10
December	0.154	3.50	7.45	89.05

Source: GFCC (2004), Central Water Commission Division, Patna

The last three columns show the percentage of coarse, medium and fine sediment to the total amount of sediment found in the flowing water. The percentage of coarse sediment is very low, medium has moderate percentage, while the fine sediment is very high. It is quite clear that there has to be greater carrying capacity to carry bigger-sized sediment. That is why, the concentration of large-sized sediment is less and it happens with all the rivers of the world especially in less sloping areas like plain. It can be seen from Figure 6 for the site – Triveni prepared on the basis of data as summarized in Table 5. It is apparent that the proportion of coarse sediment in relation to medium and fine is less and in their comparison; its line is close to the base of the graph. Very high concentration of fine sediment is visible. Monthly average concentration of fine sediment is very high starting from more than 70 percent to 100 percent. Medium sediment is less than 25 percent and that of coarse is less than 7 percent at Triveni in different months of the year.

Figure 6: Month-wise Average Percentage of Sediment Types at Triveni



Monthly Average Silt Load at Dumariaghat

Dumariaghat is located in plain between Triveni (in the foothills) and Lalganj (in the south, upstream to the confluence with the Ganga). The river has a bit higher level of sediment concentration in comparison to Triveni especially in the lean season. In this stretch, the amount of water in the river is relatively greater and probably it holds more sediment. The minimum sediment is observed in the month of February (0.254 gram per liter of water) and March (0.236 gram per liter). After that, it keeps on increasing and the maximum is observed during August (1.812 gram per liter) and September (1.861 gram per liter). The declining trend is seen from October, the end of the monsoon rain (Table 6).

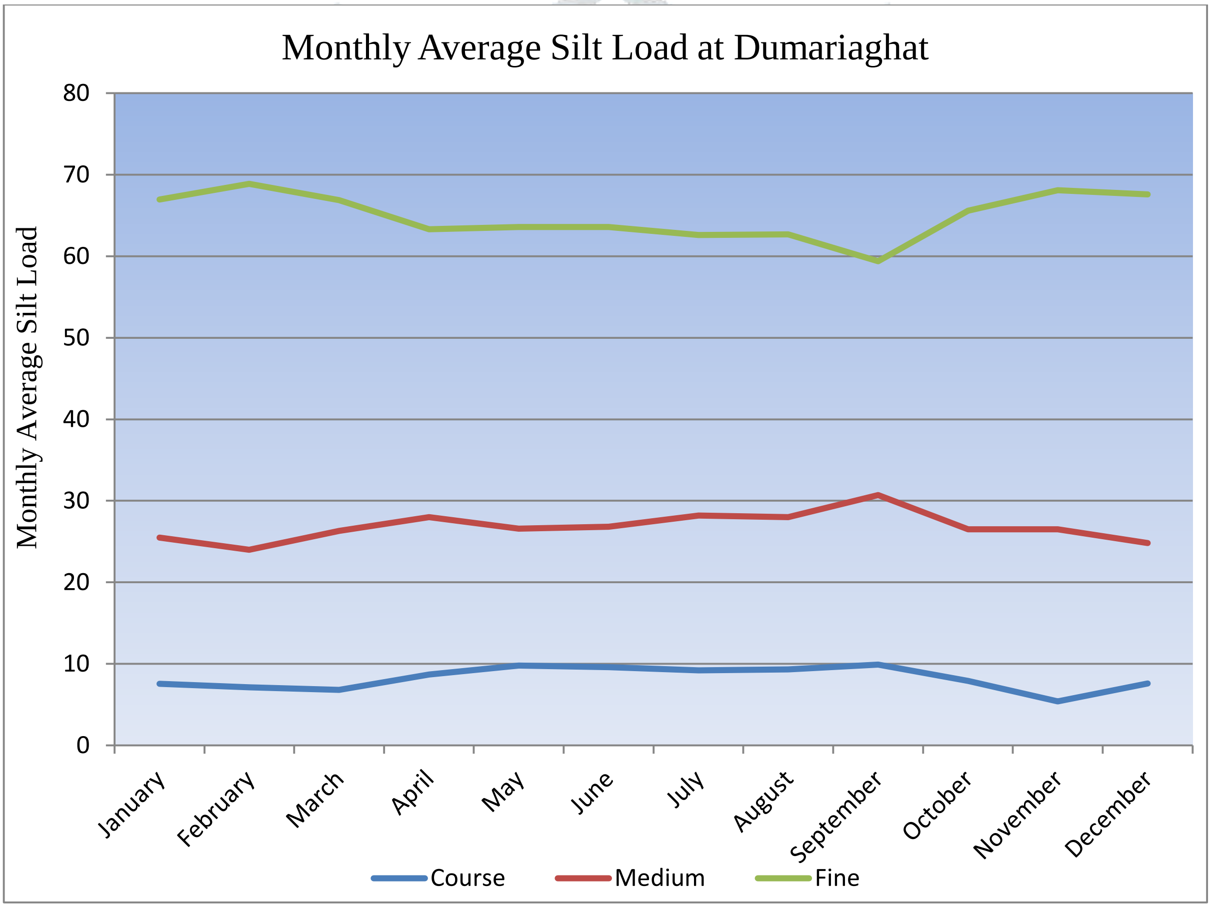
Table 6: Monthly Average Silt Data for Gandak River at Dumariaghat

