The Geographical Journal of Nepal
Vol. 13: 107-142, 2020
Doi: http://doi.org/10.3126/gjn.v13i0.28155
Central Department of Geography,
Tribhuvan University, Kathmandu, Nepal

Basin characteristics, river morphology, and process in the Chure-Terai landscape: A case study of the Bakraha river, East Nepal

Motilal Ghimire
Central Department of Geography, Tribhuvan University
Email: motighimire@gmail.com
Received: 20 December 2019; Accepted: 15 January 2020; Published: March 2020

Abstract

The study aims to illustrate the basin characteristics, river morphology and river processes in the Chure- terai Landscape. The basin and morphological variables used in the study were derived from the satellite imageries available on Google earth, digital elevation models, and relevant maps. The cross-section survey and hydrometric data, incorporated in the study were obtained from the secondary sources, reports, and documents. The Bakraha River basin is underlain by the rocks of the Siwalik group in the south. The rocks are highly deformed and fractured and have the steep and variable slope and are subject to strong seismic shaking. The network of drainage is dense, with the predominance of colluvial streams that receive sediments from slope failure and erosion. The steep profile of the river demonstrates the ability to transport a huge sediment load during a high flood. The climatic regime and daily annual extreme rainfall between 100-300mm can initiate shallow landslides to large and deep-seated landslides. Landslides very large, small to shallow types are quite numerous, which indicates terrain highly susceptible to slope failure and erosion. The forest cover is above 84% but largely has been degraded and interspersed by agricultural patches and settlements with population dependent on agriculture and livestock. The lower catchment has dominant agricultural land use. The role of riparian vegetation for bank protection and flood control is limited. In the hilly areas, the river reaches are mainly sinuous to straight controlled by bedrock and in Terai, the reaches are straight, wandering to meandering towards the south. River slope is very steep, up to 15.2% in hills and mild in the meandering reaches in Terai decreasing to 0.1%. In the straight reaches, sediments are mainly boulders, gravels, bedrocks and sands in the hill, while in meandering reaches in Terai, sediments are sand and silt. The discharge varies 200-

734 cusec from upstream (close to outlet) to downstream, (16.5 km away). The estimated sediment load transport during extreme flood events highly varies. Potential sediment load decreases from straight to meandering reaches, with some fluctuations in certain locations, owing to change in local morphological conditions. Bank erosion, bend scour, confluence scour, and protrusion scours, and avulsions are the river processes, which provide a source of sediments to the river. Change in planform and cross-section view of the river morphology indicate the river is unstable and dynamic due to the frequent shifts between accretion to erosion processes.

Keywords: *Basin characteristics, river morphology, river process, Chure hills, Terai*

Introduction

Basin and morphologic characteristics of the river are the intricate components of the river system. The geology, tectonics, topography, climate, land use, and human activity determine the geomorphic and hydrologic characteristics of the basin in the hill catchments (Horton, 1932). The basin characteristics, in turn, influences the hydrological response and river morphology downstream. The river morphology basically determined by the valley topography and the characteristics of the river basin (geology, soil, mechanical properties). The shape, pattern of the rivers is also the result of a long history of changes in climate, in tectonic activities, in land use, in human interference. Investigating river morphology and its linkages to catchment's physical condition provide a holistic understanding of the geomorphology and hydrology of the river system, high land low land and linkages observed in terms of channel morphology, flood, channel stability, and riverine ecology (Van Appledorn, Baker and Miller, 2019). Hence the study of the fluvial system both at the basin and reach scale will help to understand the river processes and prescribe the counter measures to address issues of soil conservation and watershed management, flood, bank erosion, and channel avulsion problem. These hydrologic phenomena are themselves the outcome of multi-scalar interactions among climate, landscape physiography, river-valley morphology, and local channel hydraulics. Numerous studies carried out in the past illuminates the relation between basin and morphologic characteristics of the river system and have provided a plethora of scientific knowledge and approach that can be applied for soil erosion control, watershed and river ecology management, river hazard and disaster management projects (Hey, Newson and Thorne, 1997; Horton, 1932; Kline et al., 2003; Montgomery and Buffington, 1997; Richards, 1982; Rosgen, 1996; Van Appledorn et al., 2019; Rajaguru et al., 1995). In Nepal, where the rivers basins are developed in complex geology and active tectonics modified by the climate-driven denudation processes, constitute high relief, dissected and steep topography. In such conditions, weathering and erosion processes are intense and active which contributes to high sediment yield in the rivers and thereby has a profound impact on the morphology of the river and related disasters downstream. There is extreme variability in discharge and sediment load (Kale, 2002). Earthquakes and landslides also have a great impact on these rivers from time to time. Few studies on the river morphology of Himalayan origin river exist (Gupta, Atkinson and Carling, 2013; Kale, 2002; Khanal, Shrestha and Ghimire, 2007; Shrestha, Tamrakar and Miyazaki, 2008; Shrestha and Tamrakar, 2012; Sinha et al., 2005; Thakur et al., 2014; Carson, 1985), many of them in Nepal were done from the hazard perspective and only a few have given a particular attention on the river morphology. Few notable studies on the landscape and process of upper catchment in Siwaliks exist (Dhital, Khanal and Thapa, 1993; Ghimire, 2001; Ghimire, 2011; Ghimire, 2014; Shrestha and Tamrakar, 2012; Ghimire and Higaki, 2015; Khanal, 1989) that provide illuminating findings. Hence, in this context an attempt is made to investigate the basin and morphologic features of the Bakraha river, which origins in the southern flanks of the Mahabharata range and also drains the Siwalik region in eastern Nepal.

Conceptual framework

The river system is an open system, which governs by various factors controlling and operating at upstream and downstream (Schumm, 1981). Channel morphology, a major component of a river system is a result of these factors. These factors can be divided into those that are enforced on the watershed (i.e., independent) and those that adjust to the enforced conditions (i.e., dependent) (Hogan and Luzi, 2010). The independent landscape factors controlling channel morphology are geology (including tectonics and structure), climate, and human (Figure 1). The geology of mountain catchments is determined by processes acting at the landscape scale, and can include volcanism, tectonics, and, to a lesser extent, surficial processes weathering, erosion, mass movement. Inside watershed, these processes control the distribution, structure, and type of bedrock, surficial materials, and topography (Montgomery, 1999). Climate is an independent factor at the landscape scale, as it is driven by atmospheric circulation patterns and locally modified by topography and in interaction with geology influence soil and vegetation. Human modification of the landscape can also significantly change watershed conditions.

The geologic, climatic, and human conditions which are enforced on watershed determine the dependent landscape variables of sediment supply, stream discharge, and bed and bank material (Buffington and Montgomery, 2013; Montgomery and Buffington, 1993; Schumm, 1981). These dependent landscape variables in combine determine the characteristics of the channel. The channel responds to changes in these variables by adjustments in one or many of the dependent channel variables. Time is another important independent variables since the origin of the landscape.

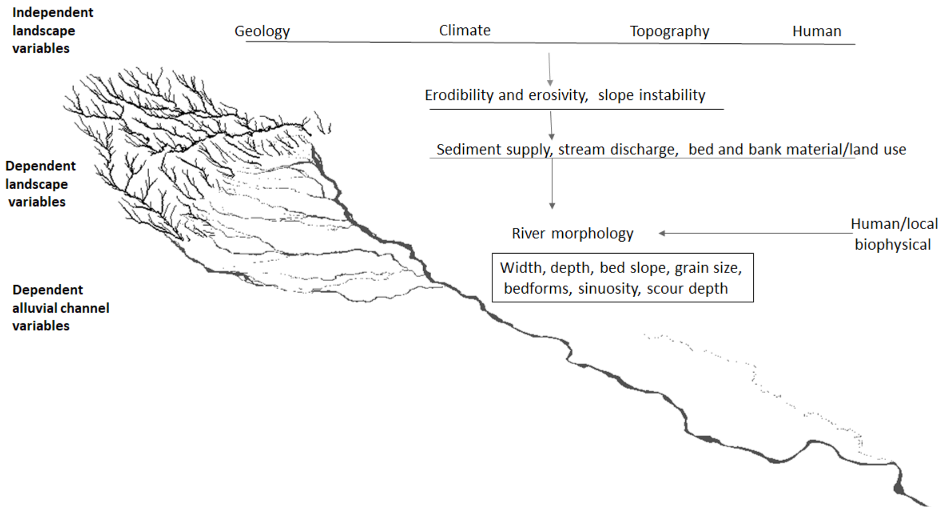


Figure 1: Conceptual model showing the relation between basin characteristics and river morphology (eg. Bakraha river) modified after (Hogan and Luzi, 2010) and (Montgomery and Buffington, 1993).

Methodology

Evaluation of the river basin and morphologic characteristics requires parameters pertaining to 1. basin geomorphology and morphometry: drainage network and density, basin shape, slope, hypsometric integral, terrain ruggedness; 2. Geology; 3. land use, and geomorphic processes. Similarly, morphology at reach scale includes channel pattern, shapes (Plan and cross-sectional), and slope, hydrology and sediment characteristics. The application of GIS and remote sensing in combination with field surveys are inevitable tools for generating the terrain parameters (including morphometric parameters) and the morphologic characteristics of the river. These geospatial tools have been widely used in the study of both river basin and morphology at reach scale (Gupta et al., 2013; Khanal et al., 2007; Sinha et al., 2014; Uddin, Shrestha and Alam, 2011; Van Appledorn et al., 2019). This study has also used geospatial data derived from the satellite imageries, Digital Elevation Model and Topographic and Geological Maps in a GIS framework.

The approach for the morphological assessment involves steps such as 1. Analysis of basin characteristics including geology, morphometry, and land use; 2. Establishing the geomorphic and morphologic characteristics of the bedrock and alluvial reaches of the river; 3. Analyzing the river processes and their implications to flood, bank erosion and avulsion; and 4. Analyzing the morphological changes, as well as aggradation and degradations of the Bakraha River.

The main datasets were topography, drainage, geology, river morphology and the hydrometric data i.e., water level, discharge, velocities, and depth provided by Matt McDonald and Total Management Services Pvt. Ltd (TMS) (2018). These data obtained or derived from the satellite imageries, DEM topographic and geological and other thematic maps. Summary of the data used for examining basin and morphological characterizes, their availability and source are presented in Table 1.

Table 1: Data type, sources and methods and techniques of analysis

Data	**Parameters / variables**	**Sources**	**Method and technique of analysis**
Geology	Rock type and structure	Geological map prepared by DMG, 1:250,000	Map interpretation
Morphometry	Drainage (network, order, drainage density, slope, hypsometric curve, sediment	5 m resolution DEM, ALOS 2007	Hydrological tools using ArcGIS
Geomorphologic map	Topography, river morphology, sediment characteristics	(Google Earth and Landsat, 2018), Contour Digital Layer (Survey Department, 2002) Field Survey, 2018	Image interpretation and DEM analysis
River morphology and hydrometric data	Riverbed of 2008, 2013 and 2018, channel pattern aggradations, degradation, channel avulsion, abandonment	Google Earth image, Landsat, 2018, Cross-section survey, 2014 (Lahmeyer International, TMS) and 2018 (Mott Macdonald, 2018).	Time-series image, cross-section survey analysis
Landslides	Type	Google Earth image, Landsat, 2018	Visual interpretations
Sediment material and transport	Median grain size, hydraulic variables at selected cross-sections	From literature and existing studies in Nepal, HEC-RAS hydrodynamic model (Mott MacDonald, TMS, 2018).	Hydrodynamic model (Mott MacDonald, TMS 2018).
Land Use Map	Land use category	Google Earth image 2018, Chure-Terai Madhesh Conservation and Management, Master Plan	Image interpretation and update of land cover 2015.

