Avulsion as a landscape-forming event: A Case study of River Kosi using Space Technology and Geospatial Approach

Prafulla Kumar Panda,M.L.Naraismham and Madhusmita Ghadai
Department of Civil Engineering
Centurion University of Technology and Management, Odisha
Email : Prafullapanda@cutm.acin/ hammln@cutm.ac.in

Abstract:

Floods are the most common Disasters; their frequency, magnitude and the cost of the damage are on the rise all over the world. The River Kosi in the north Bihar plains presents a challenge in terms of long and recurring flood hazard. The 18th August 2008 avulsion of the Kosi River draining the parts of North Bihar in eastern India which flooded a large area and adversely affected more than 30 million people may be regarded as one of the greatest avulsions in a large river in recent years. Understanding the phenomenon of river avulsion and mapping of avulsion prone areas may provide important inputs to plan mitigation strategies and declare warning to the people who are residing in the avulsion prone areas to change their domicile to a safer place. Keeping this in view, the present study is aimed to evaluate the avulsion threshold responsible for triggering an avulsion and accurately delineate the probable points and pathways for future avulsion in parts of Kosi river basin in North Bihar and Nepal. Dynamic geomorphic mapping has been done on satellite images for pre-and post-avulsion periods to understand the river avulsion process and landform evolution in the Kosi alluvial plain. The avulsion threshold of any river can be evaluated reach wise considering the topographic parameters which included cross-valley slope (Scv), down-valley slope (Sdv), levee slope (Ls), super elevation (he) and flow depth (h) individually as well as by integrating them. This analysis enable the classification on avulsion thresh hold for the reach in to 4 different classifications. Plan form dynamics in consequence to the Kosi barrage and embankments has also been studied and a reach-wise measurement of plan form parameters and their temporal variation has been carried out for critical periods. Critical reaches have been identified and the influence of plan form parameters on river avulsion has been assessed. The overall effect of all the parameters of topography and variation of plan form morphology on avulsion has been studied by assigning relative weightages to each parameter using one of the multi-criteria techniques in GIS Environment and an avulsion Threshold Index(ATI) has been computed. Some of the reaches upstream of the barrage are identified as probable points of Future possible avulsion and the corresponding flow paths have been defined from the Flow Accumulation Analysis. The analysis is validated with the recent avulsion that took place at Kusaha point on 18thAugust 2008. It is found that the key factors responsible for triggering the avulsion are topographic parameters while the plan form parameters are governing factors which push the river towards threshold condition for avulsion.

Key words: (Flood, Avulsion, Geomorphology, Geospatial, Avulsion Threshold Index Plan form Dynamics)

1. Introduction:

Avulsion is the relatively rapid shift of a river or a distributary channel to a new course on a lower part of a floodplain (Allen, 1965)[15] and is considered as a major fluvial hazard in large population centres (Sinha, 1998)[7]. The length of reach affected by avulsion can vary from a few tens of metres to hundreds of kilometres. The rapidity with which the discharge shifts completely from an old to new channel varies from 1 day to a decade (Jones &Harper, 1998)[16.] Avulsion involves a sudden movement around a nodal point (divergence point) and occurs when an event of sufficient magnitude (usually a flood) occurs along a river that is at or near avulsion threshold defined by the changing channel instability through time. It also implies that avulsion may not always be triggered by the largest flood in a given river, and that even a small flood can trigger an avulsion if the river is close to avulsion threshold (Jones and Schumm, 1999)[14]. One of the most common mechanisms of avulsion is 'channel reoccupation' (rapid) where the new channel occupies a pre-existing channel in the vicinity. On the other hand, 'crevasse splaying' involves a gradual process of breaching through the banks and development of a new channel through time. Avulsion cannot easily occur where a river has incised river valley, it should have another path to follow on the flood plain or alluvial fan.

Any sustainable landscape is a cumulative product of geomorphic processes operating over millennia. A geomorphic map portrays surficial features or landforms that record geologic processes on the earth's surface. Geomorphology is the science of studying the external expression and internal architecture of the planet earth.(Panda PK, Narasimham ML (2018)[1])

In river systems where avulsions occur, the process typically dominates the long term dispersal of sediment and water across their alluvial surfaces. Understanding and characterizing the controls on avulsion are important to geomorphologists studying the evolution of depositional landscapes; to sedimentologists reconstructing the history of the ancient river systems, and to civil engineers in controlling the position of waterways (Mohrig et al., 2000[13]). Avulsions cause a heavy loss of life and property. There are many rivers like Mississippi Delta (Louisiana, USA), Rhine-Meuse delta (Netherlands), alluvial fans in Arizona, river kosi draining through North Bihar plains (Eastern India) etc. where avulsions are frequent and have been a major concern for river management.

Different authors have different perspectives for avulsion and several schemes have been proposed to assess the potential of a river to avulse. As a channel belt aggrades and forms an alluvial ridge, this results in an increase of ratio between cross valley to down valley slope defined as 'avulsion threshold' (Mackey and Bridge, 1995[19]; Törnqvist and Bridge, 2002[12]) which partly determines whether an avulsion can occur or not. Another important cause for avulsion is local super elevation of some part of the channel above the surrounding flood plain (Bryant, 1999[14]; Mohrig et al., 2000[13]) produced by sedimentation, which tends to occur at higher rates near the channel than further out in the floodplain (Pizzuto, 1987). Avulsions are controlled by both autogenic (intrabasinal) and allogenic (extrabasinal) processes (Stouthamer, 2007[4]). Majority of the investigators considered that 'gradient advantage' is an important governing factor for an avulsion to occur (Mackey and Bridge, 1995; Törnqvist and Bridge, 2002[12]) despite the fact that there are other factors which influence the avulsion such as channel distribution and substrate composition (Aslan et al., 2005[9]).The Kosi is one of the major tributaries of the Ganga river which rises in the Nepal Himalayas. It enters India near Bhimnagar; thereafter it joins the Ganga river near Kursela, after traversing for 320 km from Chatra. As its water carry heavy silt load and the river has steep gradient, the river has a tendency to move sideways. It has moved about 150 km towards westward direction in the past 200 years (Wells and Dorr, 1987[25]) through 12 distinct channels. To restrict this movement further, embankments were constructed on both sides in 1955-1956. At present the river is confined within the embankments. One of the most recent avulsions of the Kosi river occurred on 18 August, 2008 when the Kosi River shifted by ~120 km eastward, triggered by the breach of the eastern afflux bund at Kusaha in Nepal at a location 12 km upstream of the Kosi barrage. This has been termed as one of the greatest avulsions in a large river in recent years (Sinha, 2009[2]). The avulsed channel 'reoccupied' one of the paleo channels of the Kosi and 80–85% flow of the river was diverted into the new course. This event was widely perceived as a major flood in the media and scientific circles. Although a large area was indeed inundated after this event, it is important to appreciate that this inundation was different from a regular flooding event. This avulsion triggered by the breach affected more than 3 million people in Nepal and north Bihar and has once again questioned the efficacy of the embankment strategy for flood control (Sinha, 2009[2]). Keeping in view the dynamic behaviour of the Kosi and in particular the August 2008 avulsion, the present study attempts to evaluate the avulsion threshold for the Kosi river using morphological and topographic data in Geospatial environment and define some probable points prone for avulsion in future. Another important aim is to understand the river avulsion and study the landform evolution in the Kosi alluvial fan. Temporal and spatial variation of the Kosi river in consequence of Kosi barrage and embankments has also been evaluated to understand how the variations of plan form parameters are regulating the river towards the threshold condition. Integration of topographic and plan form analysis using multi-criteria decision making techniques and few probable avulsion points and the pathways of future avulsion are defined. This paper presents the methodology used remote sensing and GIS based for topographic and plan form analysis, as well as for mapping the avulsion landforms in the Kosi river basin in North Bihar and Nepal.

