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RESEARCH ARTICLE

# Geomorphic assessment of morphology of Siwalik origin rivers in Far-west Nepal

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## ABSTRACT

Geology, tectonics, topography, climate, land use, and human activity impact river morphology significantly, affecting downstream morphology and hydrology. In Nepal, rivers traversing complex geology and active tectonics are subjected to intense weathering and erosion, resulting in a high sediment yield and substantial impacts on river morphology. Despite the importance of understanding river morphology, studies on Himalayan rivers remain limited. This study investigates the characteristics of basin and river morphonology of the Siwalik origin river in far-west Nepal using GIS, remote sensing, field surveys, and hydrodynamic modeling. The basin, spanning 702 km2, features distinct land use patterns, with the upper catchment predominantly forested and the lower catchment heavily agricultural. Geologically, the upper catchment is underlain by Siwalik Group rocks, while the lower reach consists of quaternary deposits. An examination of the catchment characteristics, change in plan and cross-sectional form at various channel reaches was conducted using time series optical satellite imagery and InSAR data from ALOS PALSAR and Sentinel-1. The study revealed that steep and rugged topography, high uplift rates, and intense monsoons contribute to frequent and extensive landslides, which lead to high sediment yield in the basin's upper part and impact channel morphology downstream. The study also exposed the correlation between channel slope, sediment type, and river morphology. The river processes such as erosion (bank and avulsion), deposition, and channel abandonment during the last decade have evidenced changes in the planform of river morphology. The hydrodynamic model indicates that changing hydraulic variables influence the river's processes and morphology. Cross-sectional analysis of the rivers also shows significant variability in sediment aggradation and degradation, impacting bed-level and flow patterns, indicating dynamic river processes. Notable sediment gains at certain cross-sections and losses at others indicate dynamic river processes, impacting bed-level rise, erosion, and flow patterns. A decrease in the annual rates of all river processes (erosion, avulsion, deposition, and channel abandonment) suggests stabilization in riverbanks. Comparatively, deposition remains the most extensive process, which indicates an excessive sediment load from upstream. This research provides a conceptual frame where the independent landscape factors (geology, climate, human activities) and dependent variables (sediment supply, stream discharge) shape river morphology.

Keywords: ***River morphology, geomorphology, Remote Sensing, InSAR, Siwalik Hills, Tarai***

## INTRODUCTION

River basins and morphologic characteristics are intricate components shaped by geology, tectonics, topography, climate, land use, and human activity (Horton, 1932). These factors influence the basin's geomorphic and hydrologic features, impacting downstream river morphology and hydrological response. The shape and pattern of rivers are the culmination of historical changes in climate, tectonic activities, land use, and human interference, highlighting the complex interplay of natural and anthropogenic factors (Van Appledorn, Baker and Miller, 2019).

Understanding river morphology and its linkages to catchment conditions provide a holistic view of river systems, aiding in the comprehension of channel morphology, floods, stability, and ecology (Hey et el., 1997). This knowledge is crucial for soil conservation, watershed management, flood control, and addressing issues like bank erosion and channel avulsion(Benda et al., 2003, Dietrich and Dunne, 1978). In Nepal, where rivers traverse complex geology and active tectonics, intense weathering and erosion processes lead to high sediment yields and significant impacts on river morphology and downstream disasters (Shrestha et al., 2008; Ghimire, 2020; Ghimire and Higaki, 2015; Shrestha and Tamrakar, 2012; Kale, 2002).

Despite its importance, studies on the river morphology of Himalayan rivers are limited and often focused on hazards rather than morphology. Few studies on the upper catchment processes in the Siwaliks exist, providing valuable insights (Khanal et al., 2007; Chalise and Khanal, 2002; Dhital et al., 1993; Ghimire, 2020). In this context, investigating the basin and morphologic features of the Mohana-Khutiya Rivers in far west Nepal, originating from the Siwalik Range and flowing traversing Tarai, presents an opportunity to enhance understanding in this field. Hence, this study aims to examine the characteristics of the basin and river morphology of the Siwalik origin river.

## CONCEPTUAL FRAMEWORK

Rivers function as open systems, influenced by a multitude of factors both upstream and downstream (Piégay and Schumm, 2003; Schumm, 1981). Channel morphology, a significant aspect of river systems, is shaped by these factors and is categorized as an independent and dependent type (Hogan and Luzi, 2010). Independent landscape factors, including geology (including tectonics), climate, and human activities, exert a direct influence on watershed conditions. Geology, affected by processes like volcanism and tectonics, determines bedrock distribution and topography (Montgomery and Buffington, 1993). Climate, driven by atmospheric circulation and modified by topography, influences soil and vegetation. Human activities also alter watershed conditions significantly (Ghimire et al., 2023).

These enforced conditions determine dependent landscape variables such as sediment supply, stream discharge, and bed and bank material (Buffington and Montgomery, 2013). The combination of these variables shapes channel characteristics, with the channel adjusting in response to changes. Additionally, time plays a crucial role as an independent variable since the landscape's origin. Understanding these interactions is essential for comprehending river dynamics. Studies by Buffington and Montgomery (2013), Montgomery and Buffington (1993), and Schumm (1981) provide valuable insights into these relationships. A conceptual framework of the study is presented in Fig. 1.

## METHODOLOGY

We employed parameters encompassing basin geomorphology, geology, land use, and morphometric analysis to evaluate the river basin and morphologic characteristics. We used GIS and remote sensing data alongside data obtained from field surveys conducted in 2015 and 2018 to generate terrain parameters and assess morphological and hydrodynamic characteristics of the Mohan-Khutiya River basin—part of the data derived from the studies done by (Mott-Macdonald and TMS, 2018) were reviewed, updated, and used. The current lead author was involved as a river morphologist for the project.

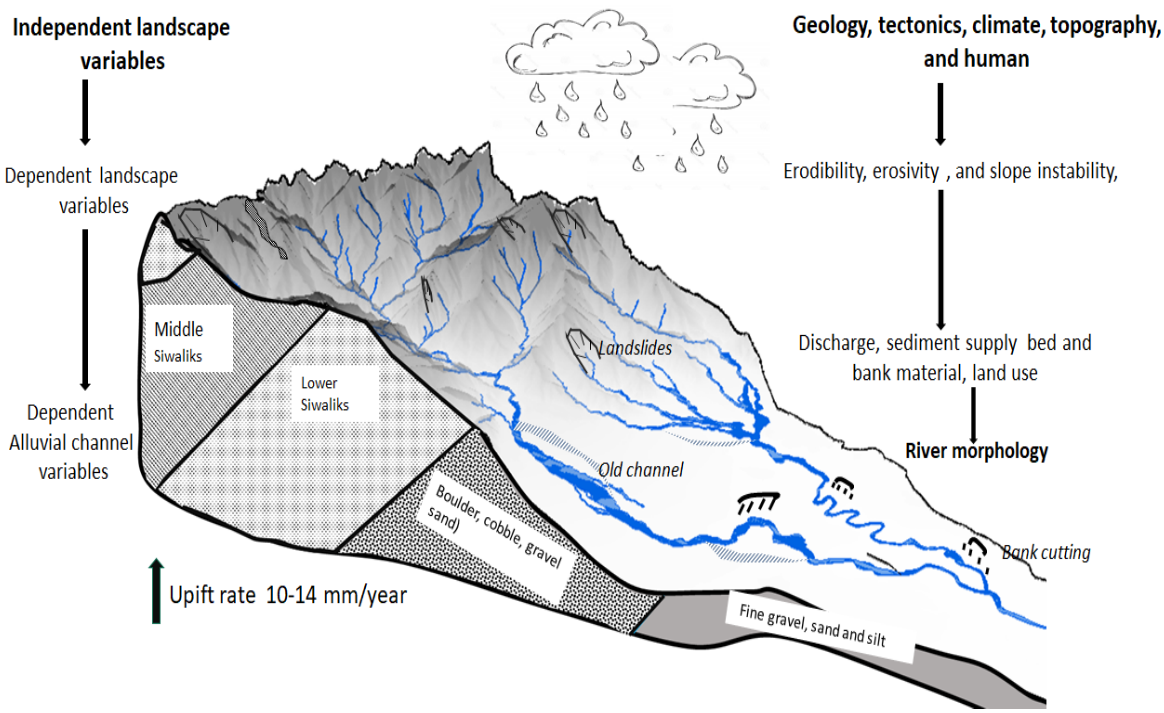



**Fig. 1: Conceptual model showing the relation between basin characteristics and river morphology (e.g. Khutiya – Shiva Ganga River), modified from Ghimire (2021).**

Methodologically, we analyzed basin features, established geomorphic characteristics of hill and alluvial sections, assessed river processes, and examined morphological changes, including channel avulsion, abandonment, aggradation and degradation of the Mohana-Khutiya River.