Month	Average of total sediment load (gm/liter)	Graded percentage of sediment to total		
		Course (%)	Medium (%)	Fine (%)
January	0.360	7.55	25.50	66.95
February	0.254	7.10	24.00	68.90
March	0.236	6.80	26.30	66.90
April	0.321	8.70	28.00	63.30
May	0.357	9.80	26.60	63.60
June	0.741	9.60	26.80	63.60
July	1.764	9.20	28.20	62.60
August	1.812	9.30	28.00	62.70
September	1.861	9.90	30.70	59.40
October	1.084	7.90	26.50	65.60
November	0.608	5.40	26.50	68.10
December	0.475	7.60	24.80	67.60

Source: GFCC (2004), Central Water Commission Division, Patna

Month-wise average sediment is classified into three – coarse, medium and fine of which the percentage share is given in the last three columns. The range of coarse sediment is less than 10 percent in all months while for medium sediment, it is between 24.00 percent (February) to 30.70 percent (September). The fine sediment has same tendency, what it is observed with medium sediment. It varies from 68.90 percent (February) to 59.40 percent (September). The difference is in terms of their contribution in the share. Since February is the month when discharge is minimum, relatively fine sediment is more while the September is the month when the discharge is more, the concentration of medium sediment has increased. Here, one point must be made clear that the total sediment is the addition of these three types and then the percentage is calculated. The quantum of the sediment is not less in September, but percentage is lessened by increased contribution of medium sediment. A visual presentation is given in Figure 7. From this Figure, it is evident that different types of sediments by their sizes show uniform distribution over the months.

Figure 7: Month-wise Average Percentage of Sediment Types at Dumariaghat



Monthly Average Silt Load at Lalganj

Out of the three selected sites for month-wise sediment analysis, Lalganj lies to the most downstream. Here, the slope is the lowest among the three but has more quantity of water in the river. The availability of fine sediment is more, therefore, the huge amount of fine-grained is carried by the running water. The concentration of sediment varies from 0.3193 gram/liter of flowing water in March to 2.2681 gram/liter in August. The coarse sediment varies from 5.23 percent to 8.32 percent, while the same is 13.49 percent to 19.46 percent for medium sediment, whereas for fine sediment it is 71.58 percent to 79.62 percent (Table 7).