2. Study Area

The study area lies in between latitude of $86^0$38'48" to $87^0$8'41"N and longitude of $26^0$6'15"to $26^0$42'50"E(Fig-1).The river Kosi is the perennial in nature where as its tributaries are ephemeral .The study area is covered approximately 6063 sq.km with hill terrain as well as thick alluvial sediments. These thick alluvial deposits occurred due to the aggradational process of river Kosi.

3. Data Source and Methodology

The present study is based on variety of data sets such as Landsat Enhanced Thematic Mapper Plus (ETM^+) with spatial resolution of 30m, date of acquisition February 2003 and 5 scene of IRS Linear Imaging Self-Scanning Sensor - (LISS-4) corresponding to path–row 27096/35, 27096/36, 27778/41 acquired in Jan 2009, 27096/37, 27778/43 acquired in feb.2009 with spatial resolution of 5.8m. 3scenes of Cartosat -1 images with spatial resolution of 2.5m. Topographic sheets from Survey of India, 1983 includes 72J and 72N (1:2, 50,000).the interpretations have been checked through selective field visit. Detailed flow chart of methodology showing at Fig No.2

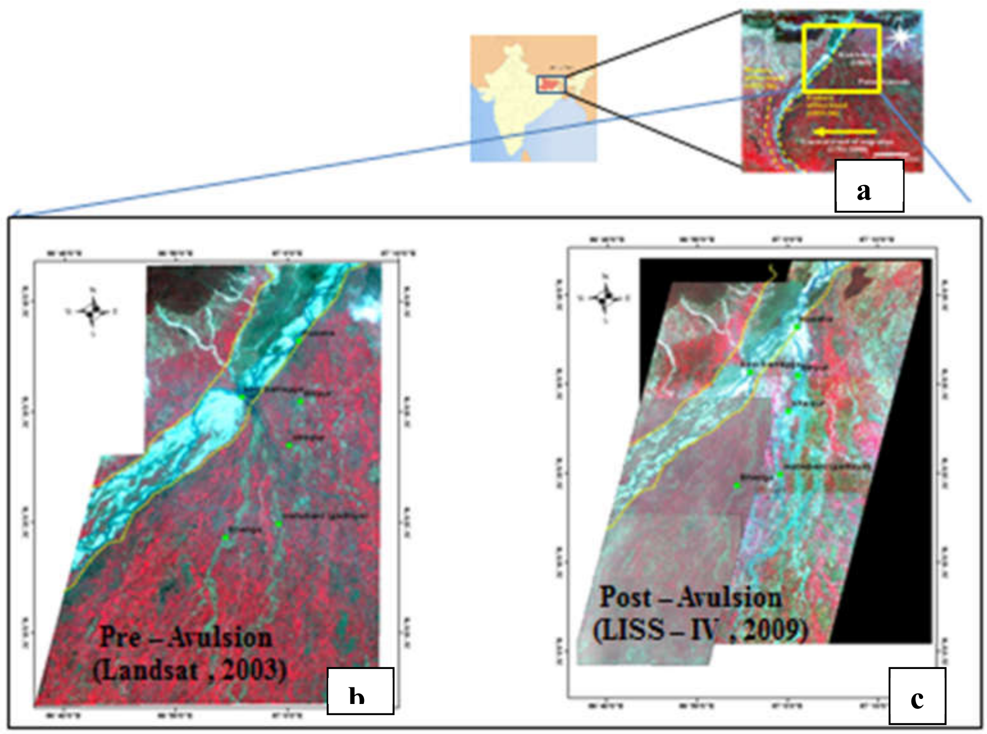


Figure :1 Location of the study area, (a) FCC of the Kosi River basin (b) FCC of the study area pre-avulsion (Landsat, 2003) (c) FCC of the study area post avulsion (Liss-4, 2009)