Study Area

The catchment of the Bakraha river basin lies between latitude 26° 22' 49.75" – 26° 51' 50.44" N), and longitude 87° 32' 24.27 - 87° 41' 24.06 E (Figure 2). The basin extends from the southern slopes of the Mahabharata range, followed by Chure Hills (Siwalik Hills, also known as sub-Himalayan hills) in the north and Indogantegic plain up to the India-Nepal border in the south. The Bakraha River is the main water course, which is joined by the key tributaries, Soltikhola and Sunjhoda khola. The catchment covers an area of 437 km^2 (Figure 2). The Bakraha river system shares the district of Ilam and Jhapa in the east and Morang in the west, both in Province No. 1. The basin has 357 settlements distributed over rural and urban municipalities with a population of about 165,435 and 37,335 households (Nepal, 2012). Madhumalla, Urlabari, Pathari, Hasandaha, and Govindapur are the major towns and villages located in this basin.

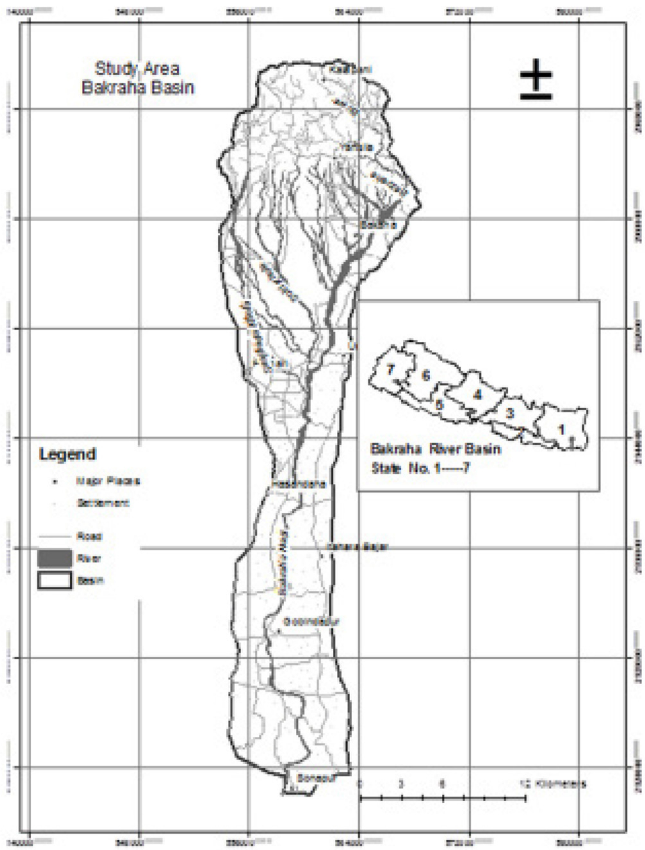


Figure 2: The Bakraha river basin location map

Basin Characteristics

Geology, structure, and seismicity

The Bakraha basin is developed in the metamorphic rocks of the Lesser Himalaya and sedimentary rocks of the Siwaliks of the Neogene age. The Siwalik hill is the youngest parallel mountain chain in the Himalayan orogeny (Gansser, 1964; Dhital, 2015; DMG, 2007) in the north, and made of Quaternary deposits in the south. The Siwalik Ranges are formed from the most tectonically active Himalayan belts, which has resulted in active deformation, dislocation, and uplift of rocks along this belt, giving rise to a complex geologic structure and unstable and erodible landscape (Lavé and Avouac, 2001, Nakata, 1989).

Based on lithological characteristics, three broad categories of the Siwalik rocks, i.e., the quaternary and recent despoisits, the Upper Siwaliks (US), Middle Siwaliks (MS) and the Lower Siwaliks (LS) and Lesser Himalaya are found (DMG, 2007) (Figure 3).

The quaternary consists of recent and post-Pleistocene alluvial deposits brought by the rivers draining the upper catchments of Chure hills and other Himalayan belts. These form a piedmont (foothill parts made of alluvial fans) adjacent to the Chure hills and a flood plain towards the south comprising the sand and silt deposits (Dhital 2015, LRMP 1986).

The US is composed of conglomerates, sandstone and few mudstone beds. This unit is divided into a lower and upper member. The lower member is represented by well-sorted, pebble- and cobble-conglomerate associated with reddish-brown sandstone and dark grey mudstone. The clasts of the conglomerate are rounded to sub-rounded and show a slight increase in size toward the younger succession. The upper member is characterized by an unsorted loose, boulder-sized conglomerate with grey sandstone and mudstone. This unit typically contains the Siwaliks sandstone boulders. The US rocks are highly erodible and susceptible to gully erosion.

The MS is comprised of fine to very coarse-grained sand as well as pebbly sandstone, which alternate with mudstone. The proportion of sandstone beds is higher than that of the mudstone. The proportion and coarseness of the sandstone increase towards the upper formation of the MS. The lower member (MS1) is comprised of fine to coarse-grained sandstone interbedded with mudstone. The upper member of the MS (MS2) contains pebbly sandstone inter-bedded with mudstones (DMG, 2007).

The LS consists of an inter-bedding of mudstone and sandstone. The mudstone is variegated dark grey in color. The sandstones are fine to coarse-grained and are thin to thickly bedded. The proportion of mudstone is greater than that of sandstone in aggregate. The LS occupies the lower section of the upper catchment.

The Lesser Himalayan rocks in the study area consist of the metamorphic rocks of Dubidanda Formation (DbD) and Kathmandu Crystalline (KC). DbD is represented by green and grey phyllites, quartzites and siliceous dolomites. KC is represented by biotite schist and gneisses. The rocks are massive but with open cracks and joints. The rocks are moderately weathered. Lesser Himalaya occupies about 49 % of the upper catchment area.

The Siwaliks is delineated as in Figure from alluvial deposits of the Terai plain by the Main Frontal Thrust (MFT) in the south. It is the most active frontal fault where the LS is thrust over the alluvium in the piedmont zone (Lavé and Avouac, 2001, Nakata, 1989). Similarly, an imbricate thrust of Main Churiya Thrust runs South East-North West in the northern part of the hill catchment. Both thrusts dip 25°–30° North East to North East. Likewise, the Siwaliks is traversed in ~NS direction by the four minor faults, with an average interval of 2 km. Numerous folds exist in the eastern part of the upper catchment. Bedrocks generally dip towards North East with an amount of 30-70^{o} (DMG, 2007). Similarly, southern section of the Lesser Himalaya is bounded by an imbricate thrust of Main Central Thrust (MCT) and bedrocks dip toward North West with an amount of 40-70^{o} (DMG, 2007). Due to the presence of active faults and major thrusts, neo-tectonic movements are frequent. The exposed bedrocks are highly deformed and fractured and consist intricate network of 2-3 joints set.

The seismic hazard measured in terms of Peak Ground Acceleration (PGA), i.e., maximum ground acceleration that occurred during earthquake shaking at a location, indicates the high earthquake hazard in the Bakraha basin. The contours of Peak Ground Acceleration (PGA), expressed in Gal (1 Gal equals to 1cm/s^2; 1 g (acceleration of gravity) =981 Gal), show PGA between 100-150 gal, which implies the catchment is subjected to violent or extreme shaking; higher intensity in the higher relief (http://seismonepal.gov.np/publications).

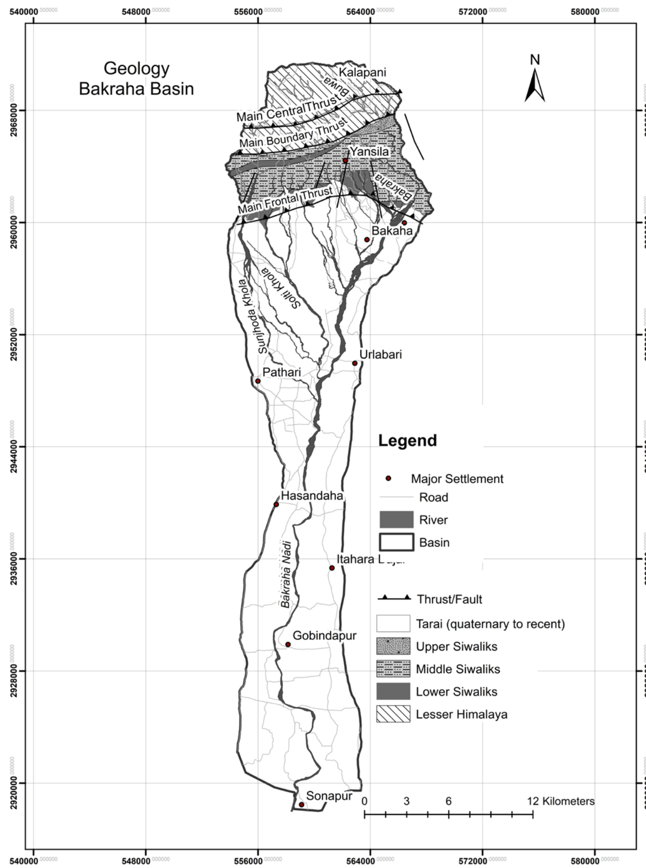


Figure 3: Geology and structure in Bakraha river basin (DMG, 2007)

Relief and slope of the hill catchment

The relief of the Bakraha River basin in mountain ranges between 230 and 2,410masl within the areal distance of 9 km. The average relief is 992masl. The highest point lies in the Mahabharata range.

The slope gradient has been recognized as the proxy indicator of slope instability in the Siwaliks (Ghimire, 2011). The average slope of the hill catchment is 28.8^{o}; such a steep slope indicates a high potential for erosion in a fragile geological setting. The slope of the hill catchment is predominantly steep, i.e., about 65.3% of the area of the total hill catchment has a slope greater than 25^{o} (Figure 4). Gentle slopes (<5^{o}) occupy 80% of the total catchment area (both hill and Bhabar-Terai). Cultivation above 25^{o} is not desirable due to the unstable slopes of Chure hills. The sub-catchment wise statistics of slope gradient is presented in Table 2.