## Data sources and techniques

Data on geology were obtained from the maps published by the Department of Mines and Geology (DMG), focusing on rock type and structure. Morphometric parameters, including drainage network and basin and river slope, were derived from a 12.5-meter resolution Digital Elevation Model (DEM) obtained from ALOS 2007, using hydrological tools in ArcGIS.

Data on geomorphology and river morphology, such as topography, geomorphic units, changes in river planform morphology and sediment characteristics, were gathered from high-resolution imagery provided by Google Earth representing 2013, 2018, and 2024. We analyzed DEM and multi-spectral imageries of Landsat 8 to complement the data interpretation. Hydraulic data such as discharge, water level and water depth, velocities and Froude number, and flood extent (one in 50 years) were produced by Mott-MacDonald and TMS in 2018 by analyzing the HEC-RAS hydrodynamic model. Cross-section surveys and field observations conducted in 2018 by Mott-MacDonald and TMS were used to run the hydrodynamic model and estimate sediment transport capacity. Information on landslides was obtained from visual interpretations of Google Earth images and Landsat imagery from 2018-2024. The landslides were data extracted from the inventory made by (Ghimire *et al.* (2020).

**Application of InSAR**

DEMs derived from Interferometric Synthetic Aperture Radar (InSAR) and from ALOS PALSAR and Sentinel-1 were used to examine the changes in cross-section form in the exact location at various channel reaches. InSAR provides high-resolution radar imagery suitable for interferometric applications. It accurately measures surface deformations or elevation by analyzing phase differences in radar signals acquired from two or more satellite passes. The generation of DEM from SAR-based interferometric techniques has been widely used in various studies (Braun, 2021; Marchetti, 2023; Nagler et al., 2015; Solari et al., 2019). We used ALOS PALSAR DEM (Resolution 12.5) data from 2010, retrieved from https://search.asf.alaska.edu/#/, accessed on 2022-11-05.

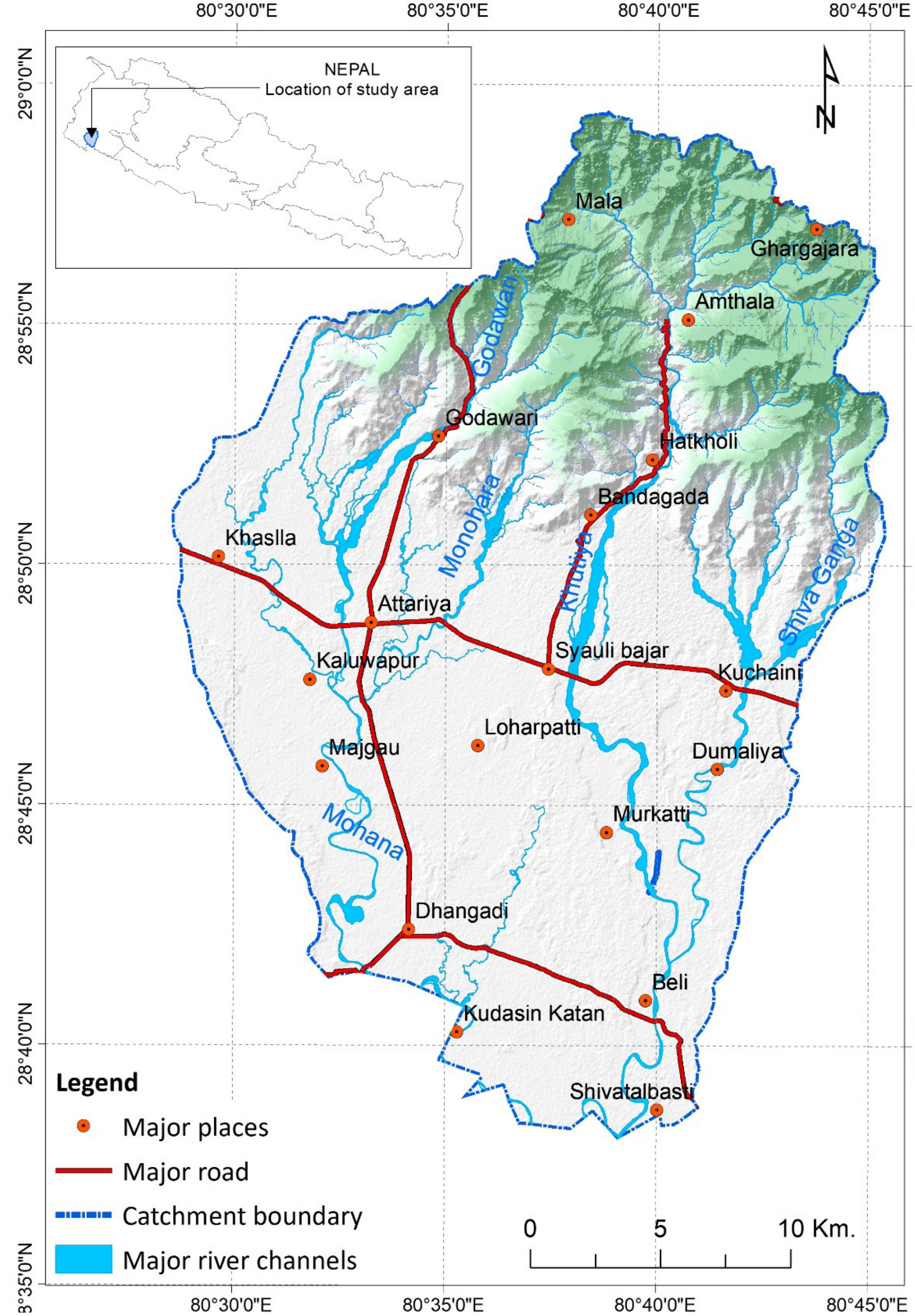
We also derived DEM covering the study area from the pair of Sentinel-1A imageries (IW, Descending mode, VV polarization) (ESA, 2023) taken on 2024-07-08, 2024-07-20 and 2018-03-30; 2018-04-23). These imageries were retrieved from https://search.asf.alaska.edu/#/, accessed on 2024-05-05. We reconstructed DEM of 13.5 m resolution using interferometric techniques available in the ESA-developed open-source software Sentinel Application Platform (SNAP). To obtain good coherence and micro-topographic variations, we considered the temporal baseline not exceeding 30 days and the perpendicular baseline above 100-150m(Braun, 2021; Ferretti et al., 2007). InSAR DEM representing riverbed and adjacent bare or small grass-covered floodplain sites were selected to create cross-section profiles. Various operations available in the Sentinel Application Platform (SNAP), such as Geocoding, enhanced spectral diversity, interferogram generation, filtering, phase wrapping and unwrapping, and finally creating DEM, were applied.

## STUDY AREA

**Location and land use**

The catchment of the Mohana Khutiya river basin lies between latitude 28°38'1.76"N to 28°58'59.15"N), and longitude 80°31'36.73"E and 80°45'24.74"E in WGS 84, UTM Zone 44 N (see Fig. 1). The basin extends from Chure Hills (Siwalik Hills, also known as sub-Himalayan hills, at low altitude) in the north and in Tarai (meaning low flat land) up to the Indo-Nepal border in the south. The catchment covers an area of 702.4 km2 in the far west of Nepal (Fig. 2). The Mohana-Khutiya river system lies in the district of Kailali in Sudurpaschim Province. This river system has 359 settlements, with over 300,000 distributed over six rural and urban municipalities (NSO, 2021). Dhangadi and Attrariya are the two major towns located in this catchment.