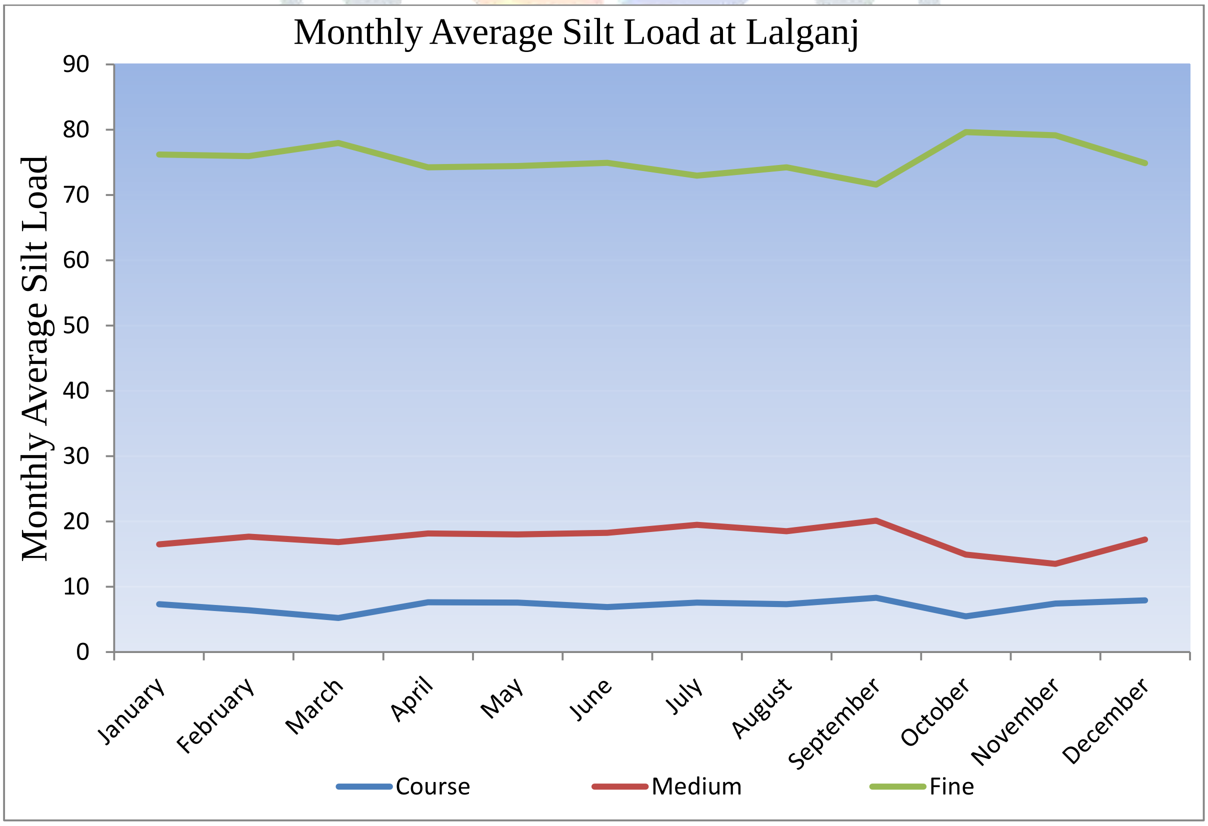
Table 7: Monthly Average Silt Data for Gandak River at Lalganj

Month	Average of total sediment load (gm/liter)	Graded percentage of sediment to total		
		Course (%)	Medium (%)	Fine (%)
January	0.5140	7.32	16.50	76.18
February	0.3546	6.37	17.68	75.95
March	0.3193	5.23	16.82	77.95
April	0.4449	7.60	18.16	74.24
May	0.4836	7.57	18.01	74.42
June	0.9272	6.88	18.23	74.89
July	2.1444	7.58	19.46	72.96
August	2.2681	7.30	18.50	74.20
September	1.9867	8.32	20.10	71.58
October	1.6335	5.47	14.91	79.62
November	1.0965	7.40	13.49	79.11
December	0.7100	7.93	17.21	74.86

Source: GFCC (2004), Central Water Commission Division, Patna

Though the concentration of sediment in the river water is associated with several factors like slope, discharge, nature of available loads etc. the overall uniform distribution of percentage is observed throughout the period. Increase or decrease in the type of sediment is alike in all the three types and, hence, showing the uniformity in the sediment. The percentages of sediment over the months have also very less departure which is obvious from Figure 8.