Table 2: Slope gradient in the Bakraha river basin

Sub Basins	Slope gradient (% of total area)						Weighted average slope	Total area (km^2)
	<5	5-15	15-25	25-30	30-45	>45		
Hill	3.9	9.8	21.0	15.7	43.2	6.5	28.8±15	106.4
Bhabar, Terai	100	0	0	0	0	0	-	330.2

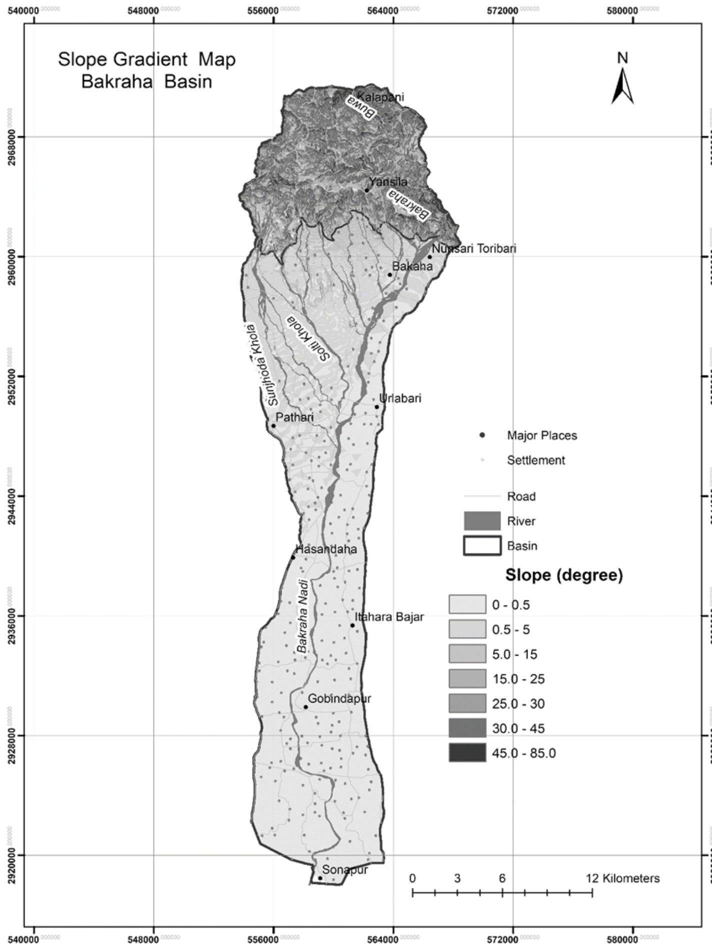


Figure 4: Slope of the Bakraha River basin

Drainage network and channel characteristics

The control drainage network and channel characteristics of the hill catchment have significant control on the downstream chararistics of the river morphology in low plain lands. The control of the bed structure, faults and system of joints in drainage development of the hill catchment is apparent, which is evidenced by trellis (stream orient in parallel) to rectangular drainage pattern (Figure 5). The drainage density is 5.4 km/km^2 for the whole upper catchment. The drainage density is very high to indicate the ruggedness and high erosion potential.

Considering the Strahler's (1964) stream order classification scheme, the number of streams by order and the bifurcation ratio is presented in Table 3. The upper catchment (hilly areas) consists drainage network (Figure) of the sixth order stream with a total of 1,997 numbers of streams with a total length of 578 km. The slope of an average stream by order decreases (r^2=0.96), which implies lower-order stream are steeper and more erosive. The average stream segment has a slope of 39%, which indicates that the upper basin streams are a colluvial type as well as a direct receiver of the sediments from slope failure and erosion. Highly steep slopes of the stream in the Mahabharata range have contributed to a high stream gradient. They also have enormous enough capability to carry a large number of sediments, including massive boulders during rainstorms in a monsoon. Lower order stream with slope > 15^o is developed on the joints of bedrock, which act as a supplier of sediment.

Table 3: Drainage network characteristics in Bakraha basin in hill catchment (Siwalik)

Stream order	Numbers of stream	Total length (km)	Mean slope (percent)	Bifurcation ratio	Slope ratio
1	1,573	293.7	42.4	-	-
2	319	131.2	29.6	4.9	1.4
3	87	92.2	19.3	3.7	1.5
4	14	27.5	15.5	6.2	1.2
5	3	28.6	7.8	4.7	2.0
6	1	4.7	3.8	3.0	2.1
Basin	1,997	577.9	39	4 (Average)	

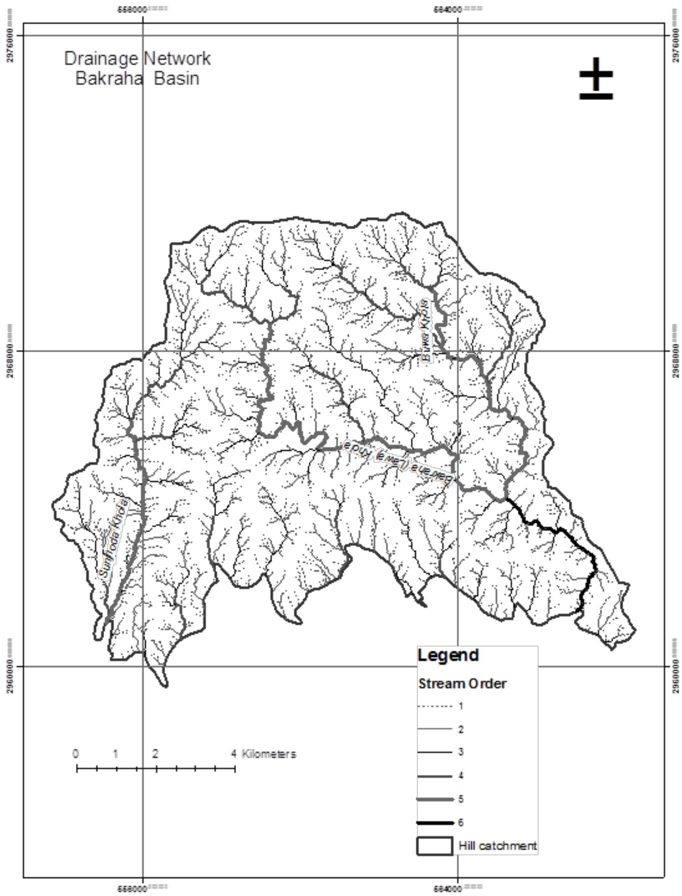


Figure 5: Drainage network of the Bakraha river basin in catchment in Siwalik hills (derived from DEM)

Land use: Geomorphic implication

The basin has two distinct characteristic land use patterns in the upper and in the lower catchment (Figure 6, and Table 4). The land use in the upper catchment is predominantly non-agricultural with forest, shrub, and grass, covering more than 84% of the total area of the upper catchment. Human disturbance in terms of agriculture appears low in the upper catchment. But numerous isolated scattered patches of cultivated land including settlement has degraded the forest ecology. Agriculture and livestock are the main activities. The socio-economic pressure on forest land for timber, fuelwood, fodder, litter, and grazing is evident for the degradation of forest and erosional scars around in the upper catchment.

Agriculture is the predominant land use in the Bhabar-Terai catchment which comprises 72.7% of the total area, whereas forest, shrub and grass cover account only 19%. The northwest part of the lower catchment is covered by subtropical sal dominated forest. The accretion or annual flood-prone areas along the river, limited riverine vegetation with grass and trees are found, i.e. at 2 km intermittent stretches.

Similarly, in the middle reach of the Bhabar-Terai catchment, the riverine forest, with patches of trees such as bamboo, shisoo, eucalyptus and fodder are found along the 5 km distance at several intermittent sections. This riverine forest has been developed or restored by the local people, as observed by the project, wherever land was available to check bank erosion and flood markings. In the remaining length, the river banks are exposed either to cultivated land or settlements, except for barren areas in channel scroll or migration areas.

Much of the agricultural land in the Bakraha basin lies in the flood plain zone, which lies south to the piedmont belt "*Bhabar*". *Bhabar* is the region south of the Siwalik Hills. It is the alluvial apron of sediments washed down from the Siwaliks along the northern edge of the Indo-Gangetic Plain. Here, forest virtually does not exist along the bank corridor, but some presence of grassland. Hence, flood and bank erosion risks, which can lead to loss of land and damage to the properties, are high.

Table 4: Land use statistics of the Bakraha river basin

Catchment	Area (km^2)	Land use (% of area)					
		Forest	Agriculture	Barren land/ grass land	Shrub land	Built-up	River bed
Upper	106.4	80.70	11.33	2.91	3.28	0.02	1.76
Lower	330.2	16.79	70.47	3.88	0.91	2.26	5.70

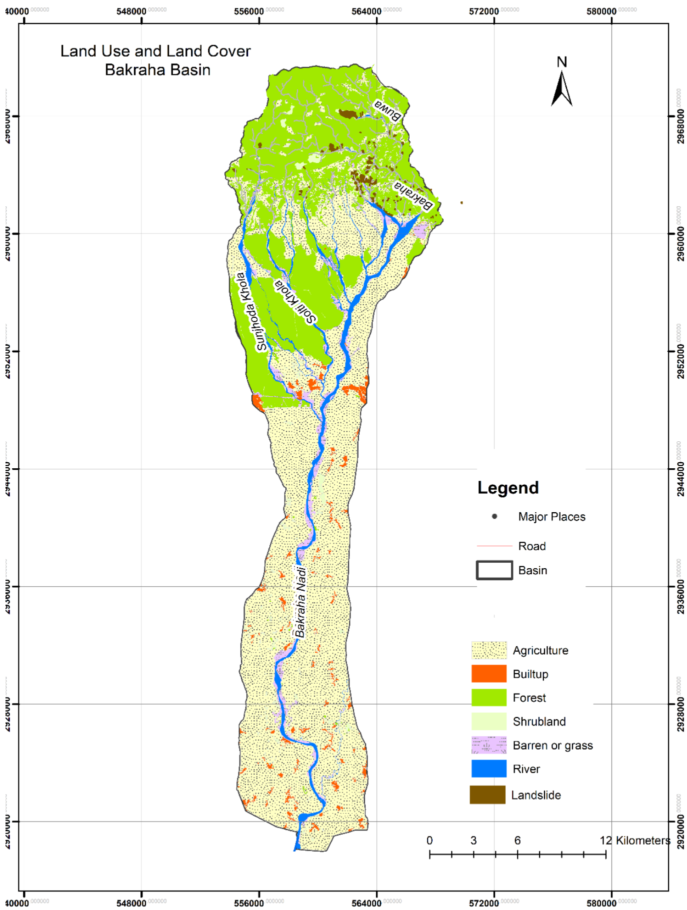


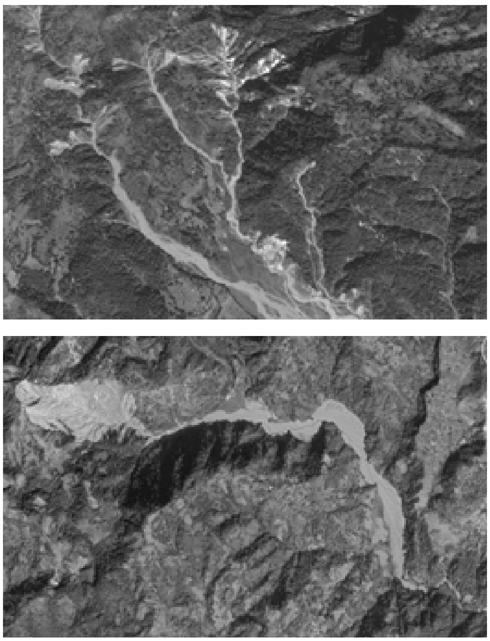
Figure 6: Land use map of the Bakraha river basin
Source: Chure Terai Madhes Protection and Management Master Plan (2016) updated and modified from 2018 imagery.

Landslides and sediments

Owing to the steep topography, active tectonic and complicated geology, the upper catchments have high numbers of large to small and deep-seated, swallow landslides, and debris flows scars. In some catchments, the landslide are spatially large and frequent (1-33 ha) and few large landslides have infilled the valleys. These landslides have contributed huge sediment loads to the rivers and streams at every monsoon. Due to the steep gradient and confined channel, and very limited flood plain in the upstream areas, a sediment load of fine to large size boulders and cobbles are transported through the narrow valleys and deposited onto riverbeds in the foothills and in Terai.