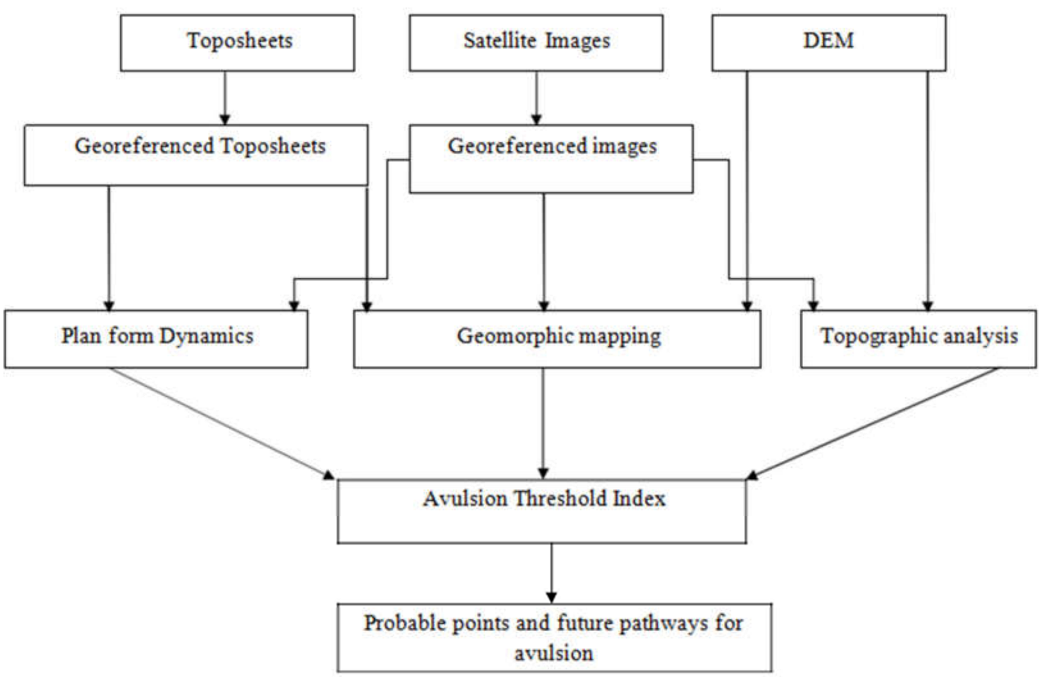
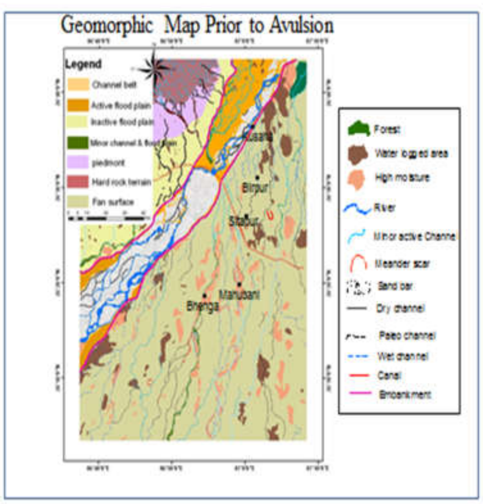


Figure : 2Flowchart showing the overall methodology

4. Plan form dynamics:

4.1Geomorphic mapping

Geomorphology is the classification, description, nature, origin, and historic development of present landforms. This element describes the predominant geomorphic processes active in the section that resulted in formation of the characteristic landforms. To understand the river avulsion and landform evolution in Kosi alluvial plain, a dynamic geomorphic mapping has been done on satellite images prior and post to avulsion. The mapping has been done in digital mode using the onscreen digitization in Arc Map GIS. Primarily, the processed images, maps were used and supplemented with information from topographic sheets and DEM. Thematic maps of geomorphic elements such as active channels, water logged areas, channel bars, meander scar, minor active channels, paleo channels, dry channels, wet channels etc were mapped, and were overlain to get an integrated geomorphic map of the area. Each geomorphic element was coded in different colours and ID is given in the thematic map. The detailed geomorphic map of the study area prior to and post-avulsion are shown in (figures3 and 4). The following sections describe the different geomorphic elements and units mapped for both the periods. As listed in the figure-3, the pre-avulsion map based on the satellite image of the year 2003 consists of seven geomorphic units namely active channel belt, active flood plain of major rivers, inactive flood plain, minor active channels and its flood plain, hard rock terrain, piedmont plain, fan surface (Table-1) These major units are prepared based on the distribution of geomorphic elements and the understanding of the modern processes involved. Most of these units are mapped from the post-avulsion image as well but with some variation in their spatial distribution. In addition, an additional and distinctive unit, Avulsion deposit belt, mapped in the post-avulsion image covering a large part of the fan surface.



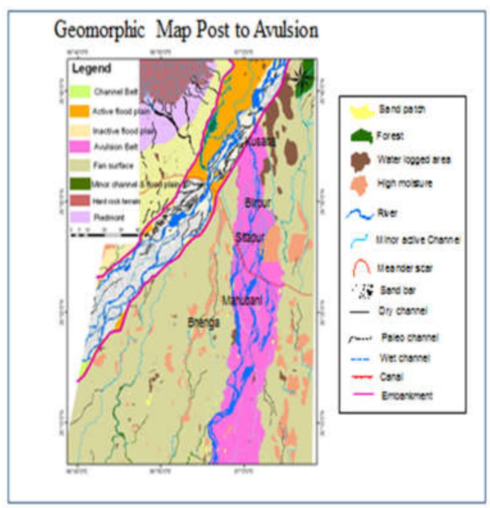


Fig no-3 Fig No-4

Fig-3 Showing various Geomorhic units and elements prior to Avulsion 2003,Fig:4 Image showing various Geomorphic Units and elements post to Avulsion in -2009

S.No	Geomorphic element	Geomorphic characteristics	Identification criteria on satellite images
1	Active channel	Active channel (AC): Area frequently or recently reworked by fluvial processes during high flow events. The active channel includes only channel-like features (i.e. elongated, appear to have been carved by flowing water); other water bodies are classified within the floodplain. The area in the active channel is occupied by water, bars, and exposed channel bed. This element defined as the portion of the river and flood plain inundated both ends connects to the main channel	These features are identified from the satellite imagery due to the dark blue to light blue colour.
2	Channel bar	Channel bars are the land forms in a river that begin to form when the discharge is low and the river is forced to take route of less resistance by means of flowing in location of lowest elevation.	Due to its greenish and bright colour it is identified from imagery
3	Meander scar	Meander scar is a geological feature formed by the remnants of a meandering water channel. They are often formed during the creation of oxbow lakes. These are the remnants of the highly sinuous paleo drainage system, which were cut off from main channel. These are identified by arcuate shape, uniform tone, isolated occurrences depressed relief characteristics.	It is identified from the satellite imagery due to its dark tone. It looks like a curvilinear stretches.
4	Paleo channel	Ancient drainage line of the stream of the river through which it might have flown in the past.	Identified from medium to dark tone, curvilinear pattern, and uniform to continuing of older stream. Also it has been identified from, in association with linear orientation of the vegetation.
5	Minor active channels	These are the important tributaries joined to the main stream.	These are identified from its dark to light blue color.

6	Avulsion deposit	Avulsion is the natural process by which flow diverts out of an established river channel into a new permanent course on the adjacent floodplain. Avulsions are primarily features of aggrading floodplains. Rivers can also avulse due to the erosion of a new channel that creates a straighter path through the landscape. This can happen during large floods in situations in which the slope of the new channel is significantly greater than that of the old channel	This is also identified from imagery due to its light green to light gray tone.
7	Water logged area	These features are identified in the low depressed areas where stagnate water bodies have been found	It is identified due to its dark tone in the image.

