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A Spatial Analysis of Sediment Connectivity of Ranikhola River System in Sikkim Himalaya, India

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Abstract:

The concept of sediment connectivity refers to the degree of linkage between sediment sources and downstream areas. It is mainly affected by the longitudinal (dis)continuity of channels associated with depressions and confluences along the channel, and it represents variations in the balance between the sediment load and the transport capacity of the channel along a line. This study analyzed the stream channels as pathways and sinks of runoff carried with sediment along a mountainous catchment. The aim of this study was to investigate the effect of streams on connectivity and the linkage between sediment source area, stream network and outlet, and their contribution to sediment connectivity patterns in the mountainous catchment. In addition, to validate the output through field investigation at specific locations considering the degree of (de)connectivity. The index of sediment connectivity (IC) is used to analyze the sediment connectivity in the study area. The shape of the glacier cirque significantly influences the connectivity in the upper hanging valleys (Messenzehl et al., 2014). IC decreases when channels are considered conduits and sinks for sediment-loaded runoff, particularly on upper hill slopes. The map shows that the closer the distance to the channels, the more significant impact on the IC. The IC channels map showed the areas closer to the main channel have high IC values (1.160 to -0.608), while sub-catchments and steep hill slopes have low values (-5.912 to -7.680). On the other hand, it is evident from the IC Outlet that the upper Ranikhola region has a low IC value (i.e. -9.21), while the lower reach of the main channel receives a high value (i.e. 2.14). So, there was a striking difference between the IC channel and the IC outlet value for the Ranikhola basin. The formation of the flat regions on steep slopes caused by terrace farming typically reduced connectivity, although, at some locations, topographic convergence brought about by terraces enhanced connectivity. In the river bed, the presence of an excessive range of loads, ranging from coarser particulate matters to erratics with a mean load diameter size of 6 to 7 feet (6 ft., which indicates medium to larger monolithic deposits), and boulders that are commonly found to be coarse to very coarse in size (ranging from approximately 6.56 metres to 13.12 metres in length), makes it easier for sand to become trapped. This study also revealed that this model is helpful when understanding the sediment movement in a catchment situated at the foothills of the mountain. However, in this context, systematic field investigation was complex to uncover the links between hill slopes and river networks.

1. Introduction

In geomorphology, the term 'connectivity' refers to the spatial and structural pattern of the hydrological and geomorphological components and the interconnections between hill slopes, floodplains, and river channels (Michaelides & Wainwright, 2002; Singh et al., 2020). Connectivity explains how energy and materials, such as energy, water, and sediment, travel through diverse landscapes and segments (Jain & Tandon, 2010). According to Singh et al. (2020), connectivity has three fundamental components: the types (hydrologic connectivity, landscape connectivity, and IC i.e index of sediment connectivity), the components (functional and structural connectivity), the dimensions (longitudinal, vertical, lateral, and temporal connectivity).

IC refers to transporting sediments from the source to the downstream zone in all geomorphological regions within a landscape (Bracken et al., 2015). Furthermore, the IC in a river basin provides an understanding of sediment dynamics and transfers through various landscape components from the source to the downstream area. It involves sediment transfer from the source area to an ultimate destination by geomorphic processes, such as sediment erosion, transportation, and deposition (Bracken et al., 2015). According to Heckmann & Schwanghart (2013), IC represents "the degree of coupling," which refers to the combined effect of lateral (hillslope to channel) and longitudinal (upstream river reaches to downstream) linkages between different parts of the environment.". The sediment generation, transfer, and accumulation processes that operate within and across distinct landscape components (hillslopes, channels, floodplains, tributaries, and mainstream) influence the magnitude and efficiency of these mechanisms (Harvey, 2002; Fryir et al., 2007; Bracken et al.,

