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Changes in gradient and bed profile in geomorphological study: A case of the Kosi River in plain

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Abstract
Gradient of a river is developed by a continuous process of degradation and aggradation through dynamic action of discharge over a landmass in fluvial dominant areas. Initially when a landmass emerges due to internal forces or on the landmass already existing in areas when there is rainfall, fluvial processes are operational. The earth surface is sculptured by external process found in the area. Finally, it is the product of the balance between internal and external forces operating. In this study, fluvial process is referred with respect to the changing gradient of the Kosi River and its bed profile. The characteristics of precipitation over an area determine discharge of a river. Discharge is also impacted by several factors like slope, structure and composition of rocks, vegetative cove, porosity and permeability of the soils, available human footprints, land use and land cove change caused by human beings etc. All of them are affecting discharge and sediment yield, which ultimately makes changes over an area through which it is running. The chosen area is the Kosi River in the plain and it is characterized by enormous discharge due to torrential rainfall in association with snowmelt during summer days. It is one of the largest tributaries of the Ganga River system. It is notorious for bringing flood frequently in its plain and termed as "Sorrow of Bihar". Due to huge sedimentation from its foothills, the plain is said to be an "Inland Delta" and also called as "Kosi Megafan". The changing gradient and bed profile is an important topic of geomorphological enquiry. Therefore, an attempt has been made in this paper to (i) study the changes in gradient of the Kosi River, (ii) investigate the changing bed level, particularly, after construction of embankment in 1958, and (iii) find long term solution of channel stability and flood management.

Keywords: Kosi River, Channels, Bed and Bar, Gradient, Deposition, Channel bed Morphology

1. Introduction

The course of a river, in general, decreases in bed slope downward direction forming a concave appearance. The loads of river are very distinguishing, i.e., bigger sized-loads are found where slope is high and progressively smaller sized are found towards downstream (Ferguson *et al*., 1998 and Morris Williams, 1999a and 1999b) [7, 17, 18]. It happens because of the greater channel energy in the mountainous region supported by higher slope. Hence, it is quite obvious and it happens with all rivers of the world. The direction of the flow of the river is not alike along its entire course. With change in different parameters of discharge and slope, characteristics of bed of the rivers also changes. Once, in initial journey, river is single thread (single flowing water path). When the same river reaches in the plain, it changes from straight single tread to tortuous and meandering pattern. When sediment amount is higher in discharge, braided pattern is observed. All these things are applicable to the Kosi River.

Harmar and Clifford (2006) [12] believe that longitudinal profile of rivers in geomorphological study is relatively neglected area in contemporary analysis. Probably, it may be due to perplexing, complex and intrinsic relationships of geomorphological parameters. Traditionally, concave longitudinal profile of rivers has been explained through the concept of 'grade', where gradient is supposed to decline in the downstream direction as a function of discharge, nature of bed load as well as channel morphological characteristics (Mackin, 1948) [16]. River's gradient declines downstream, amount of water increase is observed by addition of tributaries but size of sediments also reduced to make the transport going on with progressively declining slope, is termed as 'grade' (Gilbert, 1877) [10] of river and maintaining of its equilibrium. This concept of 'grade' is hardly seen with a natural river in real field.

Because, longitudinal profile or bed level of river is a function of a variety of factors working in associations over time and space. These factors are direct components of fluvial system. Hence, change in slope, velocity, carrying capacity of flowing water, sediment load size; erosive power, transportation and deposition altogether determine the valley slope. Therefore, they are found in response to these factors (Schumm and Lichty, 1965) [26]

Generally, rivers are single thread appearance in mountainous journey but when the same river reaches into plains, its plan-view is changed due to change in slope and bed materials. The change can very clearly be explained by direction and ways of flow. By direction, it is meant about horizontal/lateral tortuous flow and ways signifies discharging paths. Hence, primarily, rivers can be grouped into two – meandering and braided (Mackin, 1948 and Schumm, 1977) [16, 26] in the plain. Channels of braided rivers are more or less similar in terms of their processes and operations of their functions (Ferguson, 1993 and Bridge, 1993) [6, 1]. Braided channels need to be studied to know the parameters of hydraulic geometry. Therefore, a comparison of morphological characteristics of braided and meandering channels helps us to understand differences between them. Gaurav *et al*. (2015) [8] have compared channels of braided and meandering river of similar river system with similar geoclimatic conditions and bed materials. They are from the Kosi River megafan. They found that in spite of comparability between two types of channels there is wide variations and dissimilarity. They could be explained by difference in discharge and sediment flux, bank stability by vegetative growth etc.

At different courses of river, river used to adjust itself due to change in different parameters of channel processes. Changes are numerous like geology, structure and composition of rocks, variations in climate, vegetation, altitudes, and most variable and dynamic force – discharge. All rivers try to achieve equilibrium in its course and in this process, they erode, eroded materials are transported to its fullest capacity, depending upon available sediment and when the sediment is more than the carrying capacity, they are deposited (Nanson and Huang, 2008) [19]. Rivers are continuously changing due to different factors like tectonic movement, climate change, human interference in the catchment and varying discharges. So, long term equilibrium is less of a reality than the theoretical possibility (Hoffmann, 2015) [13] and most of the large rivers are on way to adjust with human induced far-reaching consequences (Walling, 1999 and 2006) [29, 30]. In the plain, most common changes in the channel is its sinuosity. It is a way by which channel used to maintain gradient with respect to the size of loop of meander and the energy provided to the channel by discharge and sediment. Sinuosity of the channel depends upon discharge characteristics, sediment load with water, erodibility of the bank and bed, porosity and permeability of rocks (Dade, 2000; Stouthamer, *et al*., 2011; Pierik *et al*. 2017 and Candel *et al*., 2020) [3, 28, 20, 2].