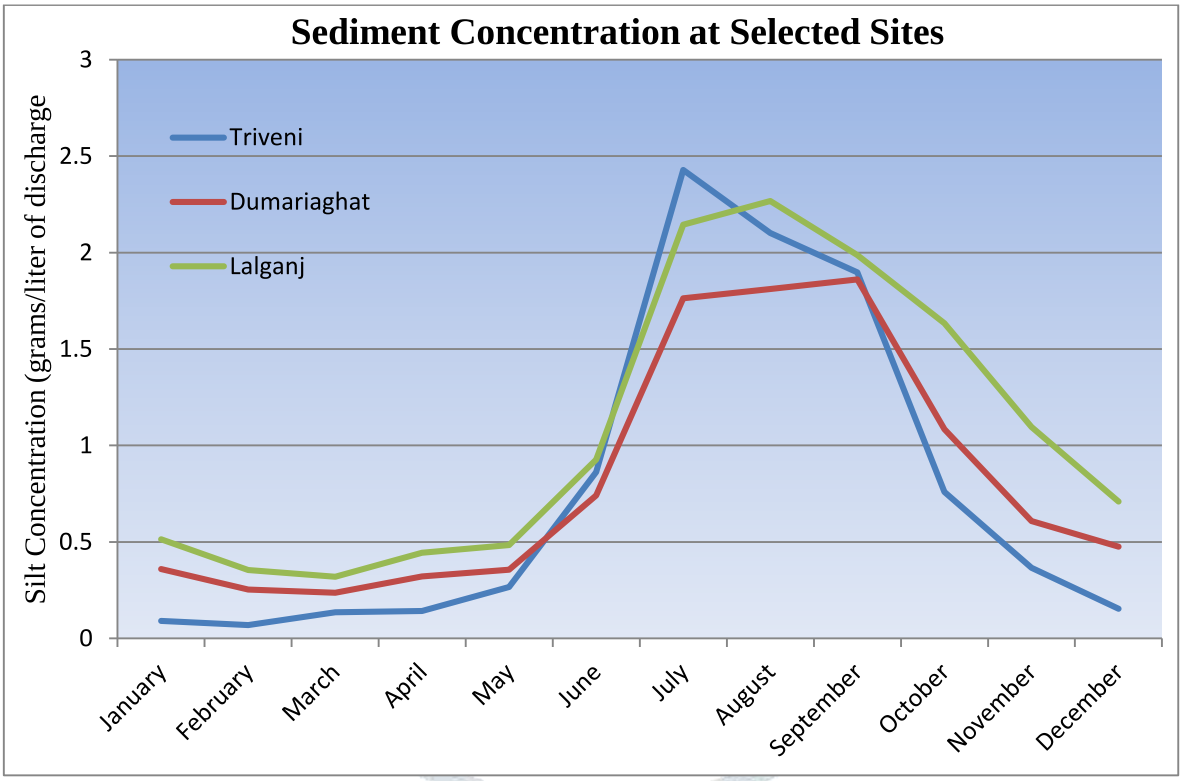
Figure 8: Month-wise Average Percentage of Sediment Types at Lalganj



Silt Load Concentration

The silt concentration is the amount of silt primarily in suspended form. The sample of the water taken from the flowing water is not from the bed of the river but from a certain depth from the water level of the channel. Hence, the sampled sediment study is based on this type of data derived every day at a certain time and the data is analyzed. When the river is at spate, the samples are taken very frequently and the sediment carried by the channel is recorded. On the basis of this type of data, daily, weekly, fortnightly and monthly data is computed. The same computed monthly data has already been discussed before through Tables 5, 6 and 7. These tables are also referring the silt concentration on monthly basis. It is shown in grams per liter of water discharge in the channel under second column. This is also computed on the basis of monthly average. For three sites – Triveni, Dumariaghat and Lalganj; the silt concentration data is plotted on the same base and has been presented in Figure 9.

Figure 9: Month-wise Average Silt Load Concentration at Triveni, Dumariaghat and Lalganj



From this figure, it is very clear that suspended silt concentration is always higher at Lalganj (lower site among the three) in comparison to Dumariaghat (middle). At Lalganj, the water is relatively more, the flow of water is sluggish as the River Ganga has still more water. Therefore, greater amount of suspended sediment is observed. The intermediate site has relatively less concentration. With respect to Triveni (uppermost site), sediment concentration is more between June to September. It is this period when the river discharges more water due to monsoon season. The slope at Triveni is greater in comparison to other two sights. Flowing water at Triveni has huge amount of suspended sediment also because of eddies effects.

Conclusions

This article investigated sediment load concentration in the Lower Gandak flood Plain for the period 1986-1999. Our results demonstrated that the Ganga Plain in general the Gandak Plain in particular is very unstable because of alluvium bed materials. Silt concentrated discharge during summer season is one of the important reasons for channel braiding and its migration. Though, the river has been embanked from both sides, channel shift is seen within the embankments and it is breached by high discharge and lateral erosion during monsoon period. Flooding is a regular feature when water discharge is high. The root cause of flooding in the Gandak Plain is excess water with concentrated silt. Excessive yield of sediment is primarily due to geological characteristics of the Himalayan catchment. Another interesting aspect of study is precipitous slopes, more discharge, poorly managed slopes, unscientific cultivation on the slope and deforestation are some of the burning issues for managing flood in the Gandak Plain. In addition, analysis revealed that all rivers descending from the Himalayas are characterized by flood creating, sediment bearing, plain forming processes but its power is decided by the intensity of rainfall and the size of catchment area. Other factors are slope, geology, land use and human interference with nature.