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2015) and to deal with longer-term climate change and anthropogenic activities (Mao et al., 2009; Mishra et al., 2019). Various natural factors, including relief, roughness, stream density, stream flow, sub-surface flow, catchment shape, soil permeability, rainfall, and water retention capacity, along with human activities such as deforestation, afforestation, agricultural drainage systems, vegetation strips, riparian vegetation, land abandonment, and landslides, all play a significant role in the process of sediment transport within a catchment (Mishra et al., 2019). A complex relationship can develop when the feedback between sediment movement, transportation, and deposition is considered, along with the roles of various landscape components and environments that influence how sediment is transferred from the sediment source points to the main river channel (Brierley et al., 2006; Webb & Walling, 1982; Bracken et al., 2015; Lisenby & Fryirs, 2017). Changes in IC, which determine the soil and water quality, affect the soil deterioration process, sediment transport, and transferring anthropogenic substances deposited in sediment (Bracken et al., 2013; Zhaoa et al., 2019). The concept of connectivity (Wohl et al., 2019) is crucial to understanding the interaction between the sources and sinks of sediments that could be implemented to estimate sediment delivery (Bracken & Crooke, 2007; Fryirs et al., 2007). It should be noted that spatial analysis of IC aims to determine the pathways and transit where sediments are transported (Cavalli et al., 2013). Additionally, this study allows us to enhance our understanding of how sediments move and our capability to forecast the movement of sediments and the resulting impacts downstream in large river systems (Baartman et al., 2013).

Several studies have been attempted on this concept (Najafi et al., 2021; Wohl et al.,2019, 2016), its types i.e., functional and structural connectivity (Vicente & Salem, 2019; Lu et al., 2019), and effects of different components such as agricultural drainage system (Calsamiglia et al., 2018), impedance influence (Zanandrea et al., 2019), erosion barriers of soil (Vicente et al., 2021; Boardman et al., 2019), catchment scale controls on IC (Lisenby & Fryirs, 2017), land-use changes and topography (Llena et al., 2019), volcanic eruption (Martini et al., 2019) its connection to debris flow pattern (Schopper et al.,2019), soil erosion (Zhaoa et al., 2019) and redistribution in lowland and high hilly catchment areas in many countries of the world. In addition, the effects of anthropogenic activities (Persichillo et al., 2018) and their management (Evrard et al., 2011; Poeppl et al., 2020) are also vital in different regions. However, so many attempts have been made with different aspects, very few have focused on the effect of stream, stream confluence, and the linkage between sediment source area, stream networks, and outlet in the catchment. In this context, some questions may arise and be tried to be solved in this study. (i) How do pathways affect the IC of a region or river basin? (i) How are sediment source area, stream network and channel outlet interconnected and lead to IC?

IC has been evaluated by previous workers using a variety of qualitative and quantitative methods, where qualitative techniques typically rely on field observations in the context of geomorphology and sedimentology, as well as monitoring of sediment flow using various instruments in fields (Harvey, 2002; Mao et al., 2009; Comiti et al., 2014), and quantitative techniques deal with the indices and models formed based on topographical data. After that, the work of the geomorphologist was concentrated on sediment cascades (Fryirs, 2012), where the processes (supply, transport, and storage of sediment) happened in the catchment area. A conceptual framework is applied to assess the connectivity of sediment in several studies (Fryirs & Brierley, 1999); some authors worked on hillslope sediment delivery ratios (Vigiak et al., 2012), alpine sediment movement using graph theory (Heckmann & Schwanghart, 2013), and used a multi-methodological approach including field monitoring, computer simulations, mapping, remote sensing and for a detailed understanding of connectivity and its pattern with different other components (Heckmann et al., 2016; Schopper et al., 2019). The Geomorphometric Index (GI) (see Cavalli et al., 2022) method was applied to find out the sediment transfer-prone area (Borselli et al., 2008; Zanandrea et al., 2019), using varied landscape components (Cavalli et al., 2013). In this study, the IC approach is employed to assess the sediment connectivity of the study area. Borselli et al. (2008) introduced the IC approach for the investigation of agricultural areas; later on, this approach acquired a large area of research after the modification by Cavalli et al. (2013), applied to assessing the high mountain region.