Channel change of the Kosi River is well documents for around 300 years. The river has shifted its course for several occasions. They are basically avulsions and it used to change its course and abandon the existing channel. Many scholars have studied shifting tendencies of the Kosi River (Ray, 1953; Geddes, 1960; Das, 1968; Prasad, 1999 and 2000; Jain and Sinha, 2004; Sinha, 2005; Jain *et al*., 2012) [25, 9, 4, 21, 22, 14, 27, 15]. It has shifted more 210 km towards west from its earlier course in the east flowing with Parman or Panar River during 1736. If one prepare a transact/cross profile along 26°15' north latitude from eastern part of its abandoned channels, it is showing continuous rise in bed level and so its shifting further westward became inevitable. As mentioned, it has been embanked since 1958, breach in embankments have been observed at several occasions in the past but the most devastating damage was caused by breach of Kushaha on 18th August 2008. One reason for channel shift is rising bed level of the Kosi River and it is also attributed apart from high discharges. Hence, it attempted here to examine changes in gradient and bed of Kosi.

Objectives, data and Methods

Objectives

The main objectives this paper are to (i) To study the changes in gradient of the Kosi River, (ii) investigate the changing bed level, particularly, after construction of embankment in 1958 (iii) find long term solution of channel stability and flood management.

Data Source and Methodology

The data used in this paper is secondary, collected from Research and Investigation Division of Kosi Project Authority, Birpur, Bihar. The primarily, this data is concerned with datum level survey conducted every year after the flood recedes and water level is low especially in the month of December-January. The survey is conducted along 66 cross sections with pre-decided azimuth radiating from eastern embankment. The widths of the two embankments are more than 5 km to 18.54 km. Along the cross sections, datum level measurement is done at a regular interval of 600 meter, but when river channel approaches, the spacing between two surveyed points are reduce. It is brought to 300 meter, 150 meter, 50 meter, 20 meter and even 5 meter interval is taken to incorporate changes in the bed level along the section. It happens so, because, sometimes river is less than 600 meter wide, it may not be taken into account if the spacing is not reduced. This data is vital for bed level analysis of the channels. Based on this it is analyzed.

The other data used is channel and non-channel area computation. It is computed with the help of channel planform collected from Research and Investigation Division of Kosi Project Authority, Birpur, Bihar. At the time of datum level survey, planform, or "plan-view" of embankment area is prepared on large sheet. Ammonia print of the map was collected and reduced to printable size used here. With help of that plan-view, channel and non-channel area is computed by planimeter to compare the changes in the bed level of the channels in the Kosi embankment area.

Data related to height of the highest flood level, average countryside level as well as the river bed level is collected from Report of Central Water Commission prepared by C.G. Desai (1982) [5]. This data helped in preparing graphical presentation of the river profile. On this data, hydraulic slope is computed and attempted to test the real profile of the Kosi River with that of the hypothetical concavity of the channel.

Along all cross sections, minimum bed levels are identified and they are plotted on a graph paper, but this data is available for three reaches only first, second and third. For fourth reach, data is not available hence; it was not possible to do. It has been done for three years, namely 1958, the year of completion of the embankment; 1968, the year when the maximum discharge was recorded so far in Kosi's known history; and 1984, when compete and detail data was available. The mean of channel bar, bed and datum level are computed for all sections they have been plotted as longitudinal profiles to see the changes occurring among these years.