Based on conventionally accepted morphological characteristics, as evident from Google Earth imagery of 2017 and 2019, the landslides in the upper catchment of the Bakraha river can be classified as rockfall, slides, debris flow, complex failures, and swallow scar type failures. Rockfall and slides including the swallow scar failures are widespread in the steep slopes and escarpments. Planer and wedge failures are also expected in the dip (slopes parallel to the direction of bedrock inclination) as well as on the orthoclinal slopes (slopes orthogonal to the direction of the bedrock inclination). Rotation failures are commonly noticed on the gentler and deeply weathered slopes.

Numerous slides of complex types are seen on the stream and gully head, from where the hillslope materials are released into the colluvial streams and further transported downstream. Numerous failures in the foot slopes, due to river undercut, were observed in the Google Earth image and confirmed during the field visit, which indicates a river incision process (Figure 6).



Source: Google Earth 2019

Figure 7: Landslides in the Bakraha river basin; **left**: landslides in the tributary headwaters of Bakraha and landslide origin sediments in the riverbed; **right:** a huge landslide to the tributaries with an estimated area of 33 ha which has led to valley infillings up to 3.53 km and highly degraded surrounding landscape due to erosion and slope failures.

Climate and hydrology: Geomorophic implications

The climate of the basin by its temperature and rainfall characteristics is largely humid subtropical climate (Cwa) according to Koppen and Geiger classification scheme. The mean monthly temperature recorded at nearby station Damak is between 16-28^{o}C. May and June are the hottest months, i.e. 33-34^{o}C, while Dec and Jan, the coldest months, i.e., 11-12^{o}C. The average annual rainfall is 2618 mm, with around 84% rainfall between June-September. The rainfall varies by 761 mm between the driest and wettest month. However, with altitude (max 2400 masl), the temperature decreases and rainfall increases and in cold winter rain in the form of snowfall in altitude above 1800 m is likey. The climatic regime favors intense weathering, a precondition for erosion. However, due to high rainfall erosivity and the erodibility of rocks, steep slopes, the deep weathered layers with mature soil are generally not well developed in the hillslopes. From the erosion and sediment delivery point of view, the historical daily annual extreme rainfall data is important, as intense rainfall acts as a threshold for initiating landslides, debris flow and gully erosion. Figure 8 describes that extreme rainfall events have a recurrence interval for 100 mm in less than 2 years, 200 mm in 3 years, and 250 mm in 6 years. The extreme rainfall events can generate shallow to widespread landslides including very large and deep-seated types. This implies sediment production potential is very high in the hillslopes.

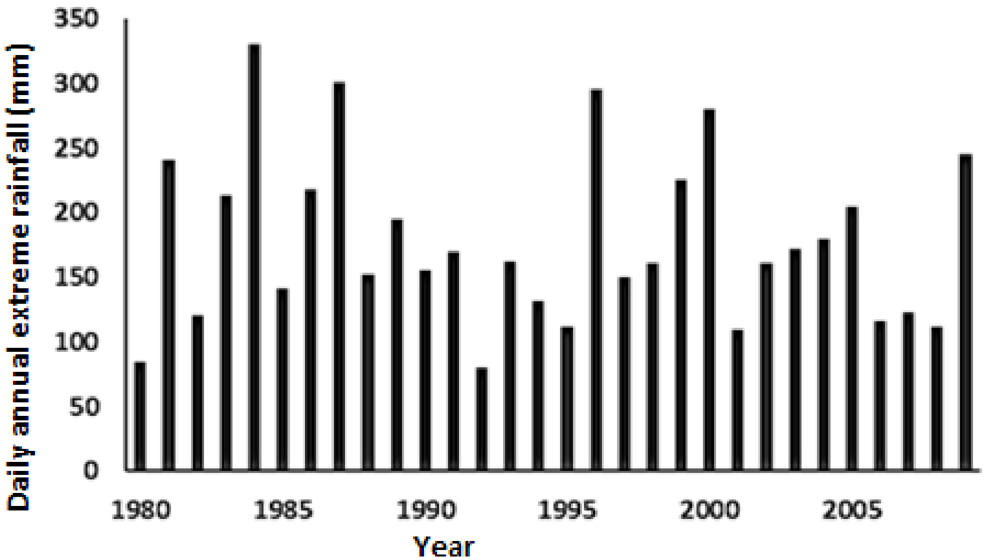


Figure 8: Annual extreme rainfall of Damak (5.7 km eastward from the Bakraha River basin).

Source: DHM (1980-2010)

Weathering of mudstone and the disintegration of the sandstone through joints and crack networks may have caused large-scale bedrock slumps. Highly weathered rocks also contribute to sediment load through gully erosion and debris torrents.

Apart from the landslides, numerous erosion scars and exposed rocks and signs of land degradation are seen on slopes, which are either due to bare steep slopes or escarpments, or sites of overgrazing and deforestation ((Figure 6 and 7).

Geomorphologic units of the river basin

The Bakraha river and tributaries can broadly be classified into five geomorphic units based on topography, river morphology, geology, and sediments. These units are described below.

1. Chure hills: Bedrock, boulder, gravel, and sand zones

This zone is represented by the Chure hills underlain by sandstone and mudstone sequence of sedimentary rock (Figure 9). This zone contains a sixth-order drainage network, with a stronger gradient that receives and transports sediments obtained from landslides, debris flow and erosion on the hillslopes, which are highly weathered and fractured mudstone and sandstone beds.

A large proportion of bedload consisting of boulders (huge size, commonly 0.5 to 8 m^3), cobbles and gravels which characterize the riverbed. In many steep and confined channel sections, exposed and incised bedrock forms riverbed. In the headwater streams, a huge amount of colluvial (landslide material) sediments are found, which are angular to semi angular in shape. In the middle section of the Lawa khola (tributary river), a relatively wider and braided riverbed is observed, implying a sediment storage system. Uplifted terraces are near the outlet, which indicates former floodplain. Streams flow in a turbulent manner and are highly muddy and viscous during a rainstorm, which enables them to pick up and transport the huge size of boulders.

Landslides and erosion control are specific measures to check in order to mitigate flood and bank erosion problems, which is a challenge in naturally susceptible steep terrain. Lowering human disturbances like cultivation, grazing, and deforestation in the hill slope catchment are also recommended. Implementing expensive structural measures in this area from the viewpoint of cost-benefit is questionable. However, less expensive check dams across the gullies of degraded catchments as well as micro catchment management for erosion control through controlled grazing and promoting vegetation cover on the steep slopes may be investigated.

2. Upper Piedmont: Boulders gravels and sand zones

This zone comprises of the alluvial fan deposits, i.e., *Bhabar*, which consist of boulder, gravel, and sand in the foothills and the adjacent area (Figure 9). From the foothill, the size of the sediment decreases, gradually the proportion of boulders decreases, where sand and gravel become dominant. River beds are wide shallow and braided. The island bars are unstable and change shape at each flood. Multiple channels (at least more than one) are present in most cross-sections. Stable bars, which allow vegetation growth, are limited. The riverbanks have irregular shapes. The Bakraha river receives huge amount of sediments from the tributary streams (split into several channels) which join at the right bank. Several radially flowing recently abandoned and paleo-channels are spotted, which indicate high instability of the channel at this zone.

These rivers have a flashy discharge (Carson, 1985; LRMP, 1986), the sediment is transported during high water level and deposited at a low water level. Increase in bed level, a shift in channel course, split off the bank, and bank erosion are very common during heavy rainstorms. Abrupt reductions in channel gradient, common in alluvial fans, due to the presence of pools and riffles in abundance, and may trigger unexpected bed aggradations raising the channel bed above the surrounding terrain. This can cause an avulsion that sends the channel to another part of the fan (Legg and Olson, 2014; Matsuda, 2004) at every next storm event. Reworking of sediment deposits by erosion, and transporting and depositing them to downstream is a common phenomenon. These reaches have no distinct flood plain. If raised embankments are constructed on a channel running on such an instable zone, the river bed becomes higher than the surrounding land surface, which can cause channel avulsion (Germanoski and Schumm, 1993; Matsuda, 2004). Hence, site assessment should be done before constructing embankments or river training measures.

Since the rivers in this zone are unstable and morphology is dynamic, the alluvial fans formed have no well-defined limits. Cross basin flow is common as evidenced by the paleo, old channels or recently abandoned channels (Figure 10). The Bakraha river fan extends over 9.3 km downstream and has a slope of 0.7%. Similarly, the fans of the tributary rivers extend to 8 km with a slope of 2.0%. The sediments of this zone are delivered from both Lesser Himalaya and Siwaliks.

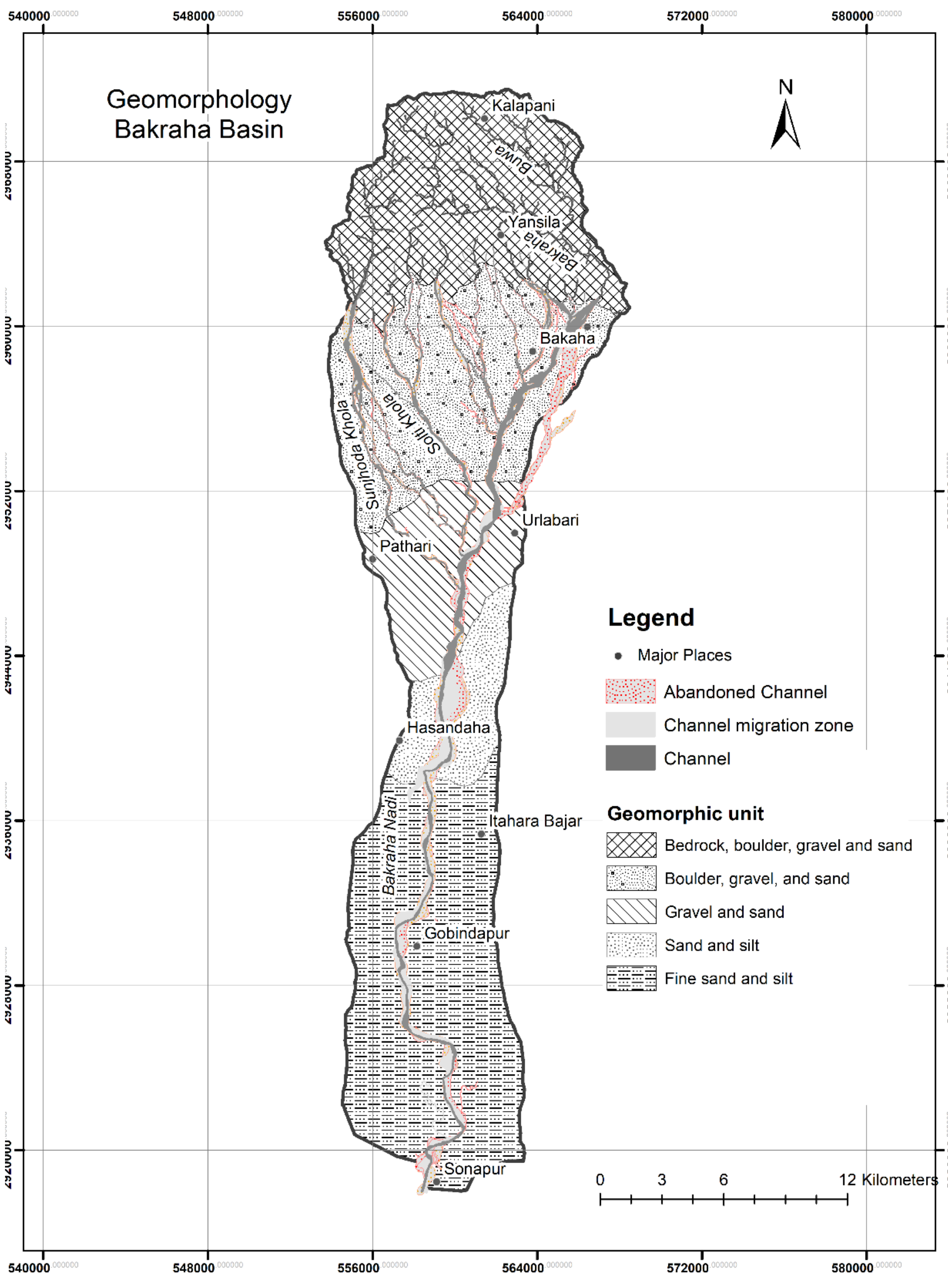


Figure 9: Geomorphic map of Bakraha basin

Note: The part of abandoned channel lying outside the basin, now is drained by Ratuwa khola in east.