The basin has two distinct land use patterns. The upper catchment is predominantly forest, shrub, and grassland (90%), with minimal agricultural disturbance. In contrast, the lower catchment is heavily agricultural and built-up (55%), with significant deforestation. The Mohana River's lower catchment has 69.5% agricultural and built-up areas. The Khutiya River's lower catchment has 51.3% forest cover. Agricultural lands are mainly in the flood plain zone, south of the Bhabar region, exposed to high flood, siltation, and erosion hazards due to minimal forest along riverbanks.




**Fg. 2: Study Area, Mohana-Khutiya River Basin**

## Geology, topography, and drainage

The Mohana-Khutiya basin is underlain by the rocks of the Siwalik Group in the upper reach and recent quaternary deposits in the lower reach. The Siwalik Ranges, the youngest Himalayan belt, are tectonically active, leading to rock deformation and an unstable landscape. The Siwaliks are divided into Lower Siwaliks (LS) and Middle Siwaliks (MS) (Fig. 3). The LS, primarily mudstone with sandstone, occupies the southern part of the catchment. In this group, the proportion of mudstone is greater than that of sandstone in aggregate. The MS contains more sandstone, with coarser grains in the upper formations and thicker sandstone beds than mudstone beds. The sandstone beds range in thickness from 1 to 30 m, while the mudstone ranges from 0.5 to 4 m (DMG, 2007; Ghimire et al., 2024).

The Siwaliks are delineated as the Main Frontal Fault, the most active fault, thrust over the alluvium in the Piedmont zone (Nakata, 1989). Similarly, Jogbudha Thrust runs South East-North West in the northern part of the Khutiya catchment. Both thrusts dip 25°–30° North East to North East. Bedrocks generally dip towards the northeast, with an amount of 30°-70° (DMG 2007; Dhital 2015).

The upper catchment's drainage is influenced by bed structure and faults, forming trellis-to-rectangular patterns with a high drainage density of 5.82 km/km². The stream's average slope is 22.8%, capable of transporting large sediments during monsoon rainstorms. Of 3890 streams with a total length of 1,479 km, 93 percent of streams (first- to second-order steams) have slopes above 25%. These streams are colluvial types that couple with hillslope processes, which deliver a huge amount of debris to the river system (Fig. 4).

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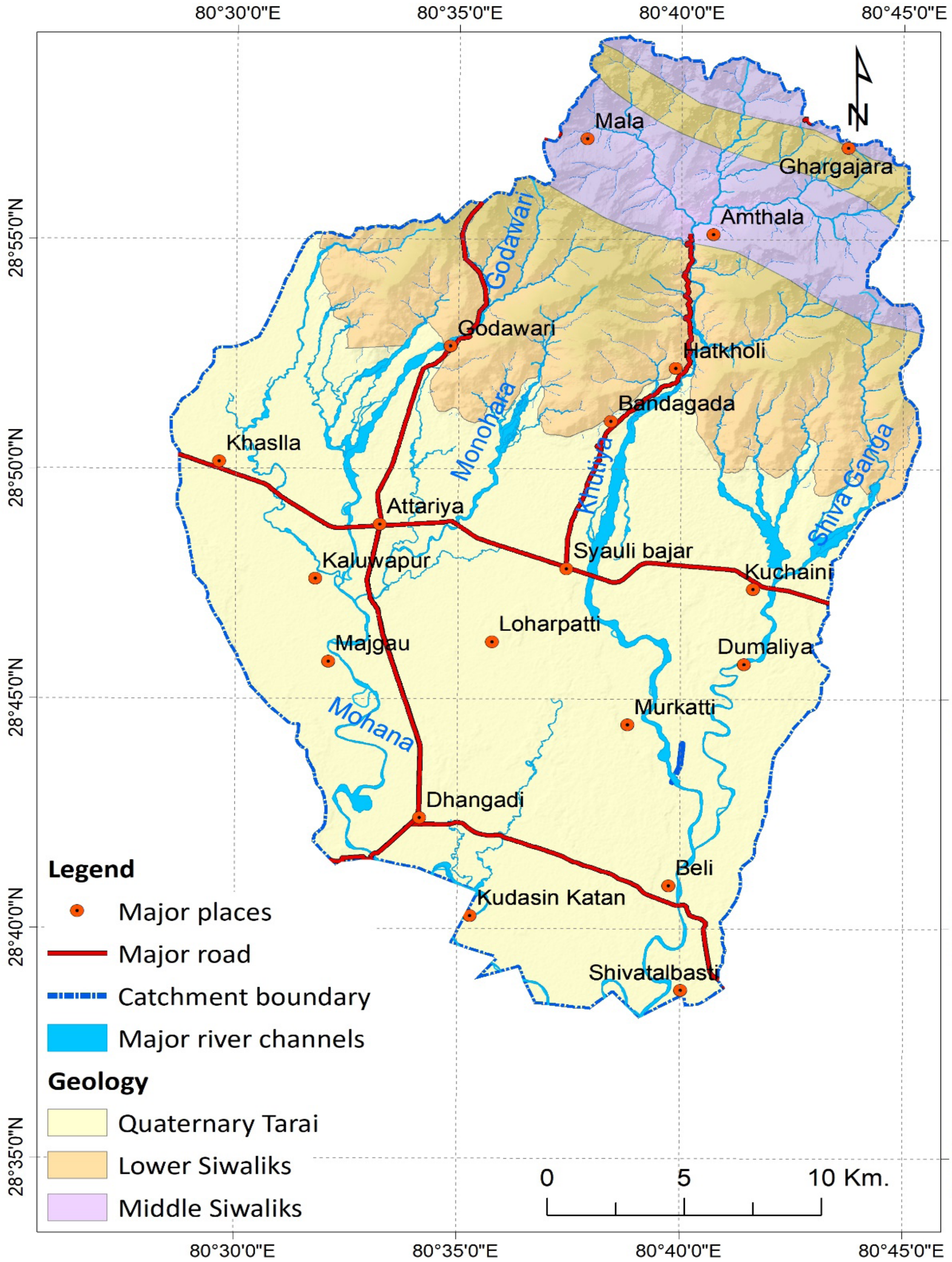



**Fig. 3: Geological map of the Mohana-Khutiya River basin**

## RESULT AND DISCUSSION

### Hillslope processes of the upper catchment and rainfall events

The upper catchment area, characterized by strong relief (160-1940 masl), steep topography (mean slopes ~ 25±10o), active tectonics, and complex geology, exhibits numerous old, active, recurring, and expanding landslides. Factors such as topography, bedding structure, fractures, tectonic uplift, and differential weathering of mudstone and sandstone influence these landslides, contributing significant sediment loads to rivers and streams during monsoons. About 1563 mm of precipitation falls annually, of which the summer monsoon contributes more than 80%. Since the last 70 years, about a maximum 24 hours maximum rainfall events above 150 mm were 30, i.e., one in 2.3 years, and have shown increasing trend (Fig. 4). Such events can trigger landslides and debris flow in hillslopes. Nine rainfall events with intensity above 200m/24 hours were recorded, capable of initiating widespread and devastating landslides and debris flow (Fig. 4). In July 7-8 ever recorded (DHM, 2024) extreme rainfall was recorded, i.e., 573.6 mm/24 hour at Hanmannagar. Apart from the rainfall, tectonic upliftment and incision rate are pronounced in creating landslides and erosion. Lavé and Avouac (2000) estimated the uplift rates in the Siwaliks of central Nepal to range between 1-4 mm/year based on the deformation of fluvial terraces. Similarly, erosion rates in the Siwaliks are estimated to be around 2-6 mm/year, varying significantly with monsoon intensity and river dynamics (Bookhagen and Burbank, 2010).