Table-1: Major Geomorphic Elements and their identification

5. Terrain Evaluation and Channel Morphological Analysis for Assessment of Avulsion Threshold

Topography is the study of terrain/relief or the vertical dimension of the land surface. Topographic analysis is the most significant component in avulsion studies because the trigger for an avulsion largely depends upon the regional slope conditions and the lowest elevation available in the region. Two sets of data have been used for describing hydrological function used in ARC GIS. The first set of data includes the elevation data (SRTM GTOPO30) from the USGS global elevation model (DEM) and second set of data includes the remotely sensed satellite data of the year 2000 for identifying the channel belt and thalweg position. The flow accumulation path of the river is extracted by giving the flow direction as the input, which gives the accumulated flow in the downstream direction. The river is not clearly delineated from this tool and hence a con tool is used by giving a threshold value. After applying this tool the river is distinctly visible. From this, the thalweg line is mapped and is divided into 2 km long reaches. Cross-sections are drawn for each reach covering approximately 10 km on either side of the channel. At every 2 km interval (fig 5).Using this data flow accumulation map for the study area after applying the fill function (fig-6) and the flow accumulation in the lower elevated area a(fig-7)are generated and same are shown here.

Fig: 5 SRTM DEM showing the thalweg line of the river with cross sections at 2km interval

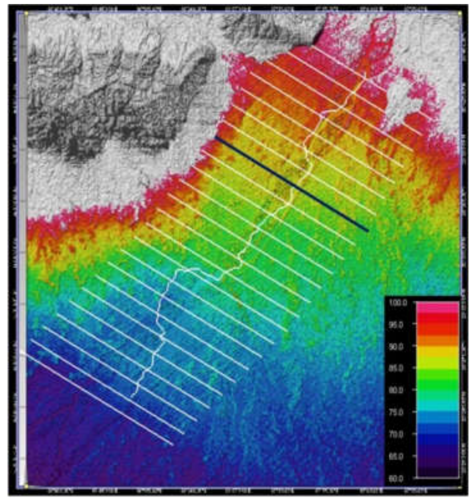


Fig-5

The slope between the present channel and the floodplain, termed as 'cross valley slope' is calculated for every reach. The slopes are calculated with respect to both the embankments. The slope between the levee and flood plain, termed as 'levee slope' is calculated for every reach. The difference in elevation between the levee and floodplain gives the measure of super elevation (h_e) and the difference in elevation between levee and channel bottom gives the channel depth (h). The ratio of h_e to h is calculated for every reach.

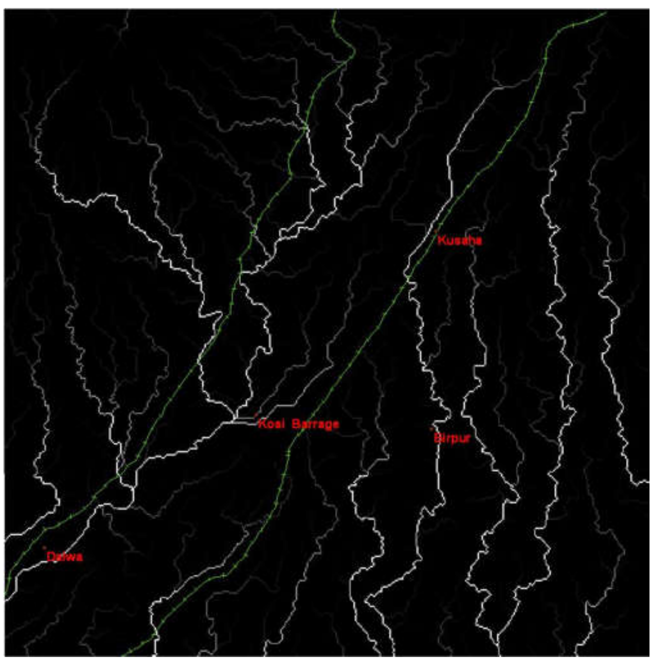


Fig no: 6

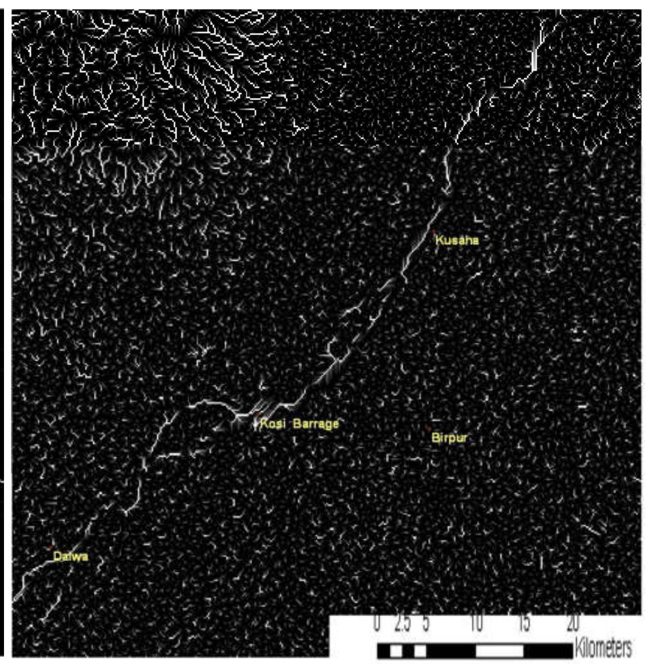


Fig no: 7

Fig 6: Flow accumulation map of the study area after applying fill function and Fig: 7 Flow accumulation map with flow accumulated in the lower elevated areas

It has been observed that the within the embankments the flow has shades of grey and somewhat white colour which means that the flow available there is not exactly the thalweg flow. It is also noticed that a solid white line (suggesting a strong flow accumulation path) is dominant at the Kusaha point outside the embankment which continues for several kilometres downstream of Birpur. This suggests that a strong gradient existed at least since year 2000 or perhaps earlier than 2000 but the river was forced to flow within embankments. It is reasonable to believe that this situation might have worsened by the year 2008 when the avulsion occurred at Kusaha. Avulsion threshold for different reaches along the river has been evaluated with respect to both the western and eastern embankments using three different approaches

Cross valley slope (Scv) to down valley slope (Sdv): Using the ratio Scv/Sdv, a reach is considered to be critical when this ratio is greater than zero. Figs 8and 9 indicate the graphical representation. The reach-wise plots of Scv/Sdv In the study window it was observed with respect to the western embankment the reaches 1-5, 7-8, 11-18, and 20-23 have a value less than zero which are considered as safe. The reaches 6, 9, 10, and 19 have values greater than zero which are considered as critical. With respect to eastern embankment, the reaches 1-3, 16-20, and 22-23 have values less than zero which are considered as safe. The reaches 4-15 and 21 have values greater than zero which are considered as critical. The avulsion threshold value with respect to the eastern embankment for the Kusaha point which falls in between the reaches 7 and 8 is 11.9.