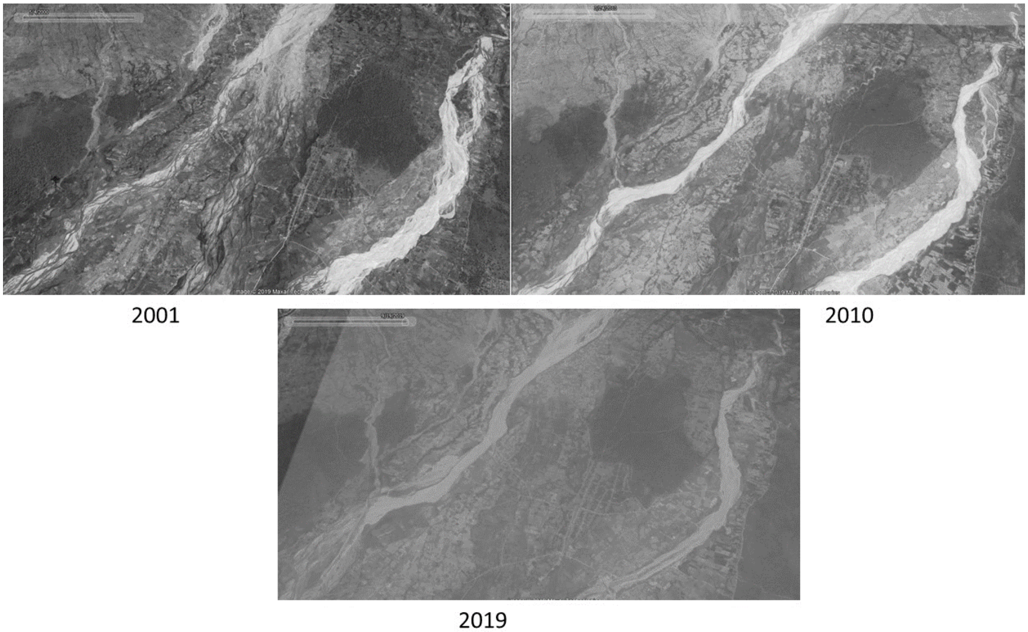


Figure 10: The Bakraha river in 2001 (bifurcated to two main channels at least since 1994, which had a confluence with the Mawa river in the east), 2010 and 2019 (diverted to single main channel by embankment)

3. Lower piedmont: Sand and gravel zone

Lower piedmont is a transitional zone of mixed load where boulders and cobbles are absent but is dominated by gravel and sand deposits (Figure 9). Channel is partially braided as well as meandering. Both alternate point bars, as well as island bars, are present. During the bankfull stage, the channel appears to be straight or sinuous. During low flow, alternate bars are so obvious that it would be better defined as meandering. Several signs of channel avulsions and lateral channel migration, which is evidenced by imprints of channel scrolls abandoned channels and times series overlay of the channel, have been noticed (Figure 10).

The width of the channel reach in this zone is wider compared to the sand and silt zone (zone 4 and 5), but narrower than zone 2.

4. Upper alluvial plain: Sand and silt zone

Upper alluvial plain, i.e., sand and silt zone is a distinct flood plain area, which characterizes the meander river zone (Figure 10). Rivers partly meander; pool formation is seen at the bends of channels. The flow of water changes direction at pools and strike against the opposite bank. Sinuosity Index is 1.16. This indicates a high amount of mixed load comprising of fine gravel, sand and silt. Channel migration by means of bank erosion and avulsion is a common river process.

Bank erosion is one of the major processes of sediment supply to the streams. An abrupt reduction of this supply through structural measures, for example, revetment of the banks, will produce an abrupt change in the sediment supply, and in the flow direction, which may mean that the river will seek to erode more sediment from its bed to compensate. Hence, a gradual reduction of sediment supply through the restoration of riparian vegetation in the channel migration zone and the periodically flood-prone area will keep up with the timescale of natural channel processes, which will lead to a gradual change in the channel behavior (Legg and Olson, 2014).

5. Lower alluvial plain: Fine sand and silt zone

This zone is flood plain with a very gentle slope, which consists of fine sand and silt. Morphology of the channel is unstable, more or less like zone 4. The channel is narrow and deep and has an irregular meandering pattern. Alternate bar deposits are observed. However, during high flows, the channel may appear to be wandering type, and during low flows, channels would appear meandering. An interesting fact is that paleo-channels with higher curvature of meandering (higher sinuosity) can be observed. This indicates a change in river morphology with a higher amount of sediments in recent times. The topography of this zone is made of channel scrolls, bank erosion, meander necks, and chute cut-offs in the distant past. Overbank flooding causing inundation, bank erosion, avulsion, and siltation is a common river process. However, the loss of agricultural land due to bank erosion at meander bends, and channel avulsion has a detrimental effect on the agricultural production and livelihood of the people.

Morphological characteristics

The reaches of the Bakraha river and its tributaries, the rivers can be divided into several reaches according to their morphological characteristics; (Figure 11, Table 5). Three types of river reaches have been defined based on sinuosity, where sinuosity, is the ratio of the curvilinear length along the curve with the straight distance between the endpoint of the reach, which will be considered straight or meandering depending on the sinuosity of the river course. Reaches with a sinuosity <1.1 at bankful flow condition will be considered straight, and those having sinuosity >1.5 will be considered meandering (Leopold and Wolman, 1957). Reaches between 1.1 and 1.5 are sinuous. Straight reaches with a steep slope, are usually short; long straight reaches seldom exist in nature. Meandering reaches, with relatively low gradient, consist of a series of turns with alternate curvatures connected at the points of inflection or by short straight crossings.

In each river, the reaches were classified considering sinuosity, sediment type, and hydraulic (depth, width, flow areas) characteristics. Detailed reach characteristics (Figure 11) for each river are discussed below.

The Bakraha River has been divided into five reaches (Table 5) . The reaches are mainly sinuous in the hills and straight or transitional sinuous (22.7 km), i.e., between straight and meandering reaches in (51 km). The sinuosity index for all five reaches is between 1.03 and 1.66. Although based on the sinuosity index the river is characterized as straight, the high width/depth ratio (>40) indicates the presence of braided channels (multiple channels within the bank), and transverse bars (Park, 1977). The channel slope is very steep (15.2%) for the Buwa khola tributary of Lawa (Bakraha) as compared to Bakraha (8.3%) in the upper (hill) reach. The slope is mild (1.03 to 0.10%) for the rest 50 km of the river length. In the first two reaches, sediments are mainly boulders, gravels and sands, while in the last three downstream reaches, sediments are sand and silt (and might contain a minor fraction of gravel).

The Solti River has been divided into three reaches (Table 5). The reaches are mainly straight or transitional sinuous (18.6 km) that is between straight and meandering reach. The sinuosity index for all four reaches is between 1.07 and 1.19. Based on the sinuosity index the river is characterized mainly as straight with the high width/depth ratio (>40). This indicates the presence of braided channels (multiple channels within the bank), and transverse bars (Park, 1977). Channel slope is very steep (25.4%) in the first 3 km of the upper (hilly) reach. The slope is moderately steep to mild (3.63 to 0.41%) for the rest of 15.5 km of river length. In the first two reaches, sediments are mainly boulders, gravels and sands, while in the last downstream reach, sediments are gravel and sand (and might contain silt also).

The Sunjhoda River has been divided into three reaches (Table 5). The reaches are mainly sinuous in the hill and straight or transitional sinuous, i.e. between straight and meandering reach in Terai. The sinuosity index for all four reaches is between 1.08 and 1.23. Although based on the sinuosity index the river is characterized mainly as straight, the high width/depth ratio (>40) indicates the presence of braided channels (multiple channels within the bank), and transverse bars (Park, 1977). Channel slope is very steep (14.4%) in the first 10.7 km of the upper (hill) reach. The slope is moderately steep to mild (3.63 to 0.41%) for the rest of 17.13 km of river length. In the first two reaches, sediments are mainly boulders, gravels, and sands, while in the last downstream reach, sediments are gravel and sand (and might contain silt also).