Study Area

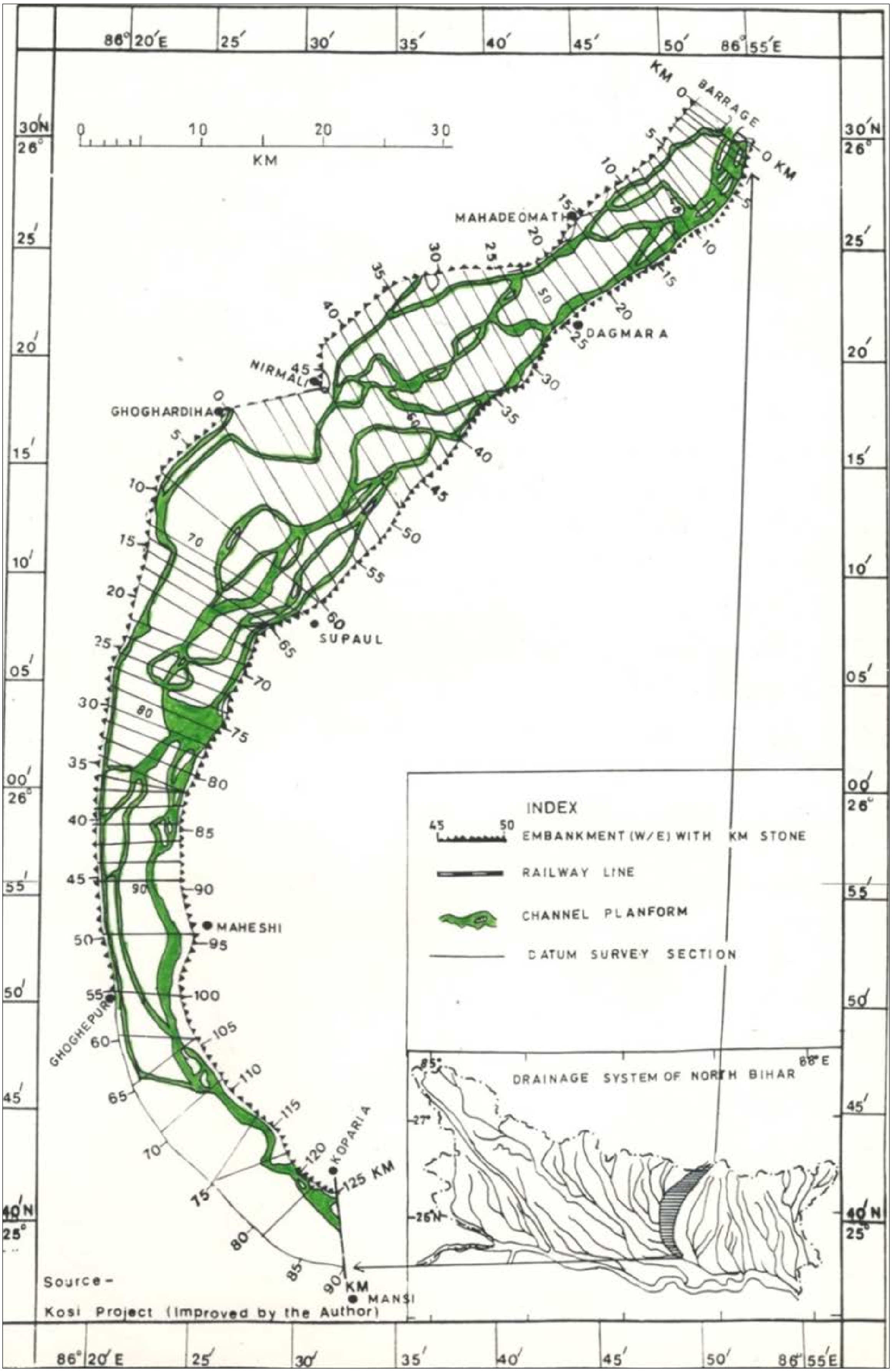
The Kosi River is one of the most important and largest tributaries of the Ganga River system bringing enormous water and sediments from the Himalayan upper contributive basin. the Kosi River is formed by seven river in the upper mountainous catchment namely the Sun Kosi, the Indrawati Kosi, the Tamba Kosi, the Likshu Kosi, Dudh Kosi (all four tributaries of the Sun Kosi), the Arun Kosi and the Tamur Kosi before they reach Barahkshetra gorge where it is Known as Triveni (confluence of three rivers). Though they are seven in numbers, but the confluence is considered of the Sun Kosi, the Arun Kosi and the Tamur Kosi. Downstream to Triveni, the river is known as "Sapt-Kosi". When the Kosi River descends down from Triveni (Barahkshetra), it spreads its sediments in the bed of its flow and breading is very clearly resulted (Figure 1).

Source: Google Earth Snapshots 01 October 2021

Fig 1: Braiding below Chatra (Image from Chatra to Bhim Nagar Barrage)

At Chatra (in Nepal), the Kosi debauches into the plain. After a distance of 42 downstream from Chatra, a barrage is constructed at India-Nepal boundary. From barrage, embankments are constructed both to upstream and downstream. To the upstream of barrage, embankments start from the foothills. It runs till Mansi-Koparia Railway Bridge along eastern side of the river through barrage at Bhimnagar. Its distance is 125 km from barrage axis. To the west side, it runs from barrage axis to Nirmali Railway station for a distance of 46.8 km. The function of embankment is performed by railway line which runs for 8.5 km, after that railway line takes a turns. From, railways turn, again embankment starts and goes for another 55 km. Hence, total length of embankment to the west side of the river is (46.8+8.5+55.0) 110.3 km. Further downstream, it is left unembanked (for 34 km) to allow its tributaries Kamla and Kareha to join the Kosi River.

The detailed analysis in this paper is mainly confined to the area within the two embankments of the Kosi River below Bhimnagar barrage. As mentioned, it is bounded by eastern and western embankments in east and west. Northern boundary is demarcated by Bhimnagar Barrage and that of to the south is by Mansi-Koparia Railway Bridge. On all sides, it is demarcated by human made structures (Figure 2). Its extension is from 25°43' north to 26°36' north latitudes and 86°20' east to 86°55' east longitudes. It covers an area of 1251 km^2 (computed by author based of planform received from Kosi Project Office, Research and Investigation Division, Birpur, Bihar).



Source: Prepared by author based on planform received (Prasad, 2008)

Fig 2: Study Area within Two Embankments of Kosi

A panoramic view of entire study area can very be had from Figure 3, which are snapshots taken from Google Earth dated 1st October 2021. From this image it is very clear that the braiding condition is prevailing in the embankment area.