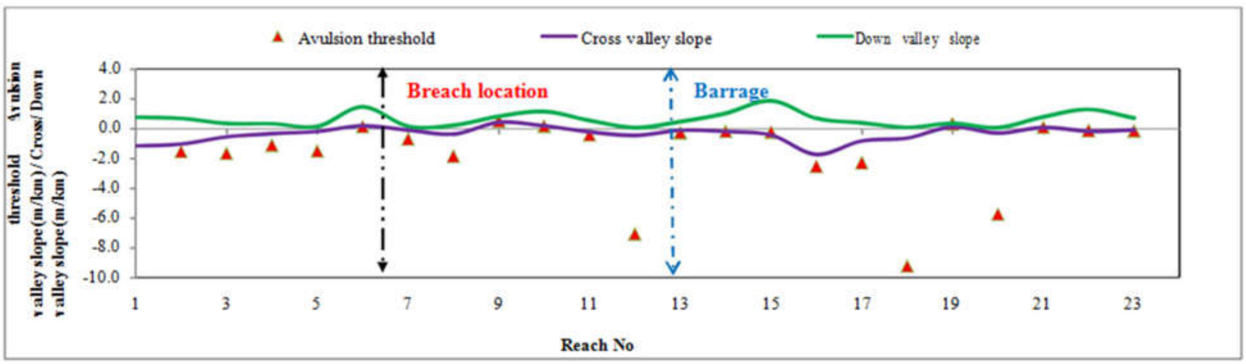


Figure: 8 Representation of cross valley slope with respect to western embankment, down valley slope and avulsion threshold values

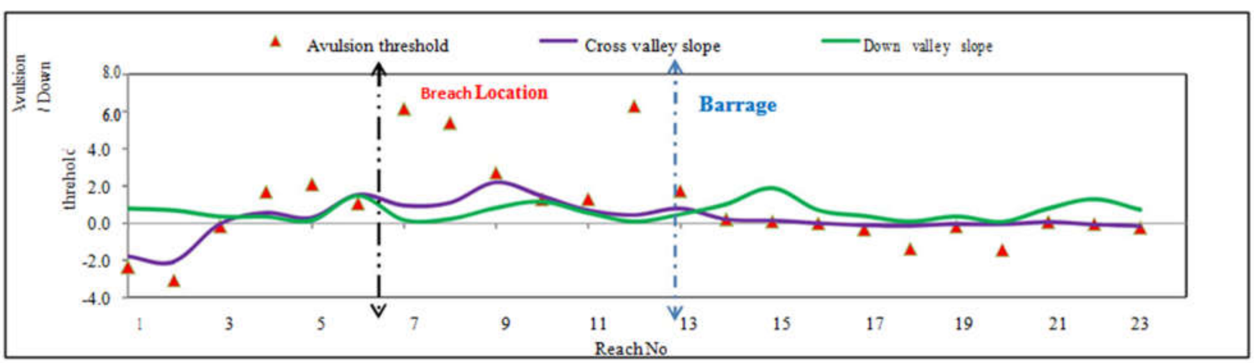


Figure: 9 Representation of cross valley slope with respect to eastern embankment, down valley slope and avulsion threshold values

(b) Levee slope (Ls) to down valley slope (Sdv):

The ratio of levee slope and down valley slope was estimated for each reach with respect to both the embankments and the results are tabulated in and graphically represented in fig 10and fig 11. This approach is not applicable for some of the reaches where the western embankment is located in highly elevated area and there is no probability of avulsion. According to this approach the reach is considered to be critical when the Ls/Sdv ratio is greater than 5. In the study window it was observed that this approach was not applicable with respect to the western embankment for the reaches 1-14. The reaches 15 and 16 have a value less than 5 which are considered as safe and the reaches 17-23 have values greater than 5 which are considered as critical. With respect to eastern embankment, the reaches 2, 6, 10-11, 13-17, and

22-23 have values less than 5 which are considered as safe and the reaches 1-5, 7-9, 12, and 18-21 have values greater than 5 which are considered as critical. The Ls/Sdv ratio with respect to the eastern embankment for the Kusaha point which falls in between the reaches 7 and 8 is 19.97.

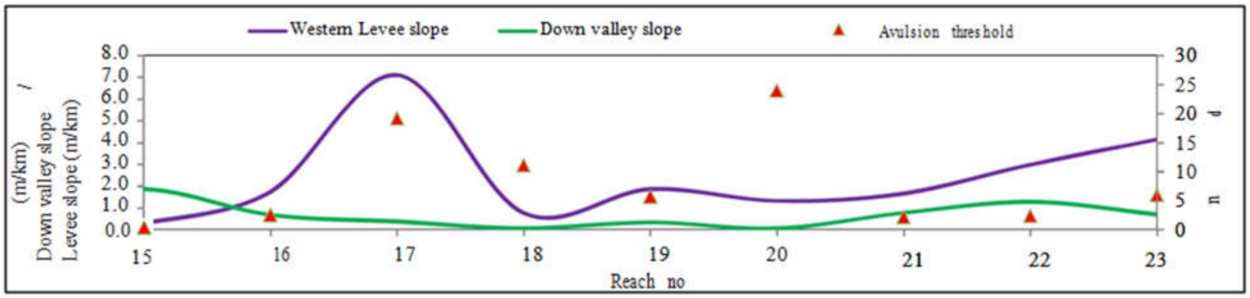


Figure :10 Representation of cross valley slope with respect to western embankment, down valley slope and avulsion threshold values