This study mainly focused on the spatial (dis) connectivity of sediments analysed by the connectivity pattern (Borselli et al., 2008), where stream channels are considered the pathways and sink of materials carried by the runoff process. The main aim is to comprehend the effects of stream paths and their influence on the connectivity and the association between sediment source regions, channel networks and catchment outlets in the mountain catchment. In addition, to validate the analysis output by field investigation, and to find out the link between the outputs and field observations serious care was taken up. However, it is important to do such an analysis because it can have implications for reservoirs, rivers, resources and natural hazards. This study will provide an understanding of spatial sediment (dis) connectivity and a scientific concept of the spatial relationship of various components with the river sediment pattern in the mountain region and the immediate downslope. Considering the connectivity between watershed components with different natural and management characteristics is crucial to assessing hydrological and erosional responses. Connectivity assessments for hydrological, erosional and sediment management are also effective screening tools for spatial prioritization.

2. Materials and methods

The Ranikhola river basin is located in the southern part of the Sikkim Himalayas of India. The river flows in a south-western direction; and joins with the Ratey River near Gangtok town continuing to the north-eastern part of the Ranikhola basin. The red square mark (Figure 1) indicates the confluence point of the Ranikhola channel at the

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southwestern part and the leaf shaped basin that indicates diagonal movement (N-E to S-W direction) of the river-channel.