Source: Google Earth Snapshots 01 October 2021

Fig 3: A Panoramic View through Google Eyes (Barrage to below Railway Bridge)

Overall, complete area within the embankment is almost flat with some variation in altitude in north-south direction. The variation in east-west is only to an extent of channel bed and bar height. Towards north, maximum height is about 72 meter near barrage while in south, it is 34 meter. So, a difference in height is only 38 meter within a length of 125 km. For the present study, embankment area is divided into four Channel Reaches (Table 1).

Table 1: Divisions of Study Area and their Expansion Details

Reaches	Location along Eastern Embankment (in km)		Cross Section	Distance along Eastern Embankment (in km)		Area in km^2
Reach I	Bhimnagar	Dagmara	B. Axis-49	0.00	25.25	156.0
Reach II	Dagmara	Supaul	50-70	25.25	62.82	545.2
Reach III	Supaul	Maheshi	70-90	62.82	94.25	293.2
Reach IV	Maheshi	Koparia	90-98	94.25	125.00	256.6
Complete Area	Bhimnagar	Koparia	Barrage Axis-98	0.00	125.00	1251.0

Source: Prepared by author based on Kosi Project Authority information

After embanking the river by 1958, entire area is surveyed every year in the month of December-January when discharge in the river is minimum and traversing river is relatively easy and convenient. The datum level survey is conducted along 66 cross sections starting from 33 to 98. The cross sections are marked on Figure 1. From cross section 1 to 32 is lying in the upstream to Bhimnagar barrage. The extension of the reaches, cross section numbers and their length along eastern embankment is given in Table 1. These cross sections are radiated from fixed azimuths from eastern embankment and their lengths are also given in Table 2.

Table 2: Kosi Embankment Area and Annual Surveyed Cross Sections

Sl No	CS No	Distance	Spacing	Azimuth	Sl No	CS No	Distance	Spacing	Azimuth
REACH I									
0	Axis	0.00	6.800	306°	9	41	11.25	7.235	328°
1	33	1.50	7.458	306°	10	42	12.75	7.011	321°
2	34	3.00	7.832	306°	11	43	14.25	7.680	321°
3	35	4,25	7.933	306°	12	44	16.00	6.275	321°
4	36	6.00	7.744	306°	13	45	17.25	6.705	321°
5	37	7.75	7.934	321°	14	46	19.00	6.210	321°
6	38	8.75	7.600	321°	15	47	20.75	5.608	321°
7	39	9.75	7.325	321°	16	48	23.50	5.505	321°
8	40	11.00	7.323	328°	17	49	24.00	5.950	321°
REACH II									
1	50	25.25	6.665	328°	12	61	44.75	15.535	328°
2	51	26.25	8.118	328°	13	62	46.50	15.495	328°
3	52	28.00	10.000	328°	14	63	48.00	12.733	328°
4	53	31.25	11.935	328°	15	64	51.75	14.840	328°
5	54	33.75	12.087	328°	16	65	53.75	16.539	328°
6	55	35.00	12.122	328°	17	66	55.80	17.071	328°
7	56	36.50	13.785	328°	18	67	58.00	18.540	328°
8	57	38.25	14.085	328°	19	68	59.50	18.100	328°
9	58	40.00	14.725	328°	20	69	60.00	17.634	300°
10	59	41.75	13.551	328°	21	70	61.25	16.080	300°
11	60	43.00	15.502	328°					
REACH III									
1	71	62.82	14.332	300°	11	81	78.50	9.279	292°
2	72	64.00	13.747	300°	12	82	81.25	9.307	292°
3	73	66.00	12.485	300°	13	83	81.25	9.110	292°
4	74	67.25	10.850	300°	14	84	81.25	8.400	280°
5	75	68.75	11.156	292°	15	85	82.00	8.560	270°
6	76	70.25	9.930	292°	16	86	82.85	8.400	270°
7	77	72.00	10.710	292°	17	87	84.25	7.972	270°
8	78	73.25	11.065	292°	18	88	86.25	7.620	270°
9	79	75.25	10.810	292°	19	89	88.00	7.490	270°
10	80	76.75	9.923	292°	20	90	89.50	7.450	270°
REACH IV									
1	91	94.25	8.853	270°	6	96	114.00	2.789	N.A.
2	92	99.00	6.060	270°	7	97	119.00	2.970	N.A.
3	93	104.25	7.310	270°	8	98	123.00	4.249	N.A.
4	94	104.25	2.105	N.A.	9	Bridge	125.00	5.000	N.A.
5	95	109.25	3.570	N.A.					
Sl = Serial; **CS** = Cross Section; **Spacing** = between embankments starting from east in km; **Azimuth** = degree from due north measured from eastern embankment,									

Source: Compiled by author based on Kosi Project Authority information

The general statistics of study area is comprehended in Table 3 from Table 2, which shows reach-wise longest, smallest and average width between the embankments. From Table 2 and 3, it is obvious that northern as well as southern parts of area are narrower and the middle part is bulged and much wider, i.e., the spacing between embankments is large.