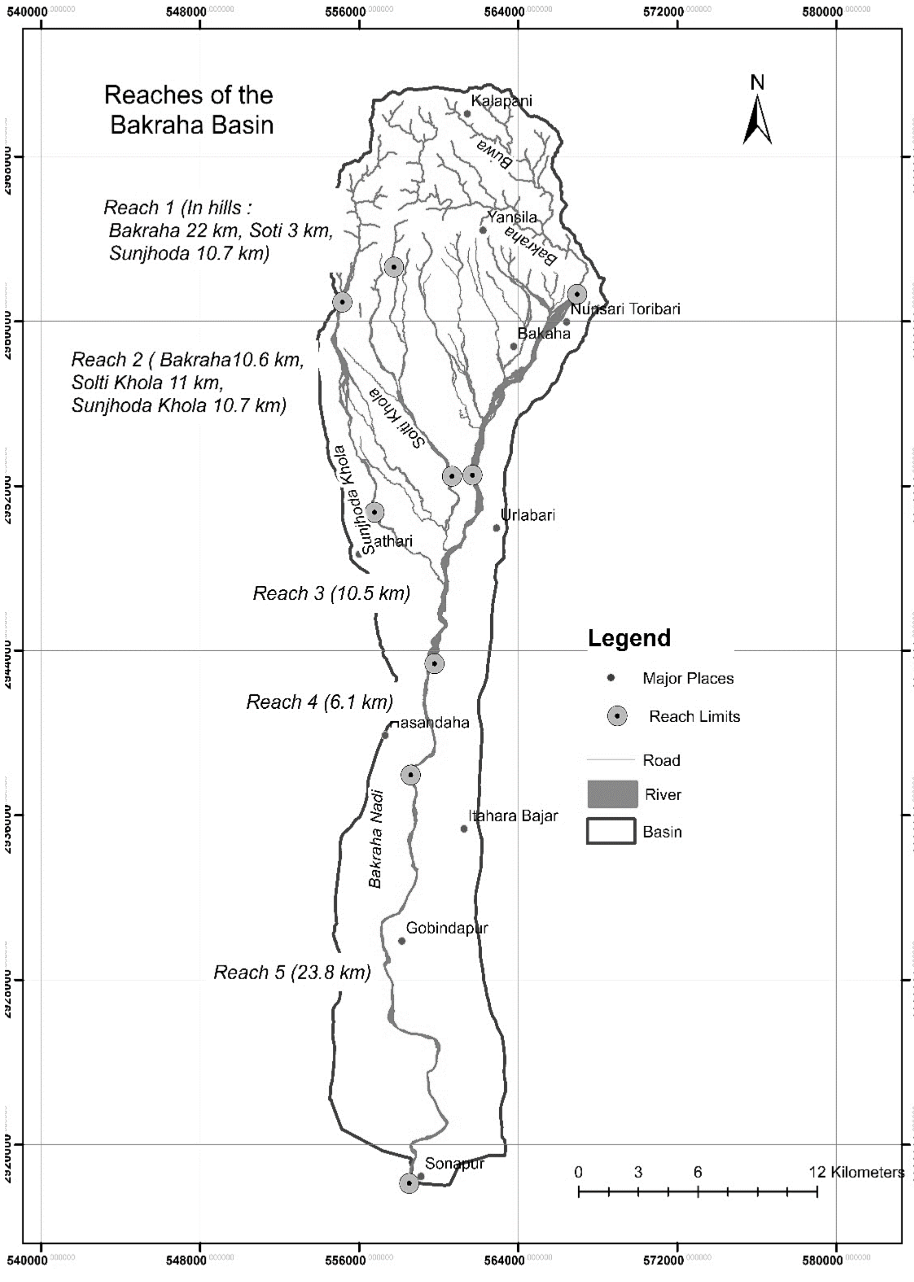


Figure 11: Reaches of the Bakraha River

Table 5: Reach-wise channel characteristics of Bakraha river system

River	Reach ID	Reach charac-teristics	Main channel length (km)	Sinuosity index	Slope %	Channel area (sq. m.)	Ave-rage width (m)	Max. depth at bank full discharge	Width depth ratio	Sediment characteristic
Bakraha River	1a	Hill (Buwa)	9.0	1.43	15.2	1,108,938	85	2.25	37.78	Sand, gravel and boulder, bedrock
	1b	Hill (Bakraha)	22.9	1.66	8.38	1,077,692	47.00	2.25	20.89	Sand, gravel and boulder, bedrock
	2	Fan	10.65	1.03	1.03	3,478,288	326.4	1.75	186.52	Sand, gravel, boulder
	3	Peripheral fan	10.5	1.09	0.28	2,605,614	247.6	2.5	99.05	Sand and gravel
	4	Flood plain, partially meander/ wandering	6.1	1.16	0.17	703,182	115.1	2.7	42.63	Sand and silt
	5	Flood plain, partially meander	23.8	1.25	0.10	2,666,300	112	3	37.32	Fine sand and silt
Solti Khola	1	Hill	3.06	1.07	25.44	70,260	23	2	11.48	Sand, gravel and boulder, bedrock
	2	Fan	11.03	1.10	3.63	918,849	83	1.25	66.63	Sand, gravel, boulder
	3	Peripheral fan	4.47	1.19	0.41	292,036	65.7	1.2	54.72	Sand and fine gravel
Sunjhoda Khola	1	Hill	10.7	1.23	14.41	408,006	38	2	19.00	Sand, gravel and boulder, bedrock
	2	Fan	11.33	1.08	2.07	1,593,663	140.6	1.25	112.47	Sand, gravel, boulder
	3	Peripheral fan	5.8	1.13	0.55	334,213	57.7	1.5	38.44	Sand and gravel

River discharge and sediment load capacity

Flow gauging stations are not available for recording river discharge. Hence the discharge calculated from 1D hydrodynamic model (Mott Macdonald, TMS 2018) for the return periods of 1 in 2, 5, 10, 25, and 50 years for the two locations, i.e., near outlet and 16.5km away from the outlet where the river receives all tributaries' water discharge is presented in Table 6. Historical daily annual extreme rainfall data (1980-2016) collected from the DHM was used to analyse extreme rainfall for the above return periods. This result was taken as input for the model (Mott Macdonald, TMS 2018) for estimating discharge for various return periods (Table 6). The discharge increases by more than three times in the downstream location from the upstream location, which implies the contribution to discharge from the tributaries is great. The sediment transport capacity was estimated by Mott Macdonald, TMS (2018) using Van Rijn (1984) sediment transport calculation method (Table 7). The author generated required hydraulic parameters for calculating sediment load capacity by running HEC-RAS 1d hydrodynamic model over topographic cross-sections surveyed in the field for the discharge of 50 year return period. The median sediment grain size of D_{10}, D_{50} and D_{90} of the riverbed was considered for predicting the sediment load transport. The table 7 shows that sediment load transport varies (10892-32 tons/day and fluctuates with locations in the downstream. Near the outlet 4.3 km downstream, if flood of 420m^3/s occurs, the sediment load is estimated to be 3717 tons per day, compared to 2287 tons per day at 10.3 km downstream at 598m^3/s discharge., which implies a large amount of sediment is settled upstream due to loss stream power, as determined by channel slope, velocity and discharge. Further 16.5 km downstream where the all tributaries contribute, the sediment load at 1538 m^3/s is 4.76 times greater than the last location. Hence changing hydraulic variables at various locations along the channel shows the morphology is very dynamic, which leads to fluctuation in sediment load capacity, influencing the process of aggradation and degradation accordingly. If the river water is unable to transfer the channel material then the same is deposited within the channel and channel height increases, aggradation occurs. Likewise, if the velocity or slope of the channel increases channel bed and bank is eroded, which causes degradation. This process changes the river morphology.

Table 6: River discharge at two locations

Return period	**Discharge [m^3/s]**	
[years]	**4.3 km from the river outlet from hill**	**16.5 km from outlet (where all Siwalik catchment tributaries meet)**
2yr	200.00	734.00
5yr	272.00	994.00
10yr	315.00	1155.00
25yr	376.00	1378.00
50yr	420.00	1538.00

Sources: Derived from Mott Macdonald, TMS (2018)

Table 7: Sediment load capacity along the Bakraha river

Distance from the outlet (km)	**Dsicharge (m^3/s)**	**Channel Slope (m/m)**	**Channel Velocity (m/s)**	**Depth (m)**	**Sediment transport load Tons/day**
(m)	(m^3/s)	(m/m)	(m/s)	(m)	tons/day
4.3	420	0.00511	2.85	1.68	3717
10.3	598	0.00198	1.34	2.83	2287
16.5	1538	0.0058	2.88	2.4	10892
23.0	1538	0.002138	1.98	2.41	1785
29.7	1538	0.001605	1.82	2.36	991
35.9	1538	0.000134	0.92	4.47	32
42.2	1538	0.002727	2.57	2.46	2942
48.5	1788	0.000946	1.07	2.07	256

Sources: Derived from Mott Macdonald, TMS (2018)

River erosion processes

Both planform and cross-sectional morphology of the Bakraha river is indicative of various river processes, which contributed to various forms of erosion and provide a source of sediments to the river. Notable river processes are bank erosion, bend erosion, confluence erosion, and deposition. These processes lead to channel migration, channel avulsion, bed level change, which changes in both planform as well as a cross-section of river morphology.

Bank erosion: The active floodplains in the Bakraha river and its catchment within the Terai region were noted as consisting of both coarse sediments in the zone 2 and 3, and fine sediment of sand and silt in lower reaches of zone 4 and 5. Thus, the floodplains and catchments are also considerable sources of sediment to the rivers through the erosion processes. Several tributaries flow to the Bakraha river including Solti and Sunjhoda rivers, whose catchments are highly landslide-prone, yielding, high sediment load and the finer mix from their respective beds are transported to the Bakraha river. As a result, the Bakraha river becomes the sink for finer materials (sand, silt, and clay). The upper reach (Zone 2 and 3) of the river including tributaries are generally composed of the non-cohesive silt, sand, gravel, and cobbles. In the case of non-cohesive sediments, bank slopes are restricted to 30–45^{o} and erosion take place by intermittent shallow slides of a few grains thick. In the lower reach, banks made of more cohesive sediments are prone to gradual undercutting or toe erosion, which destabilized (possibly even overhanging) the bank. Sooner or later the bank collapses locally and falls into the channel. The other cause of bank erosion in non-cohesive sediments is due to loss of strength of the bank under the saturated condition during flood or heavy rainfall, and the bank may collapse under the additional weight of the absorbed water (liquefaction). This will often occur only when the water level drops to a lower level.

River bend scours have been derived at several bends, which were identified from the river planform layout as obtained from the Google Earth (November, 2017) and Landsat imagery (February 2018). Higher scour along the bank due to high flow velocity and leading to bank erosion are developed at the major bends that have delivered considerable volume of sediment load downstream, which will impact the channel alignment and cause channel shifting due to generation of excessive load; over 25% of total load in alluvial river may be generated from bend and local scour along the river bends (FAP 24, 1996). In the opposite bank at the outer bend, the velocity of the flow is low and depositions of sand bars take place.

Confluence scours: There are two prominent confluences within the study area: i) the confluence of the Solti river and the Sunjhoda river with the Bakraha river, ii) the confluence of different branches within the active width of a river, which is particularly relevant in braider river, where bifurcation and joining of anabranches (confluence) are more common. Due to the confluence scour, there is an increase of discharges joining from two rivers, more sediment load is generated, which affects channel morphology downstream. This induces the development of sand bars at places (due to excessive load), and in turn, will induce scour in other places in the vicinity to preserve the conveyance for the incoming flows.

Protrusion scour develops where the flow is obstructed by the natural hard bank or by the relatively erosion-resistant bank. The magnitude of scouring is dependent on the extent of the obstruction. This phenomenon is similar to scour around bridge abutment (Simons and Senturk, 1977), where the abutment is protruded into the river. Such obstruction scour could be important at locations where there are existing structures. Topographical surveys reveal the existing hydraulic structures. The existing structure along the Bakraha river consists of 66.76 km embankments with numerous spurs and two reinforced concrete bridges (Mott Macdonald and TMS, 2018). Such structures are likely to induced channel scouring.

Channel avulsion is one of the primary controls on channel location on a floodplain of Bakraha River. It is the relatively rapid shift of river to a new channel on the lower part of a floodplain, alluvial plain. (Jones and Schumm, 1999). Several avulsions are seen in the time series imagery and by recently abandoned and or paleo-channels (Figure

10). Such avulsions occur when a triggering event, commonly a flood, forces a river across a stability threshold.

Planform and cross-section change in river morphology

Planform changes in river morphology are evidenced by erosion (bank and avulsion), deposition and channel abandonment between 2013 and 2018 channel planform; these derivations are based on Google Earth imageries of November, 2013 and March, 2018 (Table 8 and Figure 12). If we go back to 2002, the river from the 1 outlet (1 km downstream) was bifurcated into main channels the maximum extent of 2.63 km and made confluence at 9 km downstream (Figure 12). In the Bakraha river, the total area lost from the bank erosion and avulsion is 2.1 km^2. If divided by the length of the river from foothill (50 km), this would yield a 42m of bank erosion uniformly distributed along one bank; or in other words, the river would have widened by 42 m. In the tributary rivers, the total area lost from bank erosion and avulsion is 0.9 km^2. If divided by the length of the river (48.3 km), this would yield 19 m of bank erosion uniformly distributed along one bank; or in other words, the river would have widened by 19 m.