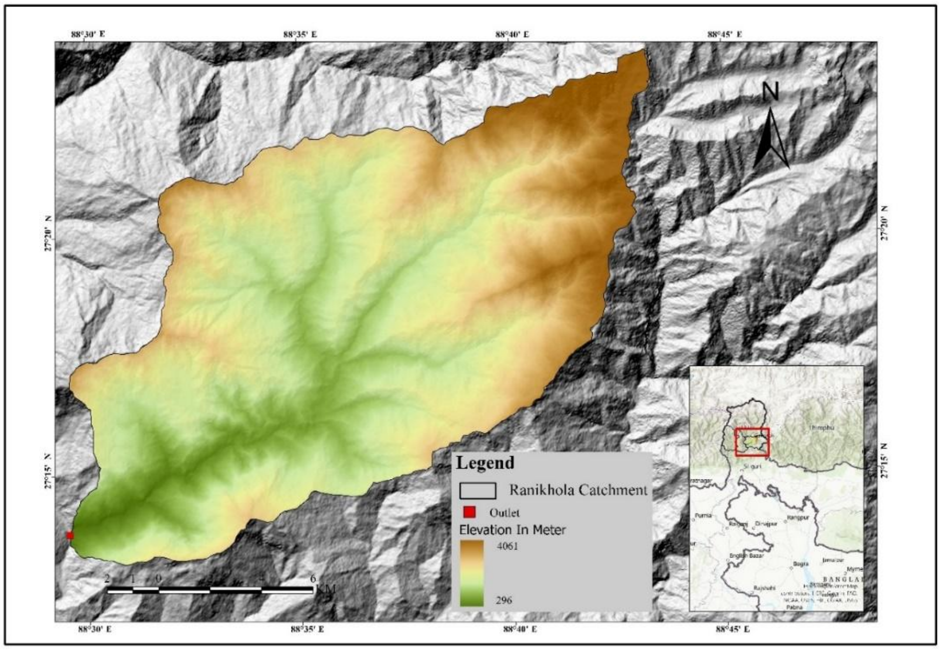

Figure 1a Geographical identity of the Ranikhola basin

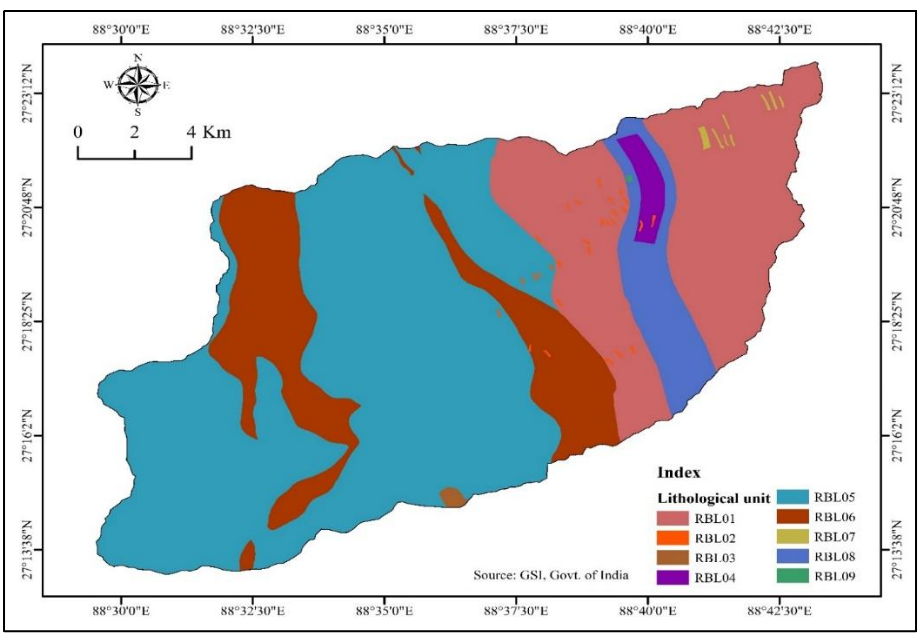

Figure 1b Geological set-up of the study area (Ref. to Table 1) [Dutta et al., 2024]

flow and rejoin with the Roro River near Ranipool (Figure 1). Ranikhola River is one of the major tributaries of the Teesta River, also known as Rongni Chu, in the local language around Gangtok town. The watershed constitutes a total area of approximately 254 km^2. Geologically, this region comprises three rock formation groups: Kangchenjunga Formation, Chungthang and Gorubathan (Table 1). In the central and western parts of the watershed, over 50% of the rocks are formed of the Daling Formation. The river basin has a diverse sediment composition, where small to large boulders, pebbles, cobbles, fine sand and silts are concentrated within the main channel and the river banks. Some deposits from the Meso-Proterozoic and Proterozoic eras are concentrated in the upper catchment area. The elevation varies from 300 to 4100 m a.s.l, where the highest elevation is located in the northern part and the lowest elevation is in the southwestern part. Most of the area is spread over a high mountainous portion with extremely steep slopes, having an average angle of 30 to 40 degrees. The steep slopes are seen in the northern part, and medium slopes are located in the southern part of the basin. Most rainfall occurs between July and September, and the average annual rainfall is more than 300 mm. A significant amount of snow falls in higher altitudes of the watershed normally found in January. The average annual range of temperature varies from 0^o to 25^o C. The vegetation in this area comprises dense forests, open forests, alpine scrubs, grasslands and conserved forests, which are enriched with a wide variety of flowers. The Northern basin consists of hanging valleys, deep ravines and hummocks, glacial moraines of rounded or elongated hills, cirques, convex slopes and depressions. In contrast, the southern basin is associated with V-shaped valleys and river terraces, and the middle region gradually evolves into a typical flat trough with concave slopes. The rocks in the upper section of this area are particularly fragile and highly susceptible to rock falls, landslides and riverine erosion. Numerous rock-fall events with relatively low magnitude and debris flows are also highly active here, often moving talus sediments in the basin and carving pronounced channels deep into bedrock cliffs. Natural streams with varied flow characteristics over steep slopes, excessive surface runoff, artificial drains and gushers, and distinct anthropogenic activities are the driving forces for increasing the landslide potential. These activities shift sediments away from their initial sites and modify their structures. All these factors aggravate the accumulation of sediments in the downslope of the basin.

RBL 01 group is the main source of material influx in the river system, which receives hydrated quartzite, mica schist, Gneiss, and calcium-based granulitic rocks. As per composition, they receive amorphous impurities, which are highly related to the denudation processes in this excessive rainfall-infested belt. The other major group of formation is RBL 05, which shows the huge concentration of quartzite resulting from the last Tertiary metamorphism of sandstone having imprints of cracks and fissures. In turn, this formation abundantly supplies clastic materials within short periods of weathering responses. Another dominant formation is RBL 06, composed of erodible chlorites and schists mixtures. In gross hydration,

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carbonation and chelation processes are really in continuous action to supply sediment load to the network system. The maximum concentration points or tri-juncture of the river is located at 27°15'59"N/88°35'21"E which receives 70 to 75% of the load, gets in-fluxed till its mouth before debouching into the Teesta major and shows a high rate of load infested over the flashy nature of the river Ranikhola channel in freshet season.