Table 3: Reach-wise Summary Statistics of Cross Sections

Detail	Reach 1	Reach II	Reach III	Reach IV	Complete Study Area
Longest Cross Section (Serial No)	37th	67th	71st	91st	67th
Length, Longest Cross Section (km)	7.937	18.540	14.332	8.853	18.540
Smallest Cross Section (Serial No)	48th	50th	90th	94th	94th
Length, Smallest Cross Section (km)	5.505	6.665	7.450	2.105	2.105
Mean Width (km)	7.00	14.05	9.93	4.77	9.863

Source: Prepared and computed by author based on Table 2

Results And Discussions

Mean Gradient

Mean gradient of any river is steep in its upper region from where it is originating till it reaches to the plain formed by it. But with the Kosi River, intensity of gradient is probably the highest in the world for a substantial distance running into the mountain stretch. It is encompassing in its catchment and draining from the highest mountain of the world, Mount Everest. In a distance of about 350 km, vertical drop in height is observed to be about 8780 meter, and it gives a gradient of 25 meter per km. The slope becomes 28 meter/km when it is calculated upto Triveni. These statements are made on the basis of calculations from the highest peak, but the river is not originating from there. It is less than 20 meter/km till Triveni and from there to till barrage it is slopping by 6.54 meter/km (Prasad, 1999) [21].

Channel Gradient and Longitudinal Profile

Longitudinal profile of a river is the plotting of height along river distance on a paper. It indicates drops in altitude when we walk/move along the river. Therefore, a longitudinal profile is a graph of "distance downstream (L), versus elevation (H)", so that:

H=f(L) -- (equation 1)

Given a tendency to treat channel profile as an ideal shape, the initial problem to determine the possible form that this functional relation, H=f(L) might take. Hack (1957) [11] argued that channel slope (s), can be expressed as

$$s = \frac{-dH}{dL} = \frac{\text{differential decrease in Height downstream}}{\text{differential Length downstream}}$$ -------- (equation 2)

And this slope and distances are related by a logarithmic function

s = k+n Log L-------------------------------------- (equation 3)

Where:
k and n are the index of channel profile concavity

This logarithmic function assumes that channel height decreases downstream rapidly in relation to the slope (-dH/dL) which is proportional to the height so that:

$$\frac{-dH}{dL} = nH$$ --- (equation 4)

It is giving a simple model of river profile form which tends to be concave upward. If the real profile is based on actual data, it gives any concavity. The concave segment separated by concave steps, will indicate certain smaller scale fluctuations related in particular to the local channel bed topography as well as main downstream tendency of the river channel to decrease its gradient (Prasad, 1999) [21].
It is already mentioned that the river has been embanked within two embankments along its banks with more than 5 km spacing between them. It is the opinion of civil engineers and river specialist and that shifting of courses and formation of new channels (Dhars) are going on within the embankments bringing changes in the river bed configuration on year to year basis. Based on Desai (1982) [5] datum level survey and hydraulic slope along the Kosi River from Chatra downstream to its confluence (with the Ganga) at Kursela is given in Table 4 (Prasad, 1999) [21].

Table 4: Datum Level and Hydraulic Slope along the Kosi River

I	II	III	IV	V	VI	VII	VIII	IX	X
Chatra	0		117.65		110.19		102.17		3.05
		42		1.041		0.939		0.883	
Barrage	42		73.93		70.74		65.08		2.13
		32		0.501		0.430		0.415	
Baptiahi	74		57.91		56.98		51.79		1.52
		40		0.244		0.215		0.188	
Supaul	114		48.17		48.38		44.27		1.52
		97		0.128		0.125		0.255	
Dhamara Ghat	211		35.72		36.25		19.58		1.22
		85		0.030		0.034		0.028	
Naugachia	296		33.17		33.35		17.19		1.22
		23		0.127		0.071		0.237	
Kursela	319		30.25		31.71		11.73		1.22

Source: Desai (1982, page 91) [5]

I= Stations along the river, II= Distance in km, III= Distance between stations in km, IV= Countryside level in meter, V= Countryside slope in meter/km, VI= Highest flood level in meter, VII= Highest flood level slope meter/km, VIII= River bed level in meter, IX= River bed level slope meter/km, X= Observed highest flood level velocity meter/second.
Table 4 clearly speaks about the datum level for countryside, river bed as well as the highest flood level with reference to five points namely Barrage, Baptiahi, Supaul, Dhamara Ghat, Naugachia between Chatra upstream and Kursela downstream. Channel slope *–dH/dL* can be calculated which is given in Table 4. For example, the distance between first two points Chatra to Barrage is 42 km and the drop in height is 43.72 meter. Therefore, the slope is

$$slope = \frac{43.72\ meter}{42\ meter} = 1.041\ meter/km$$

Average gradient calculated above in terms of location of height of the two end points, for river length of 319 km, gives a response to the channel gradient. It can be treated to the means of adjustment by which a river attains a state of grade or equilibrium (Prasad, 1999) [21]. The channel bed level datum with response to six datum points has been subjected to the logarithmic function given in equation 3. Following the logic of a logarithmic function, the required calculations are given in Table 5.