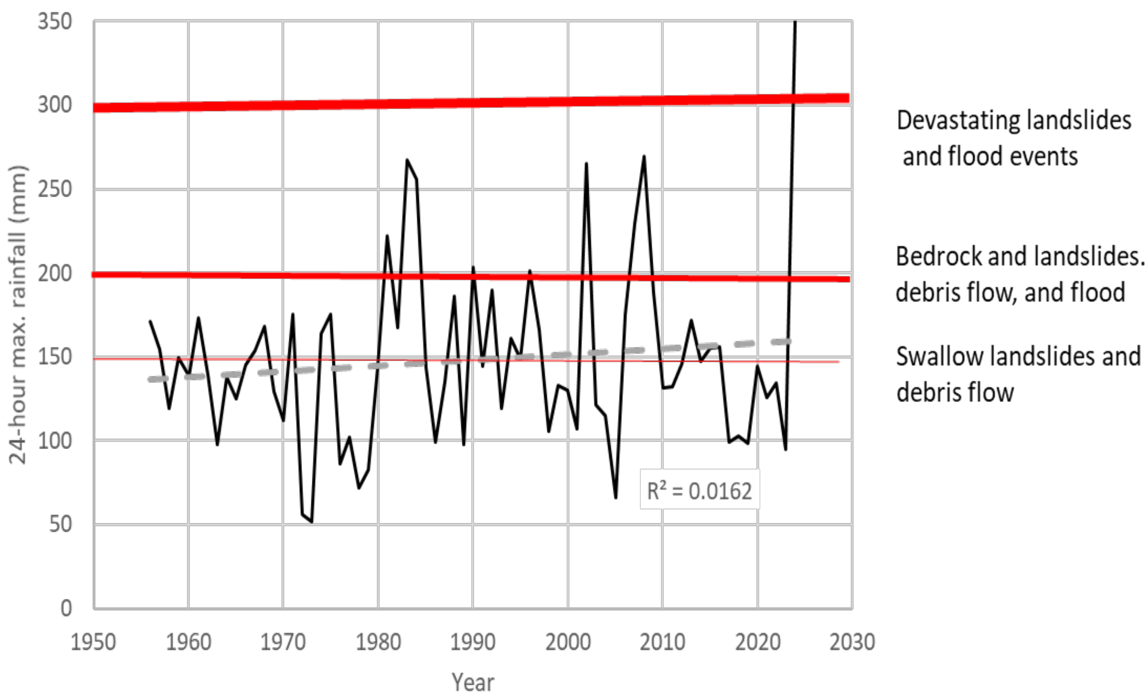



**Fig. 4: Historical observation of the 24-hour extreme rainfall events in Dhangadi (DHM, 2020, 2024).**

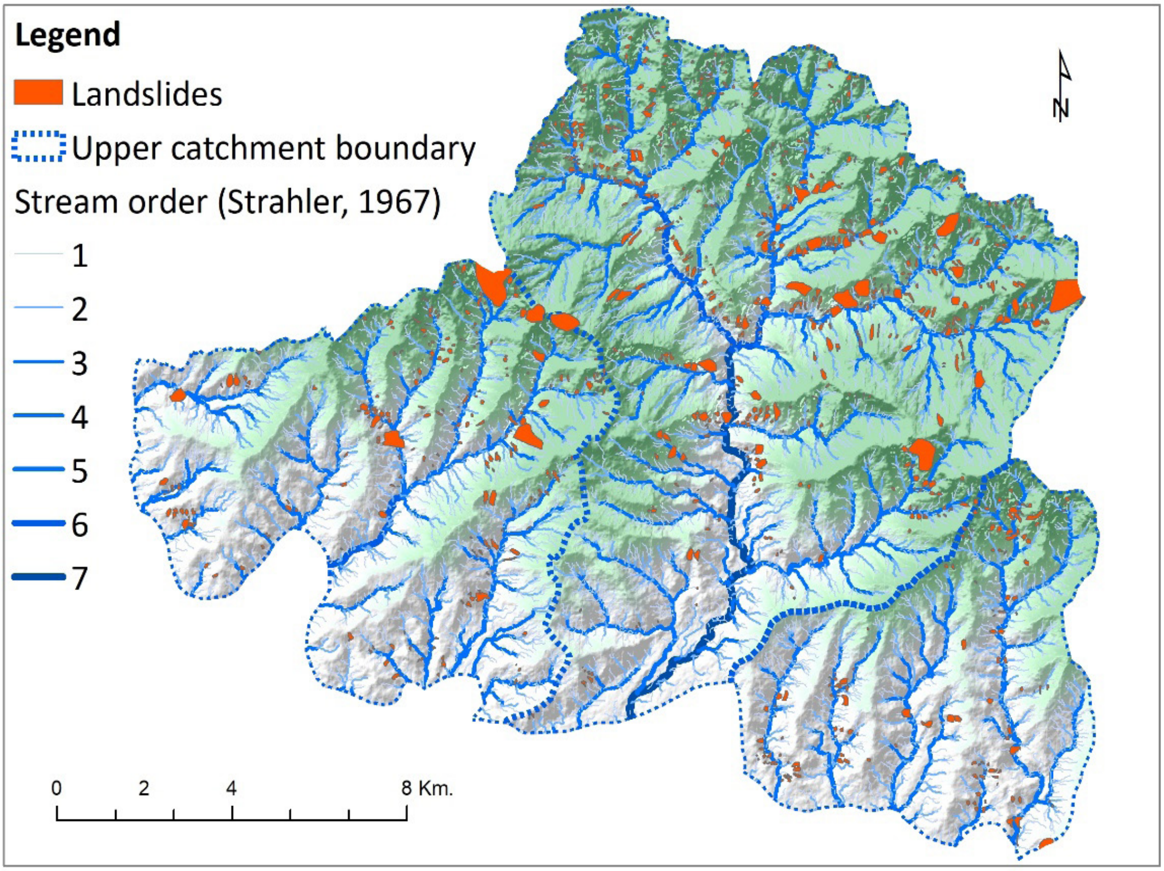



**Fig. 5: River order and landslide distribution in the Upper Mohana-Khutiya catchment.**

Numerous complex slides are seen on the stream and gully head, from where the hillslope materials are released into colluvial streams and further transported downstream. The sediment, ranging from fine clay to large boulders, is transported through narrow valleys and deposited in foothill riverbeds.

Based on Google Earth images (2020), landslides in the Mohana and Khutiya River catchment are classified as rockfall, slides, debris fall, and swallow scar failures (Fig. 5). Rockfalls and slides are prevalent on steep anti-dip slopes, while rotational failures occur on gentler, weathered slopes. Additionally, erosion scars, exposed rocks, and land degradation were recognized due to bare steep slopes, overgrazing, and deforestation. River undercutting causes foot slope failures, indicating active river incision. An inventory of 6040 landslides and erosional scars with a total area of 3484 hectares was made. Using the empirical formula, i.e., D=0.05×A0.45, where D=Depth, A =area (Hovius et al., 1997), a total volume of 4,315.75 million m3 of sediment is estimated from the currently active landslides.

## Geomorphic characteristics

The Mohana Khutiya River system is classified into five geomorphic units based on topography, river morphology, geology, and sediments (Fig. 6):

**Steep river gradient, bedrock, and coarse sediments.** This zone features the Chure (Siwalik Hill) underlain by sandstone and mudstone. It has a seventh-order drainage network with strong gradients, receiving sediments from landslides, debris flows, and erosion. The riverbed consists largely of boulders, cobbles, and gravels, with exposed and incised bedrock in steep channels. Uplifted terraces indicate former floodplains. Managing landslides and erosion is crucial to reduce sediment delivery to the lower catchment. The river morphology is controlled by bedrock and geological structure. Reducing human disturbances like cultivation, grazing, and deforestation is recommended, while expensive structural measures to control erosion are often questionable.

**Alluvial fan deposits:** This zone comprises alluvial fan deposits, which feature decreasing sediment size from boulders to sand towards south. Riverbeds are wide, shallow, and braided, with unstable island bars. Flashy discharge causes sediment transport during high water levels. The Khutiya River has a significant fan base, while others, like Mohana and Manohara, have smaller fans. Embankment construction requires site assessment due to the risk of channel avulsion (Fig. 6 and 7).

**Upper alluvial plain deposits.** A transitional zone dominated by gravel and sand deposits, with braided and meandering channel patterns. Evidence of channel avulsions and lateral migration is present. The channel width is intermediate between zones 2 and 4/5 (Fig. 8).

**Middle alluvial plain deposits**: This floodplain area features meandering rivers with pool formation at bends. Bank erosion is a major sediment supply source. Abrupt reductions in sediment supply can cause the river to erode its bed. Gradual sediment supply reduction through riparian vegetation restoration is recommended (Fig. 6).

**Lower alluvial plain deposits**: A floodplain with gentle slopes featuring fine sand and silt deposits. Channels are narrow, deep, and meandering with alternate bar deposits. Overbank flooding, bank erosion, avulsion, and siltation are common. Bank erosion at meander bends significantly affects agriculture and livelihoods.