Therefore, at a particular location of higher vulnerability to erosion, the erosion (landward shifting of the river bank) could considerably be higher than the above uniform values. Area reclaimed from aggradations is higher in both rivers than area lost from erosion, which is indicative of an excessive sediment load from the upper catchment. This is also consistent with the high density of channel networks in the Siwalik part of the catchment as a higher channel density that will bring more sediment to the lower catchment. Cross-section change in morphology of the channel between 2014 and 2018 at the four locations corresponding to varying geomorphic characteristics along the channels was examined. The surveyed sections at two-time points were selected that closely matched the location, i.e., within ± 60 m. The cross-section profile of the channel and bank indicates that the processes of aggradation and degradation occurred over the period at different points in the same surveyed sections. Degradation in the form of bank and bed scouring (1-1.5 m) and aggradation in the form of deposition at bed or bank (< 2m) can be observed in various points across the examined cross-sections. This indicates that morphology is highly dynamic, as the form of river changes in the plan as well as the cross-section view (Figure 13a and b). It is because of the erosion and sedimentation process and their negative feedback relationship over time. Large discharge and heavy sediment load during flood cause the river to be extremely unstable, because of which it frequently migrates as a result of the bedlevel rise induced lateral erosion and avulsion in the upper reach; alternate bar shift, wandering bend scouring along induced lateral erosion and bed sediment souring and avulsion has been because of consistent change in the river morphology. Similarly, construction of embankments and spurs to check bank erosion and avulsion issue on either bank of the river has greatly influenced the river morphology and the river processes, which needs to be understood through scientific research using hydrodynamic models.

Table 8: Land lost due to the bank erosion, and area deposition due to the excessive sediment load in the Bakraha river and its tributaries

Channel process	**Area: channel aggradation and degradation (km^2)**	
	Bakraha	**Tributaries**
Bank erosion	1.5	0.8
Erosion by avulsion	0.6	0.1
Deposition	3.0	1.2
Channel abandonment and deposition	0.0	0.1
No change	8.0	6.4
Total	13.1	8.6

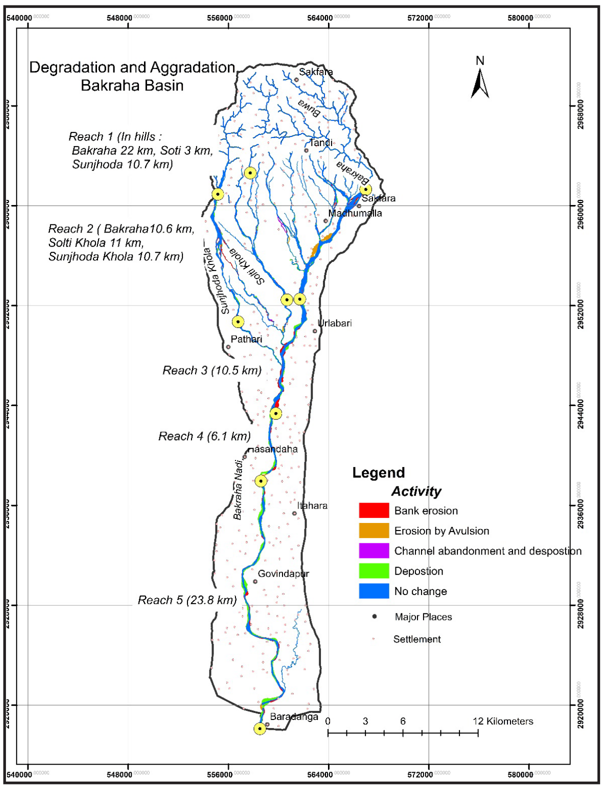


Figure 12: Degradation and aggradation in various reaches of the Bakraha river

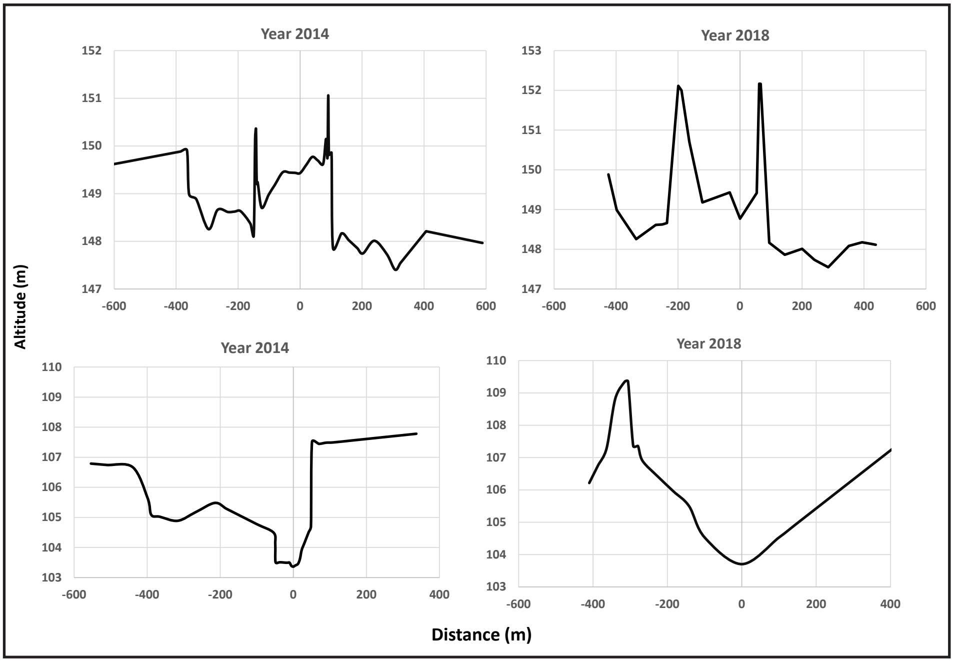


Figure 13a: Top right and left cross-section profile at 7.4 km (sand, gravel and boulder) bottom, same at 15.6 km (sand and gravel) from the outlet at the foothill.

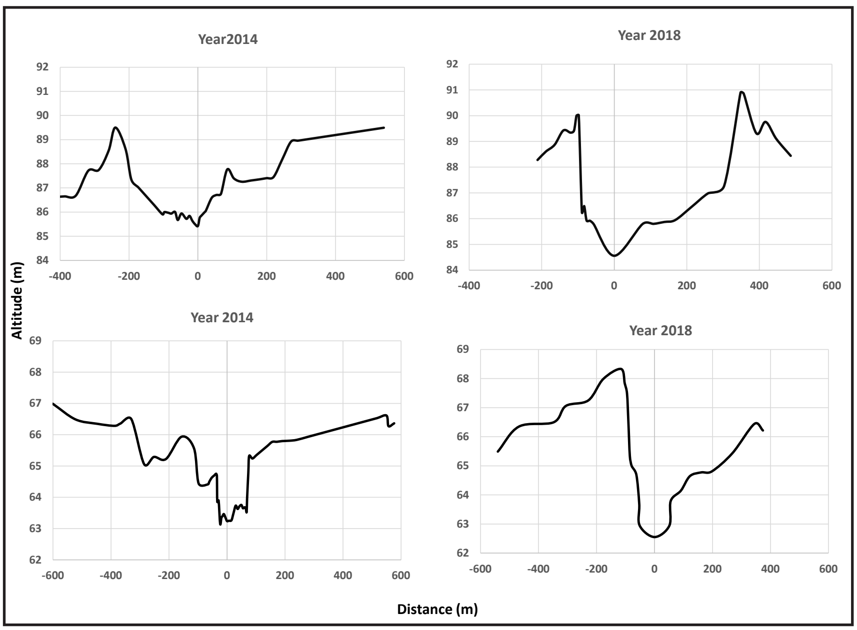


Figure 13b: Top right and left cross-section profile at 30.4 km (sand and silt) bottom, same at 47.8 km (fine sand and silt) from the outlet at the foothill.

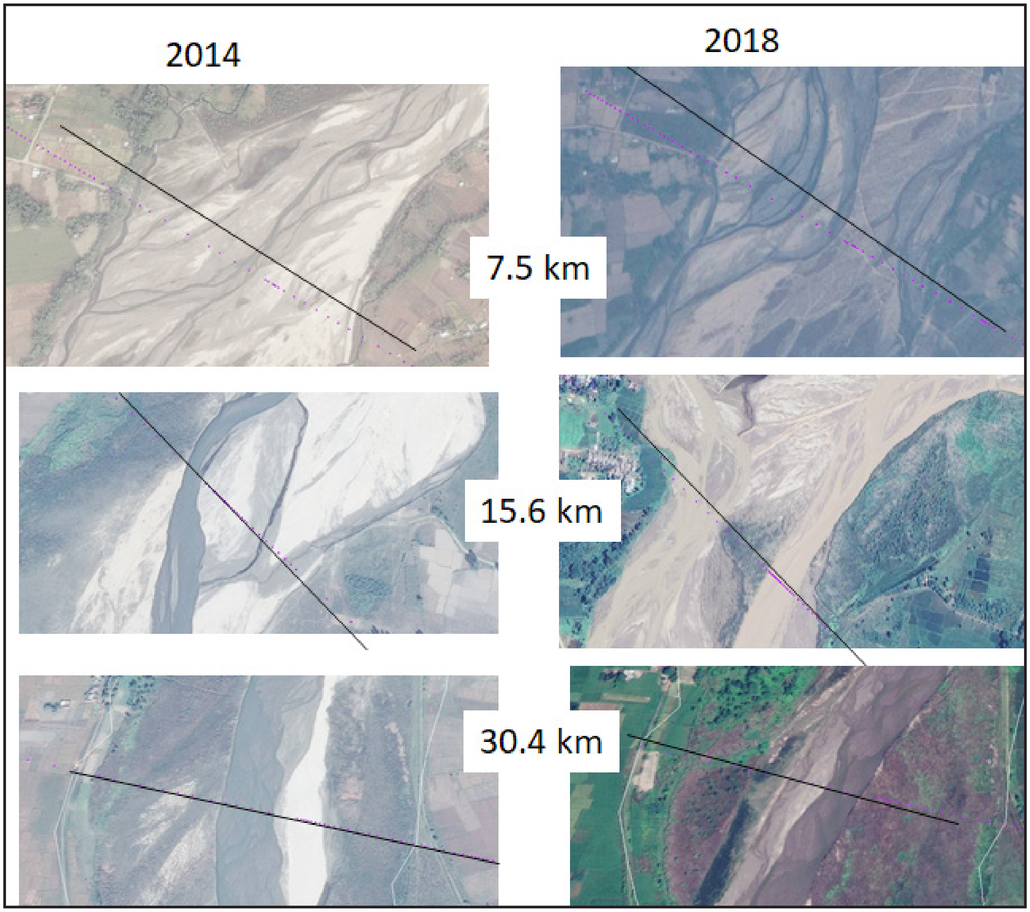


Figure 14: Plan view of the river section, where cross-section change analysis was done.

Summary and Conclusions

The Bakraha river basin is underlain by the rocks of the Siwalik group in the north, quaternary to recent deposits in Tarai towards south. The rocks are highly deformed and fractured. The average slope of the upper catchment is steep and variable, around 29± 15^{o}. The seismic intensity measured in terms of PGA is between 150-200 gal/sec^2. The catchment consists of a drainage pattern controlled by structure, drainage network of the sixth-order stream with a drainage density of 5.4 km/km^2. The average stream segment has a slope of 39%, which indicates that the upper basin streams are a colluvial type as well as a direct receiver of the sediments from slope failure and erosion. The catchment has dominantly forest land, which is degraded and contains various sporadic and interspersed patches of agricultural land, animal husbandry, and settlement. All these conditions make the hill catchment very fragile and unstable. The climate is subtropical humid and has a recurrence interval for 100 mm in less than 2 years, 200 mm in 3 years, and 250 mm in 6 years, which can initiate shallow landslides to large and deep-seated landslides. Landslides detected from the imagery shows are mostly (80%) large to huge, i.e., 1-33 ha. Unmapped shallow and old landslides scars observed in the field are quite numerous. The large landslides have infilled the valley floor. All these biophysical characteristics and human disturbance indicate the hill catchment is susceptible to landslides and erosion and has provided a huge amount of sediments to the rivers and stream.