Table 1 Lithological settings of the Ranikhola basin in Sikkim

ID	Age	Group Name	Formation	Lithologic unit
RBL01	Proterozoic	Central Crystalline Gneissic Complex	Chungthang	Quartzite, Mica Schist, Gneiss, Calcgranulite
RBL02	Proterozoic	Central Crystalline Gneissic Complex	Kanchenjunga Gneiss	Banded Migmatite, Garnet Biotite Gneiss, Mica Schist
RBL03	Proterozoic	Central Crystalline Gneissic Complex	Chungthang	Calc Silicate Rock
RBL04	Cenozoic (Unclassified)	NA	NA	Tourmaline Granite
RBL05	Proterozoic	Central Crystalline Gneissic Complex	Chungthang	Quartzite
RBL06	Proterozoic	Daling	Gorubathan	Chlorite Sericite Schist And Quartzite
RBL07	Mesoproterozoic	Lingtse Gneiss		Mylonitic Granite Gneiss
RBL08	Proterozoic	Daling	Gorubathan	Biotite Quartzite
RBL09	Mesoproterozoic	Lingtse Gneiss		Mylonitic Granite Gneiss

Source: Geological Survey of India, Govt. of India.

2.1 Materials

In this study, the ALOS PALSAR Digital Elevation Model (DEM), having a spatial resolution of 12.5 m, is used to obtain an accurate and detailed representation of the Ranikhola basin. With the filling technique in ArcGIS software (version 10.4), the possibility of regional depressions is eliminated by serving as sinks that could influence the results. Morphometric analysis is crucial and is used to develop Connectivity (Cavalli et al., 2013; Messenzehl et al., 2014). Here, the IC used the surface roughness (Bracken et al., 2015; Fryirs, 2013; Wester et al., 2014; Wohl et al., 2017; Alfonso et al., 2022) as well as the features of the drainage area and the length of the prospective sediment flow path to determine specific deposits. An ArcGIS toolbox that employs the methodology outlined (Cavalli et al., 2013) was used to calculate the IC. ArcGIS Desktop 10.4 software implements the model using the TauDEM 5.2 (Tarboton, 2012) tool package. The D-infinity algorithm was developed by Tarboton (1997) and then used in the connectivity index by Cavalli et al. (2013), who, in the frame of a European project named SedAlp, developed an ArcGIS Toolbox (Cavalli et al., 2015) implementing functionalities of TauDEM 5.2 (Tarboton et al., 2013).

2.2 Methods

2.2.1 Index of Sediment Connectivity

To evaluate possible connections between hill slopes and features like channels, basin outlets, lakes, and roads that serve as targets or sinks for transported sediment, IC evaluates the potential link between hill slopes and features (Zhao et al., 2022). As a pixel-based indicator, the IC indicates how likely the sediment will reach the sinks within a defined area. The IC is based on DEM and surface runoff impedances related to different land uses and as a result, aims to assess the effects of topography and land cover on sediment transfer processes.