Table 5: Computation of Estimated Longitudinal Profile of Kosi Channel Bed

Height meter (H)	Distance km (L)	Log $_{10}$ (L) (V)	H-$\overline{H}$ (h)	V-$\overline{V}$ (v)	vh	v^2
65.08	42	1.6232	30.14	-0.5183	-15.6216	0.26863
51.79	74	1.8692	16.85	-0.2723	-4.5883	0.07415
44.27	114	2.0569	9.33	-0.0864	-0.8061	0.00716
19.58	211	2.3243	-15.36	0.1828	-2.8078	0.03342
17.19	296	2.4713	-17.75	0.3298	-5.8540	0.10877
11.73	319	2.5038	-23.21	0.3623	-8.4090	0.13126
ΣH=209.64 $\overline{H}$ = 34.94		ΣV=12.8487 $\overline{V}$ = 2.1415			Σvh= -38.0867	Σv^2= 0.62339

Equation 3 is

s = k+n Log L

Where:

$$L = \frac{\Sigma vh}{\Sigma v^2} = \frac{-38.0867}{0.62339} = -61.0961$$

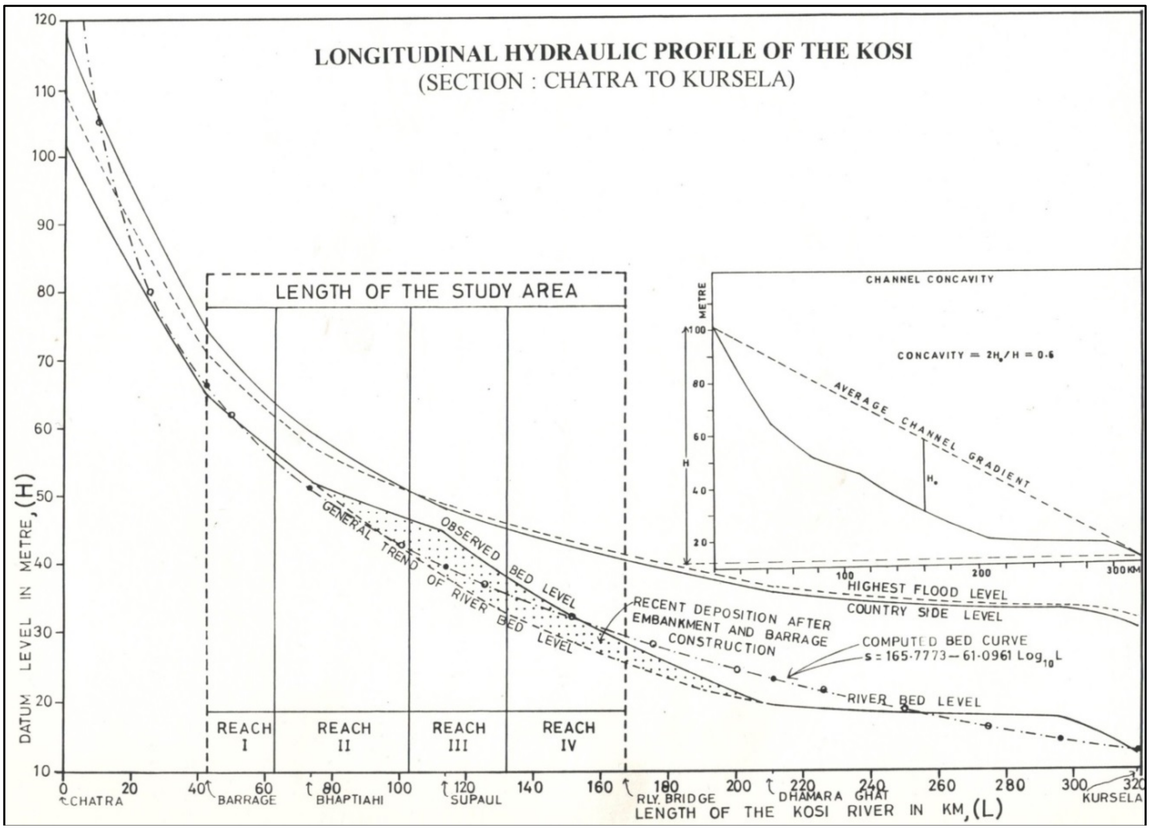
$$k = H - b\overline{V} = 34.94 — 61.0961 * (2.1415)$$

= 167.7773
It gives a logarithmic curve,

S = 165.7773 – 61.0961 Log_{10} *L*------------------ (equation 5)

Following equation 2.5, the estimated longitudinal profile for bed level of the Kosi has been superimposed in Figure 2 This estimated longitudinal profile appears to be more concave upward compared to the profile drawn with the datum heights. The concavity of the alluvial channel segment is also calculated by a concavity index as follows:

Concavity =$2H_0/H$---------------------------------- (equation 6)
Where H_0= difference in height at the median channel distance between the height on average channel gradient as well as the datum point itself.
H = is the total height difference between the two points.