The results show that it has contributed to the field of fluvial river dynamics particularly with respect to discharge and its associated sediment load. Also, they help in understanding seasonal variation in discharge which demonstrates sediment yield and it shows a rhythmic pattern. The analysis of sediment carried by water at different sites helps in revealing aggradation and degradation tendencies of the river.

It is also important to note that authors faced difficulties in getting sufficient data as discharge of the Gandak river system is under restricted category. The silt load for Lalganj for the year 1988-89 was found to be very high and its explanation was not given satisfactorily even by Gandak Project Authority as well as GFCC. It seems an error, but it has to be error free data for better analysis. Sediment concentration needs to be reduced for overcoming the problems in the plain. For this, integrated research particularly in the field of human activities and land-use practices on the mountain slope are most important. The awareness among the people on the slope is the prime concern of the two governments Indian and Nepalese. Proper cooperation and coordination in the field of land and water management in general and river basin in particular could go a long way towards solving the problems of land and people in the plain.

Further research needs to be carried on in studying river behavior by taking the help of modern technologies of remote and GIS as substantive spatial and chronological data is available for repeated periods. On this basis, monitoring of changes even in shorter duration of a few weeks or months is also possible. This would help to study changing scouring-filling-migrating tendencies or planform variation by identifying different features through its spatio-temporal analysis. Certain collected – available data need to be corroborated with satellite data for which appropriate information has to be there for better analysis. Therefore, suitable data pertaining to detailed discharge, sediment, gauge level of water flow at different sites has to be collected for which data collecting agencies must work in association and coordination for availability of the same. Many times, available data is also not easy to get. Hence, data inventory and their availability are of prime concern for appropriate study and analysis.

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REFERENCES

CWPRS (2012). Morphological studies of River Gandak using satellite and SOI Data, Central Water and Power Research Station (CWPRS), Khadakwasla, Pune

Das, K.N. (1968). Westward shift in the courses of the Kosi, *The Geographical Journal of India*, 1: 23-31.

Geddes, A. (1960). The alluvial morphology of the Indo-Gangetic Plain: Its mapping and geographical significance, *Transactions, Institute of British Geographers*, 28: 253-277.

GFCC (2004). Updated comprehensive plan of flood management of Gandak River System, Ganga Flood Control Commission (GFCC): Patna, Ministry of Water Resources, Government of India

Gole, C.V. and S.V. Chitale (1966). Inland delta building activity of Kosi River, *Journal of Hydraulic*

Division, Proceedings of the American Society of Civil Engineers, 93:111-126.

ICIMOD (2017). The Gandaki basin: maintaining livelihood in the face of landslides, floods and drought, Himalayan Adaptation, Water and Resilience Research, Working Paper 9, Kathmandu http://lib.icimod.org/record/32707/files/hiaware529_WP_9_Gandaki%20Basin.pdf (Last accessed on 09 October 2021)

NCAER (1964). Traffic survey of Gandak River, National Council of Applied Economic Research, New Delhi, January, pp. 5-11

Prasad, R. (2000). Progression of the Kosi Channels, *Annals of the National Association of Geographers, India,* 20(2): 47-65.

Prasad, R. (2002). Recent changes in the bed level of Kosi in the plain, in S.K. Tandon and B. Thakur (eds.) Recent Advances in Geomorphology, Quaternary Geology and Environmental Geosciences: Indian Case Studies, Manisha Publications: New Delhi pp. 157-180.

Prasad, R. (2008). Land degradation due to channel shift: A case study of the Kosi Embankment Area, in B. Thakur (ed.) Perspective in Resource Management in Developing Countries, 3: 178-196. Concept Publishing Company: New Delhi

Schumn, S.A. (1963). A tentative classification of alluvial river channels, Geological Survey Circular 477, United States Department of Interior, Washington.

Sinha, R. (2009). The great avulsion of Kosi on 18 August 2008. *Current Science* 97: 429-433

Sinha, R. and P.F. Friend (1994). River systems and their sediment flux, Indio-Gangetic Plains, Northern Bihar, *Sedimentology*, 41: 825-845.

SLUSI (1988). All India Soil and Land Use Survey of India Atlas, Ministry of Agriculture: New Delhi.

Wells, N.A. and J.A. Dorr (1987). Shifting of the Kosi River, North India, *Geology*, 15: 2040- 207.

Wentworth, K.C. (1922). Grain size classification: https://www.planetary.org/space-images/wentworth-1922-grain-size