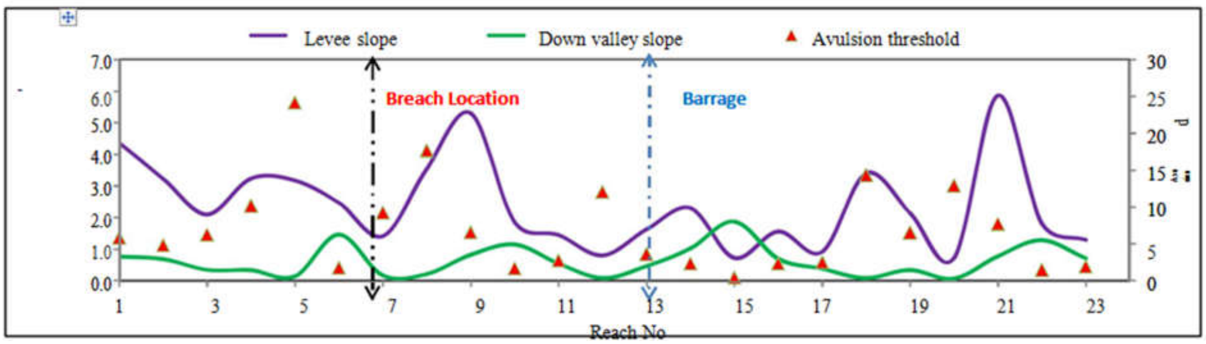


Figure:11 Representation of cross valley slope with respect to eastern embankment, down valley slope and avulsion threshold values

(c) Super elevation (he) to Flow depth (h):

The ratio of levee slope and down valley slope was estimated for each reach with respect to both the embankments and the results are tabulated and graphically represented in fig 12 and fig 13.This approach was not applicable for some of the reaches where the western embankment is located in highly elevated area and there is no probability of avulsion. In this approach, the reach is considered to be critical when the avulsion threshold is greater than 1. In the study window, this approach is not applicable for the reaches 1-14 with respect to the western embankment. The reaches 15-18, 20, and 22-23 have values less than 1 which are considered as safe and the reaches 19 and 21 have values greater than 1 which are considered as critical. With respect to eastern embankment, the reaches 1,-3, 16-20, and 22-23 have values less than one which are safe but the reaches 4-15 and 21 have values greater than one and considered as critical. The avulsion threshold value with respect to the eastern embankment for the Kusaha point which falls in between the reaches 7 and 8 is 4.45.

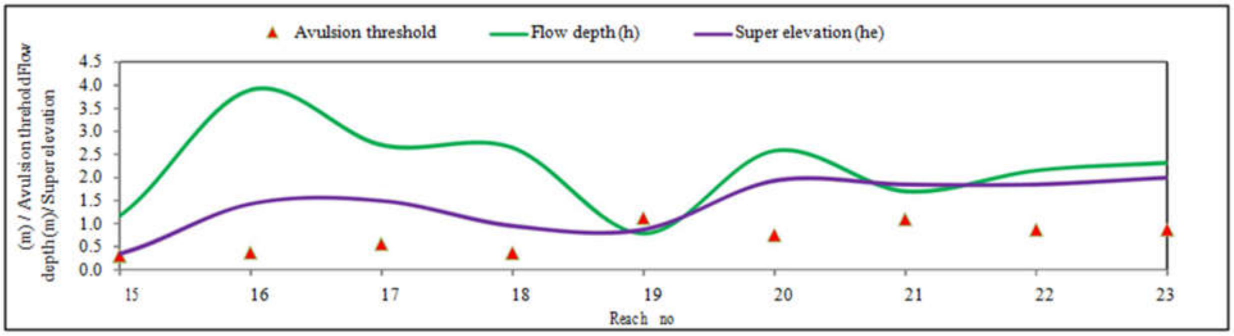


Figure: 12 Representation of cross valley slope with respect to western embankment, down valley slope and avulsion threshold values

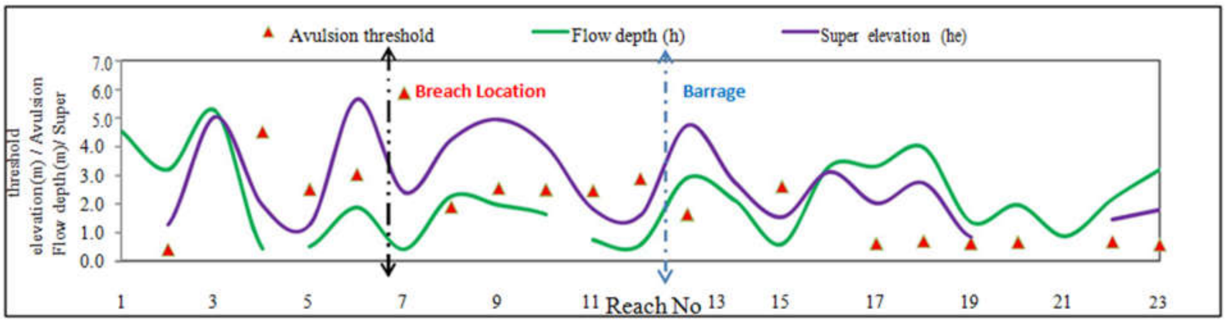


Figure: 13 Representation of cross valley slope with respect to western embankment, down valley slope and avulsion threshold values

Table-2 Integrated approach for determination of avulsion threshold

Scenario	**Scv/Sdv**	**Ls/Sdv**	**he/h**	**Implication**	**Avulsion threshold**
1	Low	Low	Low	Slope along Cross section is not increasing and Slope along downstream is not decreasing	Safe
2	High, decreasing trend	High, decreasing trend	High, increasing trend	Slope along Cross section is increasing and Slope along downstream is not decreasing	Less critical
	High,	High,	High,	Slope along Cross section is	

3	increasing trend	increasing trend	decreasing trend	not increasing and Slope along downstream is decreasing	Medium critical
4	High, increasing trend	High, increasing trend	High, increasing trend	Slope along Cross section is increasing and Slope along downstream is decreasing	High critical