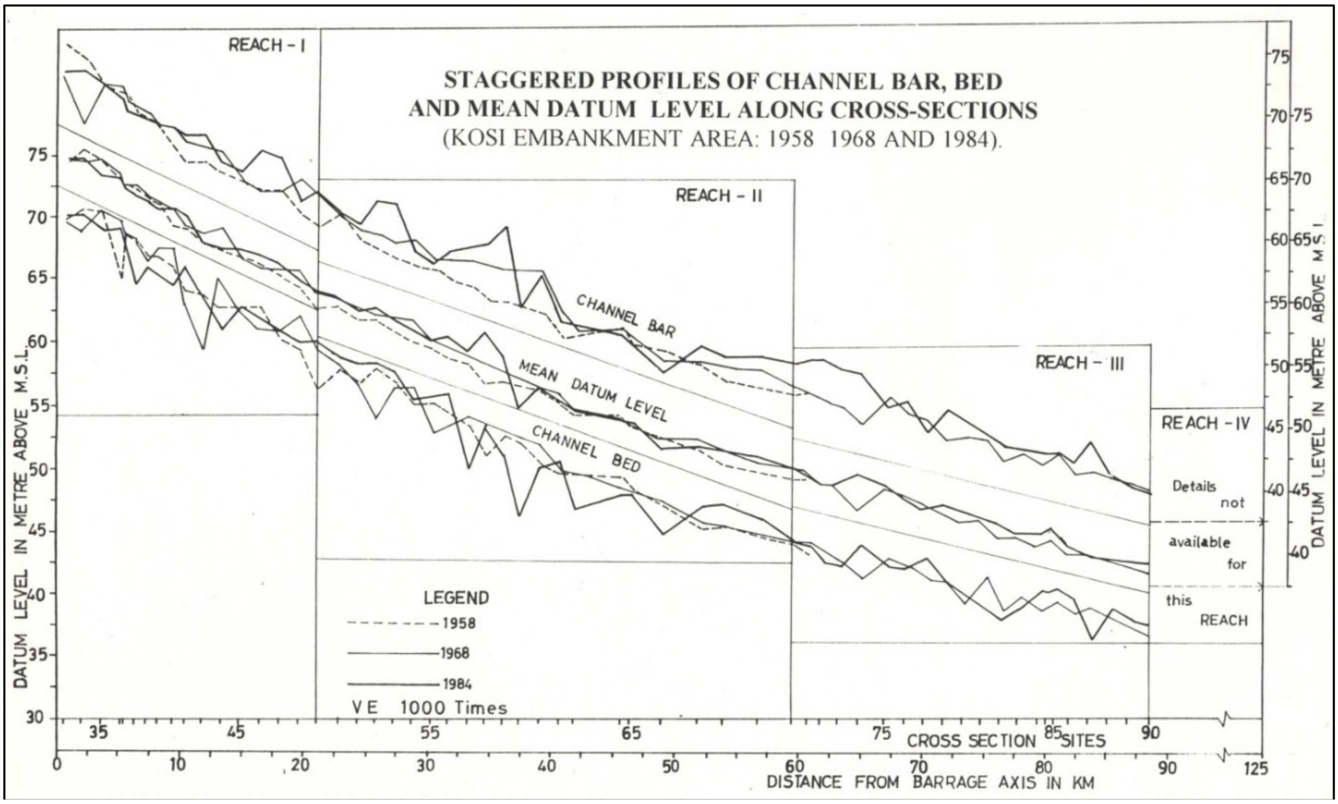
Source: Prepared by author based on data analysis

Fig 4: Profiles of Highest Flood Level, Average countryside Level and River Bed Level

The channel concavity drawn on the inset diagram in Figure 4 yields a value of 0.6. The empirical data worked out by Hack (1957) [11] and Knighton (1984) confirm that "longitudinal profiles are more concave where bed material size decreases more rapidly and conversely, it is suggested in their work that profiles have little concavity if particle size remains constant or decreases downstream." In the present context, alluvial channel reaches concavity is 0.6 which suggests that the decreasing character of the bed material size downstream indicating a rapid transition from shingle to sand bed conditions (Prasad, 1999) [21].
Figure 4 illustrates the datum level measured at various points along the Kosi River. Three datum levels are superimposed (a) the highest flood level recorded, (b) countryside average level and (c) bed level of the Kosi Channel. The average slope for these three sets from two end points – uppermost and the lowermost is 0.284 meter/km for river bed, 0.246 meter/km for highest flood level and 0.274 meter/km for countryside average slope. It is very clear that bed level of the Kosi River has steeper gradient in comparison to two other datum levels.
It is obvious that datum level of countryside is higher than observed highest flood level in the upper part. Therefore, upper part is flood free but lower part is flood prone because countryside level is lower. Roughly, 97 km downstream to Chatra (55 km down from barrage axis along eastern embankment) witness frequent flooding. As long as one goes downstream, the intensity and flood water stagnation is becoming more. The exit of flood water is slower, velocity is lower, and flood water is deeper southwards.

Longitudinal Channel Form Variations: Downstream to the Barrage
The datum heights for each of cross section sites are indexed into their respective mean for sites 33 to 90. This indexing of mean datum is done for three selective years namely, 1958, 1968 and 1984. The superimposition of channel bed, bar and mean datum level in staggered form for these years

have been shown in Figure 5. By examining this figure, it is clear that bed instability is higher in Reach I and upper part of Reach II. From lower part of Reach II, there is relative stability. It is happening so, because in this segment, variation in bed is changing slowly while in the upper segment, it is quite remarkable. It is also because; discharge coming from barrage has greater velocity as slope is higher water is restless. No stable and fixed channel has been carved out. Therefore, shift in bed position is remarkable on year to year basis. As long as one is going down, slope is reduced progressively as well as spacing between embankment areas also increasing (Prasad, 2002) [23]. Because of these two reasons, water gets spread over larges area and relatively stable channel seems to exist. This has attributed to smaller changes in the channel bed (Prasad, 1999) [21].