The lower catchment has dominant agricultural land use, 72.7%, and has the subtropical forest at its northwest, through which several tributaries flow. Limited riverine trees and grass are found in the lower reaches at the intermittent stretches. Hence, the role of riparian vegetation for bank protection and flood control is limited. The morphological and sediment characteristics of the channel is represented by bedrock, boulders, cobbles, gravel, and sand in the upper catchment. In many steep, sinuous and confined channel sections, exposed and incised bedrock forms the riverbed. In the headwater streams, a huge amount of colluvium (landslide material) sediments is found, which are angular to semi angular in shape. In some sections of the mid-upper catchment, channels have developed occasional floodplain with terraces 1-2 tier terraces. At the foothill or piedmont zone (Bhabar), sediments are mainly boulders, gravels and sands, the channel is braided and have straight reached. Towards the south, the size of the sediment decreases, gradually the proportion of boulders decreases, where sand and gravel become dominant. Riverbeds are wide shallow and braided with undefined or low bank height. The island bars are unstable and change shape at each flood. These rivers have a flashy discharge, the sediment is transported during high water level and deposited at a low water level. Increase in bed level, a shift in channel course, split off the bank, and bank erosion is very common during heavy rainstorms. The channel reach in the transitional zone consists of gravel and sand deposits and gradually has become narrow and of defined banks. Channel is partially braided as well as meandering. Both alternate point bars as well as island bars are present. Channel avulsions and lateral channel migration are common river processes. Sand and silt zone is a distinct flood plain area. Rivers meander; sinuosity Index is 1.16-1.25, which indicates a high amount of mixed load comprising of fine gravel, sand, and silt. Channel migration by means of bank erosion and avulsion is a common river process. Alternate bar deposits are observed. However, during high flows, the channel may appear to be wandering type, and during low flows, channels would appear meandering. An interesting fact is that paleo-channels with higher curvature of meandering (higher sinuosity) can be observed. This indicates a change in river morphology with a higher amount of sediments in recent times.

The annual discharge varies 200-734 cusec from upstream (close to outlet) to downstream, (16.5 km away). The estimated sediment load transport during extreme flood events highly varies. The sediment carrying capacity immediately downstream of Siwalik Hills is higher due to steep slope gradient, and normally in lower reaches, the river has less sediment carrying capacity. However, the sediment load fluctuates with the location in the downstream owing to change in the hydraulic variables, dictated by variable morphological conditions at reach. Bank erosion, bend scour, confluence scour, and protrusion scours, and avulsions are the river processes, which provide a source of sediments to the river. Change in planform and cross-section view of the river morphology indicates the river is unstable due to the frequent shifts between accretion to erosion processes.

Acknowledgments

The author acknowledges Mott MacDonald, and Total Management Services Pvt. Ltd, Nepal for providing the opportunity to work as River Morphologist for an Asian Development Bank-funded Project "Preparation of priority river basin flood risk management project in Nepal" undertaken by Government of Nepal, Department of Irrigation. A substantial data used in this paper were incorporated from the project. The author also express special thanks to Dr.Kaji Iqbal Hassan, a senior hydrologist from Mott MacDonald for his guidance and support.

References

Buffington, J. & Montgomery, D. (2013). Geomorphic classification of rivers. *In: Shroder, J.; Wohl, E., ed. Treatise on Geomorphology; Fluvial Geomorphology, Vol. 9. San Diego, CA: Academic Press. p. 730-767*.

Carson, B. (1985). *Erosion and sedimentation processes in the Nepalese Himalaya*. ICIMOD Occassional Paper. Kathmandu

CBS (2012). *National Population and Housing Census 2011* (National Report), Volume 01, Kathmandu: National Planning Commission Secretariat, Government of Nepal/ Central Bureau of Statistics.

Dhital, M. R. (2015). *Geology of the Nepal Himalaya: Regional perspective of the classic collided orogen*. Springer International Publishing, Switzerland.

Dhital, M. R., Khanal, N. & Thapa, K. (1993). *The role of extreme weather events, mass movements, and land use changes in increasing natural hazards*. A report of the.... causes of the recent damages incurred in South-central Nepal during 19-20 July 1993. ICIMOD, Kathmandu

DMG (2007). Geological maps of Exploration Block 1-10. *Petroleum Promotion Exploration Project.* Kathmandu: Department of Mines and Geology.

Department of Survey (2002). *Topographic Maps and Digital Topographic Data*. Kathmandu, Nepal: Government of Nepal, Department of Survey.

Gansser, A. (1964). *Geology of the Himalayas*. London: Interscience Publishers, John Wiley and Sons.

Germanoski, D. & Schumm, S. (1993) Changes in braided river morphology resulting from aggradation and degradation. *The Journal of Geology,* 101**,** 451-466.

Ghimire, M. (2001) Geo-hydrological hazard and risk zonation of Banganga watershed using GIS and remote sensing. *J Nepal Geol Soc,* 23**,** 99-110.

Ghimire, M. (2011) Landslide occurrence and its relation with terrain factors in the Siwalik Hills, Nepal: Case study of susceptibility assessment in three basins. *Natural Hazards,* 56**,** 299-320.

Ghimire, M. (2014) Multivariate morphological characteristics and classification of first-order basins in the Siwaliks, Nepal. *Geomorphology,* 204**,** 192-207.

Ghimire, S. & Higaki, D. (2015) Dynamic river morphology due to land use change and erosion mitigation measures in a degrading catchment in the Siwalik Hills, Nepal. *International Journal of River Basin Management,* 13**,** 27-39.

Gupta, N., P. M. Atkinson & P. A. Carling (2013) Decadal length changes in the fluvial planform of the River Ganga: bringing a mega-river to life with Landsat archives. *Remote sensing letters,* 4**,** 1-9.

Hey, R. D., M. D. Newson & C. R. Thorne. (1997). *Applied Fluvial Geomorphology for River Engineering and Management*. John Wiley.

Hogan, D. L. & D. S. Luzi (2010) Channel geomorphology: fluvial forms, processes, and forest management effects. *Compendium of forest hydrology and geomorphology in British Columbia,* 1**,** 331-372.

Horton, R. E. (1932) Drainage-basin characteristics. *Eos, Transactions American Geophysical Union,* 13**,** 350-361.

Jones, L. & Schumm, S. (1999). Causes of avulsion: an overview. In *Fluvial sedimentology VI*, 171-178. Wiley Online Library.

Kale, V. S. (2002) Fluvial geomorphology of Indian rivers: an overview. *Progress in physical geography,* 26**,** 400-433.

Khanal, N. R. (1989) Morphometric properties of the drainage basins in the Chure range, Nepal. *Himalayan Review***,** 59-65.

Khanal, N. R., Shrestha, M. & Ghimire, M. (2007). Preparing for flood disaster: mapping and assessing hazard in the Ratu Watershed, Nepal. Kathmandu: International Centre for Integrated Mountain Development (ICIMOD).

Kline, M., S. Jaquith, G. Springston, B. Cahoon & L. Becker (2003) Vermont stream geomorphic assessment. *Vermont Agency of Natural Resources, Phase,* 1**,** 3.

Lavé, J. & J. Avouac (2001) Fluvial incision and tectonic uplift across the Himalayas of central Nepal. *Journal of Geophysical Research: Solid Earth,* 106**,** 26561-26591.

Legg, N. T. & P. L. Olson. (2014). *Channel migration processes and patterns in Western Washington: A synthesis for floodplain management and restoration*. Shorelands and Environmental Assistance Program, Washington State Department of Ecology.

LRMP (1986). *Land System Report*. Kathmandu: Land Resource Mapping Project.

Matsuda, I. (2004) River morphology and channel processes. *Fresh Surface Water***,** 299-309.

Montgomery, D. R. & J. M. Buffington. (1993). *Channel classification, prediction of channel response, and assessment of channel condition*. Seattle: University of Washington

Montgomery, D. R. & J. M. Buffington. (1997) Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin,* 109**,** 596-611.

Mott Macdonald, TMS (2018). WRPPF: *Preparation of priority river basins flood risk management project, Nepal,* A study report submitted to the Governmemt of Nepal, Department of Irrigation /Asian Development Bank

Nakata, T. (1989) Active faults of the Himalaya of India and Nepal. *Geological Society of Am.erica Special Paper,* 232**,** 243-264.

Nepal, C. (2012) National population and housing census 2011 (National Report). *Gov Nepal, Natl Plan Comm Secr Cent Bu reau Stat,* 1**,** 1-278.

Rajaguru, S., Gupta, A., Kale, V., Mishra, S., R. Ganjoo, L. Ely, Y. Enzel & V. Baker (1995) Channel form and processes of the flood-dominated Narmada River, India. *Earth Surface Processes and Landforms,* 20**,** 407-421.

Richards, K. S. 1982. *Rivers: form and process in alluvial channels*. London: Methuen.

Rosgen, D. L., & Hilton L.B. (1996). *Applied river morphology*. Pagosa Springs, Colorado: Wildland HydrologyWildland Hydrology.

Schumm, S. A. (1981) Evolution and response of the fluvial system, sedimentologic implications. Lit-tleton, CO.: Water Resources Publications.

Shrestha, M. B., Tamrakar, N. K. & Miyazaki, T. (2008) Morphometry and sediment dynamics of the Churiya River area, Siwalik Range in Nepal. *Boletin de geologia,* 30. 35-48.

Shrestha, P. & Tamrakar, N. K. (2012) Morphology and classification of the main stem Bagmati River, Central Nepal. *Bulletin of the Department of Geology,* 15**,** 23-34.

Sinha, R., Jain, V., Babu, G. P. & Ghosh, S. (2005) Geomorphic characterization and diversity of the fluvial systems of the Gangetic Plains. *Geomorphology,* 70**,** 207-225.

Sinha, R., Sripriyanka, K., Jain, V. & Mukul, M. (2014) Avulsion threshold and planform dynamics of the Kosi River in north Bihar (India) and Nepal: A GIS framework. *Geomorphology,* 216**,** 157-170.

Strahler, A. N. (1964) Part II. Quantitative geomorphology of drainage basins and channel networks. *Handbook of Applied Hydrology: McGraw-Hill, New York***,** 4-39.

Thakur, K. K., Pandita, S., Goyal, V., Singh, Y. & Kotwal, S. S. (2014) Characterisation of drainage basin morphometric parameters of Balawal Watershed, Jammu province, Jammu and Kashmir. *Himalayan Geology,* 35**,** 124-134.

Uddin, K., Shrestha, B. & Alam, M. S. (2011) Assessment of morphological changes and vulnerability of river bank erosion alongside the river Jamuna using remote sensing. *Journal of Earth Science and Engineering,* 1. 29-34.

Van Appledorn, M., M. E. Baker & A. J. Miller (2019) River-valley morphology, basin size, and flow-event magnitude interact to produce wide variation in flooding dynamics. *Ecosphere,* 10**,** e02546.