**Fifty-year flood plain:** The Flood plain is a belt along a river that can be affected by flood events of the magnitude that may recur once in 50–years, i.e., a 2% chance of being inundated by a flood in any given year (Fig 5). These floodplains are critical for flood control, as they act as natural buffers, absorbing excess water and reducing flood damage. However, these floodplains have been heavily encroached by human activity.

These classifications highlight the need for specific management strategies to address sediment transport, erosion control, and flood risk mitigation.

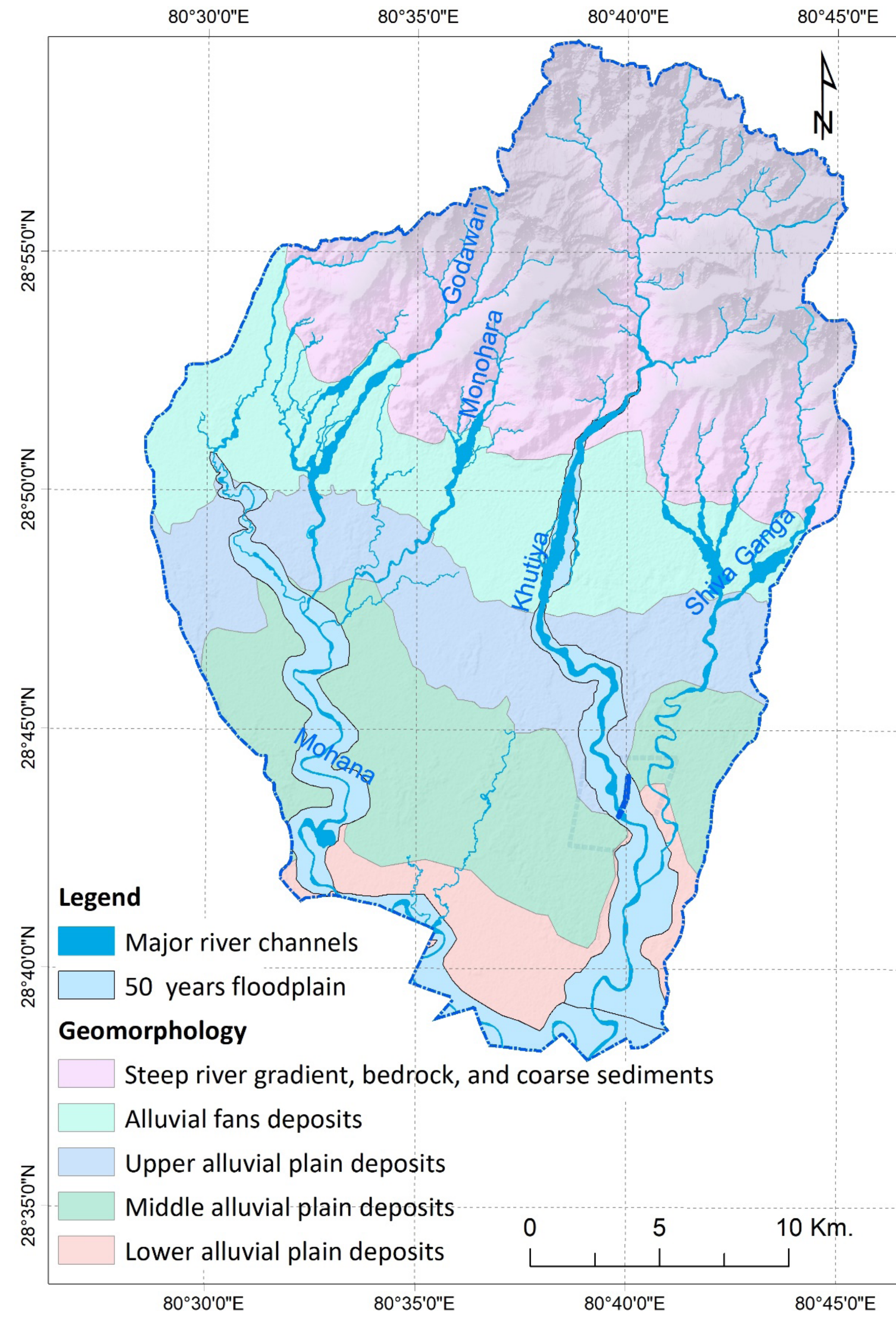



**Fig. 6: Geomorphological unit**


**Fig. 7: Boulder, cobble, and gravels near the apex of the fan of Godawari River.**


**Fig. 8: At 15km downstream from the fan apex. Unlike upstream, the river bed consists mainly of sand, gravel, and silt. Photos on the left show the upstream and right downstream of the Godavari River bridge.**

**Morphological characteristics of the river**

The morphological characteristics of the channel reaches are defined by the morphological characteristics of the channel pattern, such as sinuosity, braidedness, and meandering characteristics of the channel (Table 1). Sinuosity is the ratio of the curvilinear length of the river to the straight-line distance between its endpoints. The braidedness of a river is determined by the network of sub-channels separated by small, often temporary islands, called braided bars. Meandering refers to a series of sinuous curves, bends, or loops of a river typical in flood plains comprising sand and silts with gravel fractions.

The Mohana, Godawari, and Manohara rivers in the hilly region share similar geomorphological features. The Mohana River spans 70 km straight (13 km) and meandering reaches (57 km) (Table 1). The straight reaches have steep slopes and braided and broader channels with boulders, gravel, and sand sediments. The meandering reaches have gentler slopes and are narrow, and sediments are mainly of sand and silt, with some fine gravel.

The Godawari River, a 23 km tributary of the Mohana, generally has straight reaches. Towards the south, it tends to meandering (sinuosity of 1.4). It indicates the Mohana's sediment distribution, with braided channels and steep slopes in the first two reaches and milder slopes in the third, comprising sand and gravel.

The Monohara River, another tributary of the Mohana, extends 20 km and has similar characteristics: steep, straight reaches transitioning to a meandering third reach (sinuosity of 1.46) and a sediment composition of boulders, gravels, sands, and silt.

The Khutiya and Shivaganga rivers, key Mohana tributaries exhibit diverse geomorphological features (Fig. 6 and Table 1). The Khutiya River spans 52 km, comprising 20 km straight (39% of total length) from the fan apex depicting a broad (507 m wide braided pattern). Such an extensive fan and braided-ness indicate the massive sediment transport supplied from the hilly catchment and fan. The remaining reaches towards the south witness wandering to the meandering pattern. The straight reaches have steep slopes with boulders, gravel, and sand, while the wandering to meandering reach has mild slopes comprising sand, fine gravel, and silt.

The Shivaganga River is a 35-km tributary of the Khutiya, with five braided tributaries that meet at the fan zone. The straight and braided segment features steep slopes and similar sediments as the Khutiya's straight reaches, while the meandering segment (20 km) downstream has mild slopes and finer sediments of sand and silt.

The geomorphological features of these rivers indicate a correlation between channel slope, sediment type, and river morphology, which aligns with findings by Leopold et al., (2020), Schumm (2007), studies by Bridge and Lunt (2006), Knighton (2014), and Ghimire (2020)
.