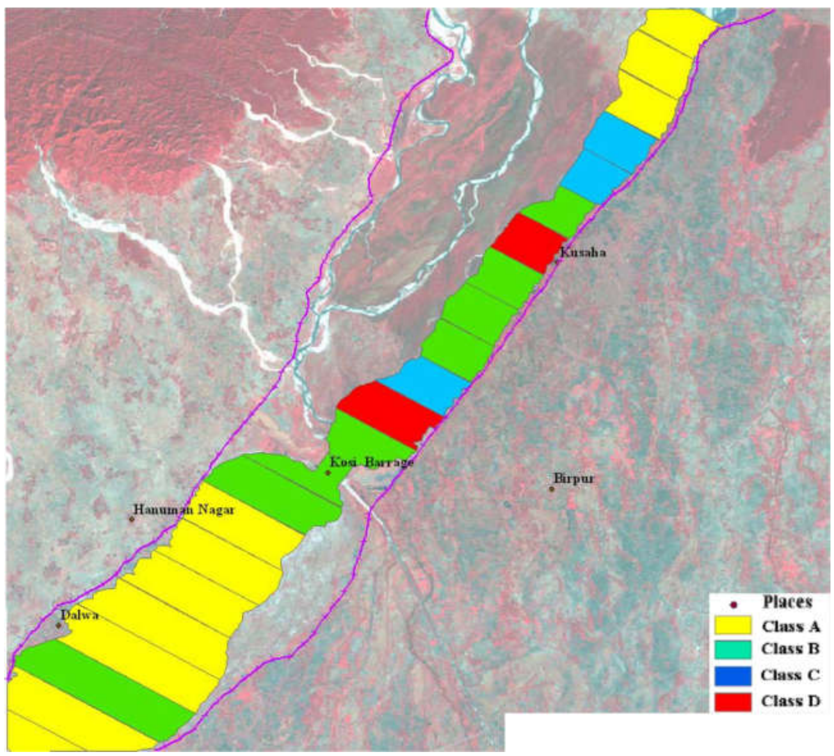


Figure: 14 classified map for avulsion threshold criticalness based on the integrated approach

5.2Major Landform changes in consequence to the August 2008 avulsion

Remote sensing based geomorphic mapping of the Kosi basin for the pre and post- to avulsion images have brought interesting changes in the regional landscape in consequence of a large avulsion which occurred on August 18th, 2008. Major changes occurred in the main channel as well outer channel. The upstream of the river was flowing eastwards (fig-15) during 2003.how ever due to heavy sedimentation and formations of large sand bars along the main channel, the river flow shifted towards east. It can be observed from the satellite image the flow direction upstream of the breach location had also gradually changed prior to breach, providing a more erosive angle of attack against the eastern embankment. The river flow become almost perpendicular in the month prior to the breach, thrusting pressure directly on the eastern embankment (C.M.Bhatt et al., 2009).The change in the angle of attack upstream of the breach could be surface a manifestation of the sub surface structural movement, as the higher Himalayas and the foot hill zone through which Kosi river emerges in to the plains near Charta constitutes a tectonically active zone (Agrawal and Bhoj, 1992, Sinha et. al 2005). Approximately 8% increase in the channel belt area has also been observed in the post-avulsion image, which is attributed to bank erosion in the intervening period.

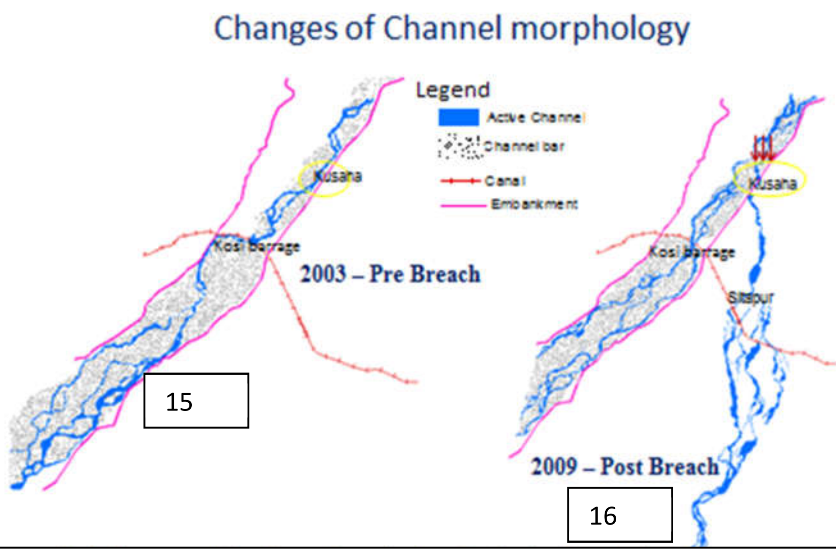


Fig 15 and 16 changes of channel morphology and for the both period pre beach and post

6. Result and conclusion

From the table 2, Scenario 1 represents the situation when all the three criteria give low values and therefore the reaches are considered to be safe. There is no chance of avulsion in these reaches.

Scenario 2 represents a condition when he/h ratio is high and shows an increasing trend in the downstream reaches which means that the cross valley slope is high and increasing. Both Scv/Sdv and Ls/Sdv ratios are high and has a decreasing trend which suggests that the down valley slope is increasing which is not a favourable condition for the avulsion to occur. This scenario is therefore considered as less probable for avulsion. However, some of the reaches may move towards threshold condition and trigger an avulsion.

Scenario 3 shows a situation when he/h ratio is high but with a decreasing trend in the downstream reaches which means that the cross valley slope is high and decreasing. From the 1st approach and 2nd approach it is evident that it has a high value and it follows an increasing trend which means that the down valley slope has an increasing trend and it is dominant when compared to cross valley slope. This is considered as a favourable condition for the avulsion to occur, and therefore, this scenario will represent the reaches critical to avulsion.

Scenario 4 is the most critical situation when all three criteria show high values and show an increasing trend in the downstream reaches. Most reaches falling in this scenario are prone to avulsion. Following the Integrated approach, the reaches 1-3, 16-20, and 22-23 are categorised under class A and are considered as safe reaches from the point of view of avulsion. Reaches 6, 8-10, 13-15, and 21 are categorised under class B which are considered to have low avulsion threshold. Reaches 4, 5, and 11 are categorised under class C which are considered to have medium avulsion threshold. Reaches 7 and 12 are categorised under class D which are considered as the most critical zones for avulsion. The diagrammatic representation for this classification by integrated approach is shown in figure 14

Remote sensing based geomorphic mapping of the Kusaha window for the pre- and post-avulsion images have brought interesting changes in the regional landscape inconsequence of a large avulsion which occurred on August 18th, 2008. The most spectacular change is the recognition of extensive avulsion belt within the fan surface primarily recognized by widespread sand deposition. It is noted that ~ 307.19 sq km of agricultural land got converted into sandy areas (moist) after avulsion making those lands barren for few years. Most of the many of the paleochannels on the active flood plain as well as on the fan surface have been reactivated after the avulsion apparently due to re-establishment of their longitudinal connectivity during the flooding which followed the avulsion. A drastic change is observed in the river morphology in consequence of the Kosi Barrage and embankments Reaches 2-4, 6,8, 11-12, 14, 16-17, 19-20, 23are still ‘critical’ during the period 2000-2009 for avulsion even after the August 2008 event. The Kusaha reach is now classified as safe but the reach next to Kusaha (reach 8) is still critical. By integrating the slope factors and variation of plan form parameters using GIS , the reaches 4, 5, 7 and 8 are classified under class D (most critical) and are considered as the future probable points of avulsion. Data integration suggests that slope parameters are governed by the temporal variation of the plan form parameters.