Source: Prepared by author based on data analysis

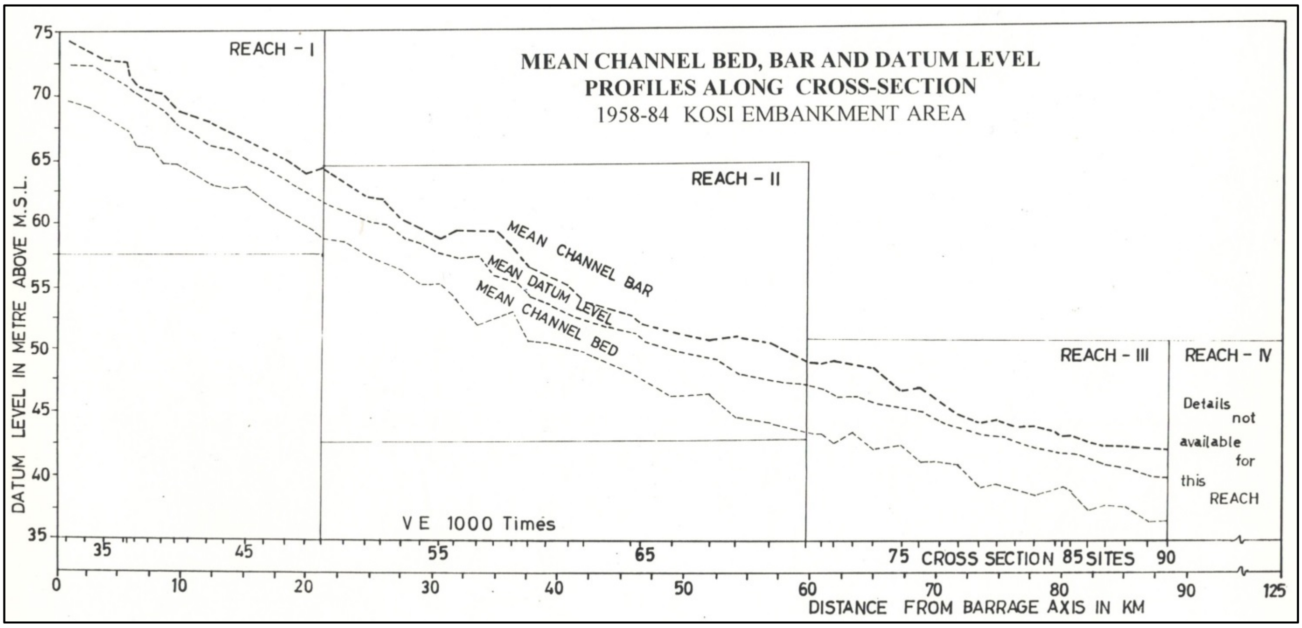
Fig 5: Superimpositions of Channel Bed, Bar and Datum Level

In Figure 5, channel bar is shown to the top of all profiles. It is apparent that entire area under two embankments has experienced wide spread aggradation over the years. It is concluded on the basis of occupying the profile of 1958 at the bottom. It happens only when there is accumulation of sediments. After 1958, aggradation is attributed to the construction of embankment. In majority of the sections, higher datum is occupied by 1968, which is probably due to large amount of sediment brought during peak discharge occurred on 5th October 1968. Hence, sediment brought and deposited was recorded during datum level survey. More or less, profile of 1984 is falling between these two profiles.

Mean datum level for these years is plotted on the same Figure 5. The mean datum level is composite index of all datum level measurements along the section during survey. In other words; it is average of datum level values. From this figure, it is quite obvious that mean bed level is quite smoothened by averaging in comparison to bar and bed level. It also quite natural that the average values for 1958 is smaller than other two years.

Mean Channel Bed, Bar and Datum Level: Downstream to the Barrage

Mean channel bed, bar and datum level is computed for the period of 1958 to 1984 and they are plotted on Figure 6. From this illustration, it is very vivid that all aspects are showing similar figures with certain gap among them. More or less, all are running parallel to each other. Some bumps like appearance are emerging, but that may due to survey error particularly in bed profile of the river. The drops in the all profiles are smooth and downward. The simple plots of these figures are not giving any concept of concavity, but smoother lowering downward slope is apparently visible. They are running smoothly downward because of the characteristics of averaging and run almost straight.



Source: Prepared by author based on data analysis

Fig 6: Plot of Mean Channel Bed, Bed and datum Level

Conclusions

River system is dynamic in character because of variations in different aspects of river morphology. Morphology of any river is the functions of interactions among different parameters. The most important and dynamic but active aspect is water flow in the river. Other important factors are slope, structure and composition of rocks, vegetation, land use and human footprint in the catchment area. Rivers have been trying to adjust with several changes that are taking in river system. With change in any of component of morphological system, changes in other components are bound to happen. Anthropogenic factors are playing very significant role in river morphology. Human interference in the natural system in any river basin is negatively impacted in terms of channel stability and maintenance of equilibrium. Human footprint has reached to large area covering in almost all the river basins of the world. The Kosi River basin is one of the most highly dense areas/ pockets of the world. Human encroachment is very high in terms of land use and obstructions in the free flow of water due to faulty several types of constructions including embankments. They are making hindrances in water flow. Due to all these reasons, sediment yield in mountainous catchment is very high. This causes more and more sediment to be carried to the downstream. Therefore, the channel bed is severely affected in both regions upper hilly as well as lower plain. It is causing huge sedimentation all along its path. Hence, channel bed profile is getting altered with sediment flux and its concavity is affected. The channel is supposed to maintain equilibrium between sediment load size, amount, bed form and discharge is probably not in congruence with the ideal relationships.

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