**Table 1: Channel characteristics of the Mohana-Khutiya River System**

| River | Reach ID | Reach Characteristics | Channel length | Sinuosity index | Slope % | Channel area ($km^2$) | Average width (m) | Maximum Depth at bankful discharge (m) | Width depth ratio | Sediment characteristic |
|---|---|---|---|---|---|---|---|---|---|---|
| Mohana, Godawari, Monohara | 1 | Hill | 5.0-9.3 | 1.12-1.2 | 14.1 | 0.34-0.62 | 25-79 | | | Sand, gravel and boulder |
| | 2 | Fan | 4.8- 8.4 | 1.1-1.14 | 1.1 | 12.1 0.26 | 164-507 | 0.75-1.5 | 99-135 | Sand, gravel, boulder |
| | 3 | Peripheral fan (Godawari Confluence) | 6.5- 13.9 | 1.5-2-0 | 0.1 | 4.24-1.97 | 109 | 1.5 | 87 | Sand |
| | 4 | Flood plain, meander (India border) | 8.6-21.3 | 1.4-2.1 | 0.1 | 9.38-3.68 | 92-168 | 2 | 25-46 | Sand and silt |
| | 5 | Flood plain, meander (India border-Khutiya) | 8.6. 21.3 | 1.79 | 0.1 | 4.42-0.62 | 144-173 | 2 | 25- 86 | Sand and silt |
| Khutiya-Shivganga | 1 | Hill | 10.9-19.91 | 1.3-1.3 | 8.3-14.7 | 3.5 | 60-74 | NA | - | Sand, gravel and boulder (upper segment |
| | 2 | Braided | 3.78-6.51 | 1.0-1.1 | 1.1-1.4 | 6.23-33 | 164-507 | 1.5-2 | 109-253 | Sand, gravel and boulder (upper segment |
| | 3 | Flood plain, Meander (Shivaganga confluence) | 15.46-19.55 | 1.6 -1.4 | 0.2 | 11.5-26.1 | 59-169 | 2-2.3 | 29-75 | Sand and silt |
| | 4 | Meander (Mohana confluence (Nepal-India border) | 9.77 | 1.45 | 0.1 | 13.4 | 137.3 | 2.25 | 61.0 | Sand and silt |

**Sediment load transport capacity and river processes**

Flow gauging stations are unavailable, so depth, velocity and water surface gradient (energy gradient) were taken from the HEC-RAS 1d hydrodynamic model (2018 model) for a 1 in 50-year return period produced by Mott-Macdonald and TMS (2018) (Table 2). Historical extreme rainfall data (1980-2016) from DHM was used as input for the model. Discharge increases over twelve times downstream from Mohana at foothill to Khutiya Mohana confluence, indicating significant tributary contribution. The contribution from the Khutiya is highest. Sediment transport capacity was estimated using the Van Rijn (1984) method (Table 2), with HEC-RAS 1D hydrodynamic model outputs for a 50-year return period discharge. The median sediment grain sizes (D10, D50, D90) were used for predictions. Compared to other methods, Van Rijn's (1984) method is better predictable.

Sediment load varies significantly downstream, from 4316 to 5.85 tons/day, depending on discharge, depth, velocity, sediment characteristics, flow and environment (Van Rijn, 1984). Table 2 shows that the first 7 km (approximately) of the rivers have a high capacity for transporting sediment. A straight channel with steep gradient characterizes the first two river reaches. But it has to be noted that, here, only point transport was estimated, the total load downstream over the cross-section in the straight reaches may be relatively smaller than in the meandering ones because of less discharge and less flow area in the upstream reach (Mott-Macdonald and TMS, 2018). There will be gravel and cobble deposition in these reaches but no sand deposition on the bed. However, bed erosion is not likely to happen as these reaches of the river is dominated by gravels and boulders.

The sediment load carrying capacity of river at downstream reaches (the sand and silt zone, with fractions of gravel) at 12, 17, and 47 km is low. The low sediment transport capacity indicates aggradation of sediments on riverbed. However, at 31 km, after the Godawari and Manohara confluence (3 km downstream) and at confluence of Mohana and Khutiya, the sediment load capacity is 2324 and 45213 tons /day, respectively. In these reaches, the net effect will be degradation as aggradation decreases.

Changing hydraulic variables along the channel show dynamic morphology, influencing aggradation and degradation. If water cannot transport sediment, deposition raises channel height (aggradation). Conversely, increased velocity or slope erodes the channel (degradation), altering river morphology.

**Table 2: Hydraulic parameters and sediment load at distances along Mohana River**

| Distance from Foot hill at fan apex (km) | Geomorphic Unit | Discharge (cu m/s) | Depth (m) | Energy Grade Slope (m/m) | Average velocity (m/s) | Velocity at Deepest (m/s) | Froude # | Sediment load (tons/day) |
|---|---|---|---|---|---|---|---|---|
| **Mohana River** | | | | | | | | |
| 0.0 | Sand and gravel | 209 | 2.51 | 0.002696 | 1.94 | 3.07 | 0.56 | 3024 |
| 2.5 | Sand and gravel | 225 | 2.93 | 0.002116 | 1.76 | 3.01 | 0.5 | 2812 |
| 7.3 | Sand and gravel | 269.05 | 3.53 | 0.002093 | 1.73 | 3.4 | 0.5 | 4316 |
| 12.4 | Sand and silt | 717.77 | 3.6 | 0.000307 | 1.15 | 1.32 | 0.22 | 110 |
| 17.2 | Sand and silt | 1014.86 | 3.76 | 0.000726 | 1.52 | 2.08 | 0.33 | 693 |
| 31.1 | Sand and silt | 1221.82 | 4.77 | 0.001008 | 2.18 | 2.88 | 0.4 | 2324 |

| Distance from Foot hill at fan apex (km) | Geomorphic Unit | Discharge (cu m/s) | Depth (m) | Energy Grade Slope (m/m) | Average velocity (m/s) | Velocity at Deepest (m/s) | Froude # | Sediment load (tons/day) |
|---|---|---|---|---|---|---|---|---|
| 46.6 | Fine sand and silt | 1512.81 | 4.74 | 0.000243 | 1.07 | 1.41 | 0.2 | 141 |
| 57.6 | Fine sand and gravel | 2557.7 | 4.58 | 0.002804 | 3.81 | 4.67 | 0.68 | 13627 |
| Khutiya River | | | | | | | | |
| 0.0 | Sand and gravel | 1045.68 | 4.28 | 0.000844 | 1.88 | 2.45 | 0.36 | 1276 |
| 20.6 | Fine sand and silt | 1493.31 | 4.48 | 0.000536 | 1.45 | 2.01 | 0.29 | 599 |
| 35.5 | Fine sand and silt | 2557.7 | 4.58 | 0.002804 | 3.81 | 4.67 | 0.68 | 13627 |

## River erosion and aggradation processes

The planform and cross-sectional morphology of the Mohana-Khutiya River reveal various river processes contributing to different forms of erosion and providing sediments to the river. Notable processes include bank erosion, river bend scouring, confluence erosion, and deposition. These processes change channel migration, avulsion, and bed level, altering the river's planform and cross-sectional morphology.

Bank Erosion: The Mohana-Khutiya River's upper catchment and the river's floodplains downstream (Tarai plain) are significant sediment sources, comprising coarse sediments in Fan deposits and Upper alluvial plain deposits and fine sediments in zones in the Lower alluvial plain. In the first two zones, non-cohesive sediments (silt, sand, gravel, cobbles) restrict bank slopes to 30-45° and erode through shallow slides. In the lower reaches, cohesive sediments are prone to undercutting and collapse due to toe erosion or reduced bank strength due to saturation during floods, leading to liquefaction. Similarly, water flow within the bank sediments causes sediment rearrangement and internal erosion (piping or sapping), destabilizing layers and leading to large-scale backslides.

River Bend Scours: River bend scour potential is high in the Mohana-Khutiya River system, particularly in the sand and silt zone. About 60, 22, 18, 37, and 49 bends were observed in Mohana, Godavari, Monohara, Khutiya, and Shivganga. The catchment of the Mohana has Lower Siwalik rocks where mudstone dominates over sandstones; therefore, in the foothill, the riverbed comprises sand and silt, which favors the development of meanders. Towards downstream, the meanders are highly pronounced, comprising sharp bends with smaller radii and non-less cohesive bank materials such as sand and silt; the bend scouring has higher rates at higher flow velocity. Bank and bend erosion contribute to increased sediment load downstream, which impacts channel alignments and causes channel shifts.

Confluence Scours: Key confluences, such as where the Godawari River and Manohara join Mohana and the meeting points of the Khutiya and Shivganga Rivers, experience increased discharge and sediment load, affecting downstream morphology. This can induce sand bar development and scour in nearby areas to maintain flow conveyance.

Protrusion Scours: Scours develop where natural hard banks or erosion-resistant structures, similar to Bridge abutment scours, obstruct flow. Topographical surveys indicate structures like embankments and bridges along the rivers induce channel scouring.

Channel Avulsion: Time series imagery and paleo-channels show rapid shifts in the Moahana and

Khutiya Rivers and the tributaries' location on the floodplain, often triggered by floods. This process significantly influences channel location and floodplain dynamics.