7. Reference:

1. Panda PK, Narasimham ML (2018) Dynamic Geomorphology of the Kosi Fan in Consequence to a Mega-Avulsion Aided by Space Inputs and Hydraulic Modeling. J Remote Sensing & GIS 7: 238. doi:10.4172/2469-4134.1000238
2. Sinha, R., 2009. The Great avulsion of Kosi on 18 August 2008 Current Science, 97(3), pp 429-433.
3. Sinha, R., Bapalu, G., Singh, L., Rath, B., 2008. Flood risk analysis in the Kosi river basin, north Bihar using multi-parametric approach of Analytical Hierarchy Process (AHP). Journal of the Indian Society of Remote Sensing 36(4): pp 335-349
4. Li, L., Lu, X., Chen, Z., 2007. River channel change during the last 50 years in the middle Yangtze River, the Jianli reach. Geomorphology, 85(3-4), pp 185-196
5. Sinha, R., Gibling, M.R., Jain, V., Tandon, S.K., 2005. Sedimentology and avulsion patterns of the anabranching Baghmati river in the Himalayan foreland basin, India. In: Fluvial Sedimentology (eds. Blum, M. and Marriott, S.), Special publication of the International Association of Sedimentologists, 35, pp 181-196.
6. Mitra, D., Tangri, A.K., Singh, I.B., 2005. Channel avulsions of the Sarda River system, Ganga Plain. International Journal of Remote Sensing, 26(5), pp 929-936
7. Jain, V., Sinha, R. 2005. Response of active tectonics on the alluvial Baghmati river, Himalayan foreland basin, eastern India. Geomorphology, 70/3-4, pp 339-356.
8. Sinha, R., Jain, V., Prasad B.G., Ghosh, S., 2005a. Geomorphic characterisation and diversity of the fluvial systems of the Gangetic plains. Gemorphology, 70: pp 207-225.
9. Aslan, A., Autin, W.J., Blum, M.D., 2005. Causes of river avulsion: insights from the Late Holocene avulsion history of the Mississippi River, U.S.A. Journal of Sedimentary Research 75, pp 648–662
10. Jain, V., Sinha, R. 2004. Fluvial dynamics of an anabranching river system in Himalayan foreland basin, Baghmati river, north Bihar plains, India, Geomorphology, 60, pp 147-170.
11. Sinha, R., Das, S., Dikshit, O., 2002. GIS-assisted mapping of catchment-scale erosion and sediment sources in Alaknanda valley, Garhwal Himalaya, India, Zeitschrift fur Geomorphologie (Annals of Geomorphology), 46/2 (June), pp 145-165.
12. Törnqvist, T.E., Bridge, J.S., 2002. Spatial variation of overbank aggradation rate and its influence on avulsion frequency. Sedimentology 49, pp 891–905.
13. Mohrig, D., Heller, P.L., Paola, C., Lyons, W.J., 2000. Interpreting avulsion process from ancient alluvial sequences: Guadalope-Matarranya system (northern Spain) and Wasatch Formation (western Colorado). Bulletin of the Geological Society of America 112, pp 1787–1803

14. Jones, L.S., and Schumm, S. A., 1999. Causes of avulsion: an overview. In Fluvial Sedimentology VI (eds Smith, N. D. and Rogers), Spl. Pub. Int. Ass. Sedimentol., vol. 28, pp 171–178.
15. Allen, J.R.L., 1965; citied in Jones, L.S., and Schumm, S. A., Causes of avulsion: an overview.in Fluvial Sedimentology VI (eds Smith, N. D. and Rogers), Spl. Pub. Int. Ass.Sedimentol., (1999), vol. 28, pp 171–178
16. Jones, L.S., Harper, J., 1998; citied in Jones, L.S., and Schumm, S. A., Causes of avulsion: an overview. In Fluvial Sedimentology VI (eds Smith, N. D. and Rogers), Spl. Pub. Int. Ass. Sedimentol., (1999), vol. 28, pp 171–178.
17. Siddique, M.Z., Jess, W. Everett and Baxter, E. Vieux., 1996. Landfill siting using Geographic Information System: A Demonstration. Journal of Environmental Engineering. ASCE, 122(6): pp 515-523.
18. Hooke, J.M., 1995. Processes of channel planform change on meandering channels in the UK. In: A.M. Gurnell and G.E. Petts (Eds.), Changing River Channels, John Wiley & Sons, Chichester, pp 87-116.
19. Mackey, S.D., Bridge, J.S., 1995. Three-dimensional model of alluvial stratigraphy: theory and application. Journal of Sedimentary Research B65 (1), pp 7–31.
20. Pizzuto, J. E., 1987; citied in Bryant, M., Falk, P., Paola, C., 1995. Experimental study of avulsion frequency and rate of deposition. Geology 23, pp 365–368.
21. Agarwal, R.P., Bhoj, R., 1992. Evolution of Kosi river fan, India: Structural implication and geomorphic significance. International Journal on Remote Sensing, 13(10), pp 1891-1901.
22. Friend, P. F. and Sinha, R. (1993). Braiding and Meandering Parameters, in J. L. Best and C. S. Bristow (ed.) 'Braided Rivers', Geological Society of London Special Publication, 75, pp 105-111.
23. Richards, K., Chandra, S., Friend, P., 1993. Avulsive channel systems: Characteristics and examples. In: "Braided Rivers", J. L. Best, C. S. Bristow (ESds.). Geological Society Special Publication, 75, pp 195-203.
24. Germanoski, D., and Schumm, S. A., 1993. Changes in Braided River Morphology Resulting from Aggradation and Degradation, The Journal of Geology, Vol. 101(4), pp. 451-466
25. Wells, N. A. and Dorr, J. A., Shifting of the Kosi River, northern India. Geology, 1987, **15**, pp 204–207
26. Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw-Hill, New York, pp 20-25.
27. Arogyaswamy, R.N.P., 1971. Some geological factors influencing the behaviour of the Kosi. Records Geological Survey India, 96, pp 42-52