**Change in river morphology: Planform and Cross-sectional form**

Planform river morphology refers to the shape and pattern of a river as seen from an aerial view or map. It encompasses the horizontal layout and patterns of river channels, including their bends, meanders, straight segments, and network configurations (Fuller *et al.*, 2013). Cross-section river morphology refers to the vertical profile of a river channel, taken perpendicular to the direction of flow (Fuller *et al.*, 2013). Understanding planform and cross-sectional morphology is essential for analyzing river dynamics, sediment transport, hydraulic characteristics, and the impact of human activities (Fuller and Smart, 2007). River processes, revealed in planform and cross-section form, are important geomorphological processes that attract a great deal of attention from river engineering scientists in many parts of the world (Best and Rhoads, 2008; Ibitoye, 2021).

Erosion (bank and avulsion), deposition and channel abandonment between 2014, 2018, and 2024 evidence changes in river morphology (Fig. 9 and Table 3). Total bank erosion over both periods is significant at 710.7 hectares. The total area affected by avulsion is relatively small (39.4 ha) compared to other processes. Bank erosion decreased from 82.7 ha/year (2014-2018) to 66.7 ha/year (2018-2024). Similarly, erosion from avulsion decreased dramatically from 8.0 ha/year to 1.3 ha/year.

Deposition remains the most extensive process compared to erosion, covering 1171.5 hectares between 2014 and 2024. This is indicative of an excessive sediment load from the upper catchment. Deposition also decreased from 141.3 ha/year to 106.4 ha/year. The total area affected (113.9 ha) by channel abandonment indicates that this process is less dominant than direct deposition. A significant decline in the deposition rate due to channel abandonment was observed, from 18.8 ha/year (2014-2018) to 6.8 ha/year (2018-2024).

A decrease in the annual rates of all river processes (erosion, avulsion, deposition, and channel abandonment) suggests an overall stabilization in riverbanks or effective erosion control measures, including successful intervention in preventing rapid channel changes or a natural decrease in avulsion events after 2018. The decreasing trends in river dynamic processes suggest that existing management practices may be effective. Studies by Fuller *et al.* (2013) and Hooke (1984) also support that effective river management can reduce erosion and avulsion rates.

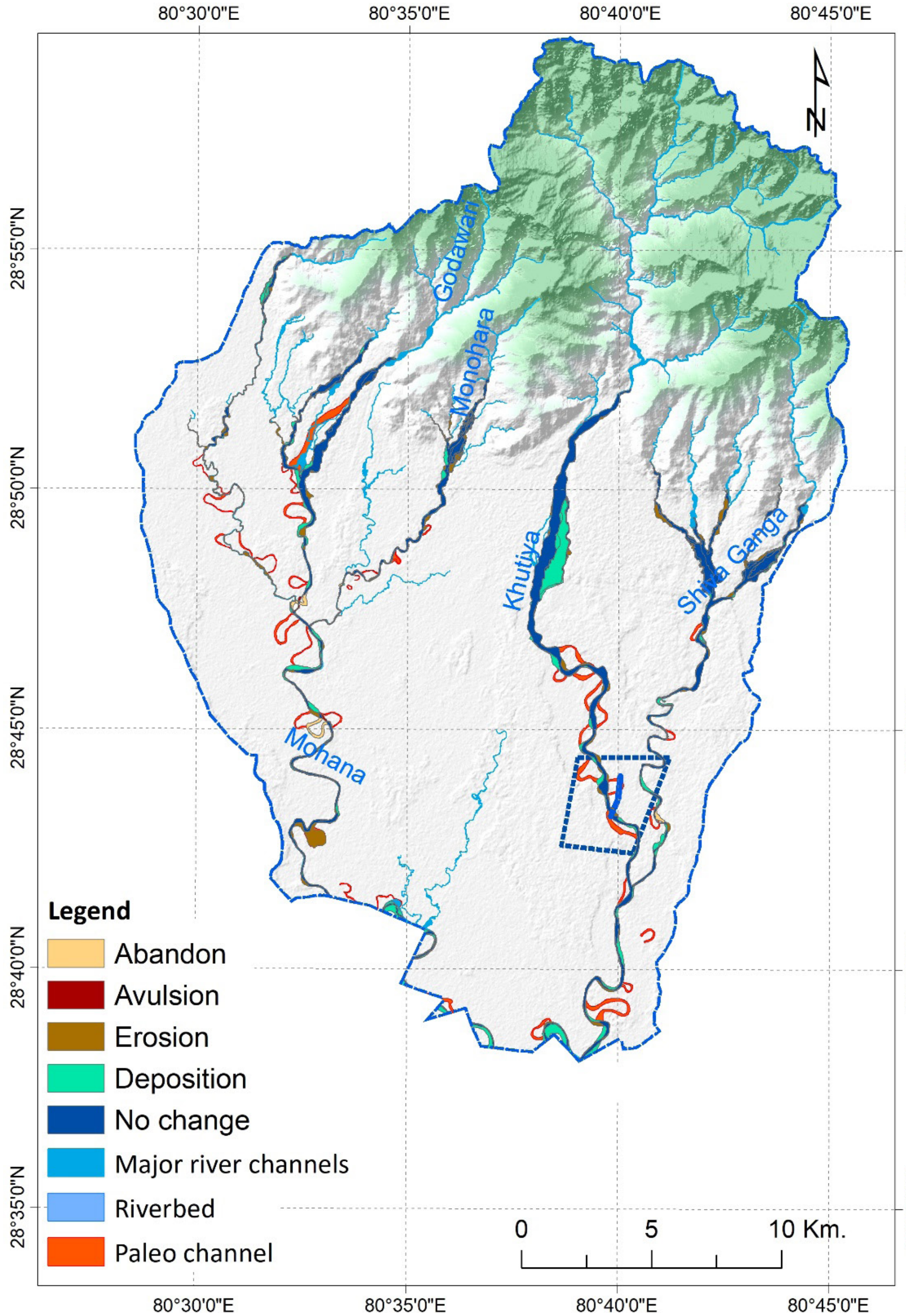



**Fig. 9: Planform change in river morphology between 2018-2024.**

**Table 3: River processes in planform of channel morphology.**

| River Processes | 2014-2018 | | 2018-2024 | | Total | |
|---|---|---|---|---|---|---|
| | Area (ha) | Ha/year | Area (ha) | Ha/year | Area (ha) | Ha/year |
| Bank erosion | 330.8 | 82.7 | 379.9 | 66.7 | 710.7 | 73.3 |
| Avulsion and erosion | 32.2 | 8.0 | 7.2 | 1.3 | 39.4 | 4.1 |
| Deposition | 565 | 141.3 | 606.5 | 106.4 | 1171.5 | 120.8 |
| Channel abandonment and deposition | 75.3 | 18.8 | 38.6 | 6.8 | 113.9 | 11.7 |
| No change | 1764.6 | 441.2 | 1667.6 | 292.6 | 3432.2 | 353.8 |

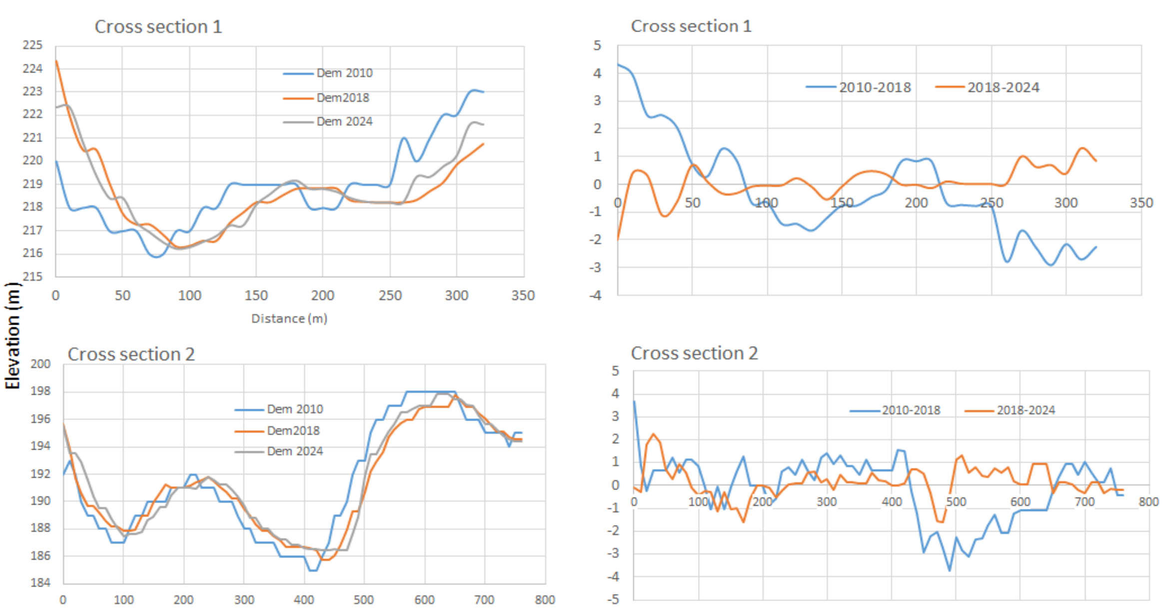
Cross-section morphology was examined using DEM derived from the Interferometric synthetic aperture radar (INSAR) data taken by Sentinel-1A in April 2018 and July 2024. The ALOS PALSAR DEM representing 2010 was also used to examine the change in the cross-sectional form of the river morphology (Kryniecka, *et al.*, 2022; Marchetti, 2023). Sentinel-1 images and ALOS PALSAR DEM were also obtained from the Alaska Satellite Facility. The cross-sectional profile at different locations of the Mohana, Godavari and Khutiya Rivers reveals that aggradations and degradation processes are significant in all cross-sections (Table 4 and Fig. 9). However, there is substantial variability in sediment aggradation and degradation across different geomorphic zones (Table 4). Within the river, with the same cross-section, there is also remarkable variability in the river processes (Fig. 9). There was a significant net gain of sediment in m3/m at CS1 (fan zone), CS4 (Sand, silt and gravel) and CS8 (sand and silt zone). At this location, the net gain of sediments was 93, 1209.9, and 253 m3/m, respectively. CS2 witnessed the highest net gain (1209.9 $m^3/m$) in a fan zone, followed by CS10, i.e., 722.6 m3/m in a fine sand and silt zone. Huge deposition in these areas (although sediment characteristics differ) could potentially lead to bed-level rise and impact flow patterns.

Significant to substantial sediment loss was observed at CS3 (fan), CS6 (sand, silt, and fine gravel), CS9 (fine sand and silt), and CS12, CS13, and CS14 (fan). CS6, CS9, and CS13 indicate significant sediment loss, which could imply an increase in erosion and sediment transport downstream.

The decline in bank erosion and avulsion rates suggests stabilization of riverbanks or effective erosion control measures. Several river training programs, such as constructing levees, embankments, spurs, or other structures to ensure the river flows safely within its banks, especially in areas prone to erosion or flooding, have been constructed in the Mohana-Khutiya basin by the Government of Nepal. This aligns with studies by Fuller *et al.* (2013) Hooke (1984), and Thorne *et al.* (1997) emphasizing that effective river management can reduce erosion and avulsion rates.

**Table 4: River processes observed in cross-sectional channel morphology**

| Cross-section | Degradation | | | | Aggradation | | | | Annual Balance (m3/m) | Zone |
|---|---|---|---|---|---|---|---|---|---|---|
| | Total depth (m) | Yearly average | Length (m) | Vol/m/year | Total rise (m) | Yearly average | Length (m) | Vol/m/year | | |
| CS1 | -5.55 | -0.97 | 140 | -136.2 | 7.69 | 1.35 | 170 | 229.2 | 93.0 | Fan (SCGB) |
| CS2 | -13.67 | -2.40 | 300 | -719.7 | 24.44 | 4.29 | 450 | 1929.5 | 1209.9 | Fan (SCGB) |
| CS3 | -12.94 | -2.27 | 290 | -658.6 | 7.05 | 1.24 | 360 | 445.4 | -213.2 | Fan (SCGB) |
| CS4 | -7.05 | -1.24 | 250 | -309.3 | 10.92 | 1.92 | 250 | 479.0 | 169.7 | Sand, silt, fine gravel |
| CS6 | -15.83 | -2.78 | 280 | -777.5 | 6.22 | 1.09 | 280 | 305.3 | -472.2 | Sand, silt, fine gravel |
| CS8 | -9.63 | -1.69 | 360 | -608.5 | 10.43 | 1.83 | 470 | 860.0 | 251.5 | Sand and silt |
| CS9 | -10.91 | -1.91 | 350 | -670.2 | 5.91 | 1.04 | 240 | 249.0 | -421.2 | Fine sand and silt |
| CS10 | -5.61 | -0.98 | 370 | -364.2 | 10.16 | 1.78 | 610 | 1086.8 | 722.6 | Fine sand and silt |
| CS11 | -5.62 | -0.99 | 120 | -118.4 | 3.61 | 0.63 | 80 | 50.7 | -67.7 | Sand and silt |
| CS12 | -17.27 | -3.03 | 200 | -606.0 | 8.81 | 1.55 | 160 | 247.3 | -358.7 | Fan (BCG) |
| CS13 | -23.75 | -4.17 | 210 | -874.9 | 7.67 | 1.35 | 210 | 282.6 | -592.3 | Fan (BCG) |
| CS14 | -14.15 | -2.48 | 130 | -322.7 | 1.00 | 0.18 | 30 | 5.3 | -317.5 | Fan (SG) |




Cross section 3
Dem 2010
Dem2018
Dem 2024
Cross section 3
2010-2018
2018-2024
Elevation (m)
Cross section 4
Dem 2010
Dem2018
Dem 2024
Cross section 4
2010-2018
2018-2024
Cross section 6
Dem 2010
Dem2018
Dem 2024
Cross section 6
2010-2018
2018-2024
Elevation (m)
Cross section 8
Dem 2010
Dem2018
Dem 2024
Cross section 8
2010-2018
2018-2024


**Fig. 10: Cross section forms the river morphology measured at various locations.**

## CONCLUSIONS

This study employed a comprehensive approach to investigate the basin and morphologic features of the Mohana-Khutiya Rivers in far-west Nepal, employing GIS, remote sensing, field surveys, and hydrodynamic modeling. These methods enabled a detailed analysis of the river morphology and its influencing factors across a basin of 702.4 $km^2$, characterized by distinct land use patterns in upper and lower catchment and complex geological settings. Geologically, the upper catchment is underlain by Siwalik Group rocks, while the lower reach consists of quaternary deposits. The study revealed that steep and rugged topography, high uplift rates, and intense monsoons contribute to frequent and extensive landslides, which lead to high sediment yield in the basin's upper part and impact channel morphology downstream. The study also exposed the correlation between channel slope, sediment type, and river morphology. During the last decade, river processes such as erosion (bank and avulsion), deposition, and channel abandonment have evidenced changes in the planform of river morphology. The hydrodynamic model indicates that changing hydraulic variables influence the river's processes and morphology. Cross-sectional analysis of the rivers also shows significant variability in sediment aggradation and degradation, impacting bed-level and flow patterns, indicating dynamic river processes. Notable sediment gains at certain cross-sections and losses at others indicate dynamic river processes, impacting bed-level rise, erosion, and flow patterns. A decrease in the annual rates of all river processes (erosion, avulsion, deposition, and channel abandonment) suggests stabilization in riverbanks. Comparatively, deposition remains the most extensive process, which indicates an excessive sediment load from upstream.

Lastly, this research provides valuable insights into the complex interplay of factors shaping river morphology in the Mohana-Khutiya basin. The findings can inform better management practices and policies to mitigate risks and enhance the sustainability of riverine systems in the region through effective soil conservation, watershed management, and flood control strategies.

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## AUTHOR CONTRIBUTIONS

Dr. Motilal Ghimire prepared the study concept and research design. He conducted fieldwork and generated spatial data from satellite images, including InSAR data, Digital Elevation Models, and published maps. His specific contributions were to the study of basin characteristics and the morphology of the river under investigation. Dr. Puspa Sharma contributed to data generation and updating using remote sensing sources. She also assisted with data analysis, cartography, writing, and manuscript formatting.

## CONFLICT OF INTEREST

The authors declare no competing interests.

## DATA AVAILABILITY STATEMENT

The data supporting this study's findings are available from the corresponding author upon reasonable request.

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