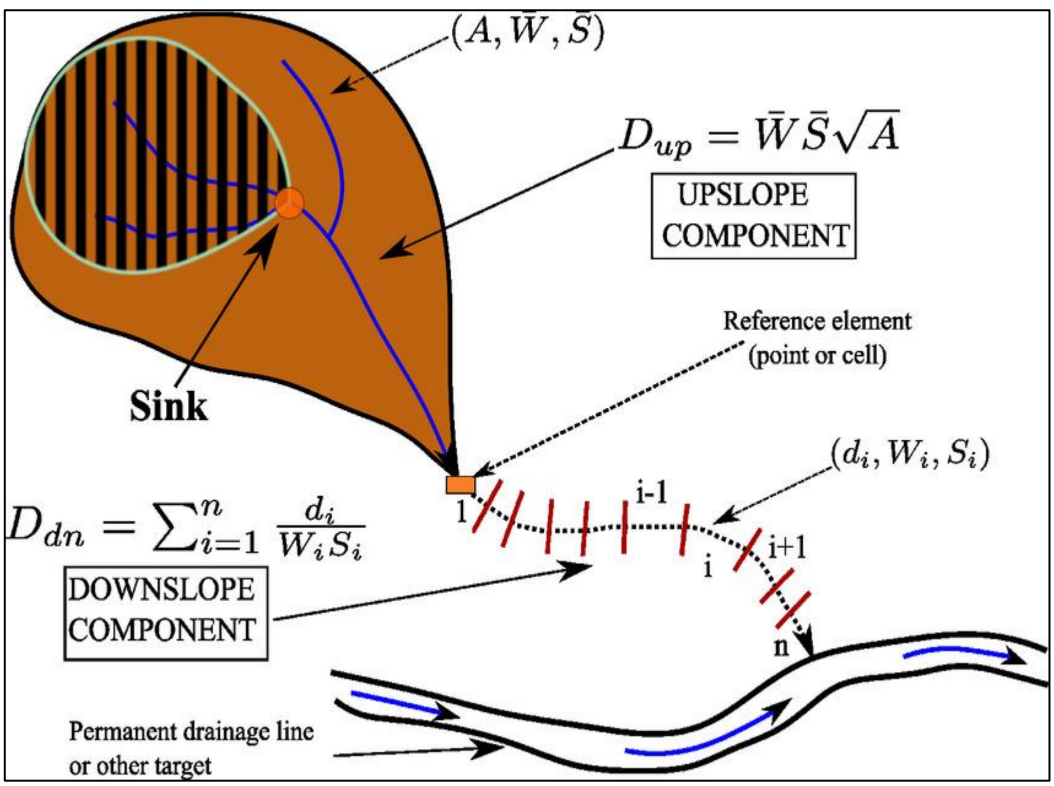

Figure 2 Upslope and downslope component of Sediment Connectivity (Borselli et al., 2008).

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The study of morphological changes within a catchment is particularly suitable for studying the changes in IC induced by those changes. It can vary between $-\infty$ and $+\infty$ (Torresani et al., 2021), which is the logarithmic ratio of the upslope component (D_{up}) to the downslope component (D_{dn}) wherein higher IC values signify more connection within the sediment (Alfonso et al., 2022) supply. This study depicted the possibility of sediment routing that is generated upslope and moving downhill as well as the length of the flow within a channel and every particle must travel the physical distance to reach the closest target. The drainage area and flow route characteristics were taken into consideration in the connectivity index. The downslope component (D_{dn}) focuses on the likelihood that sediment and runoff will end up at a certain sink along the river networks. The upslope component (D_{up}), which considers the slope and size of the contributing region, reflects the possibility for downward routing of overland flow (Figure 2) occurring upslope and executes a stream power-like framework. IC for each cell of the catchment is calculated by considering the features of the sediment contributing area (D_{up}) and the sediment flow through river networks to the outlet (D_{dn}) (Crema and Cavalli, 2018). The choice of a specific target, or the target portion of an objective, is an important step in an IC analysis because it determines the perspective on which the analysis is based, for instance, an assessment based on a slope, a channel, or a specific cross-section of a river (Martini et al., 2019) may be done.

$$D_{up} = \overline{W}.\overline{S}.\sqrt{A} \qquad \text{………………..1}$$

Where the dimensionless parameter W represents the weighting factor for upslope contributing areas and is related to the type of roughness, S describes the slope and A represents the contribution area. D_{up} is the cell's contributing area that shows an upslope component.

Sediments travel through flow paths to reach their target or sink along the river networks, so here the downslope component D_{dn} has been taken into consideration for its important contribution.

$$D_{dn} = \sum_i \frac{d_i}{W_i S_i} \qquad \text{……………….2}$$

W_i and S_i are the weighting factors and slope gradient of the i_{th} cell, respectively, where d_i is the flow path length along the i_{th} cell in terms of the steepest downslope direction. It's important to keep in mind that d_i can take on two different values: cell size (l) for cardinal directions and $l\sqrt{2}$ for diagonal directions.

The final calculation of IC is done by considering each cell's contributing area (D_{up}) and flow paths along the river networks (D_{dn}) using the following formula:

$$IC= log_{10} \frac{D_{up}}{D_{dn}} = log_{10} \left\{ \frac{\overline{W}.\overline{S}.\sqrt{A}}{\sum_i \frac{d_i}{W_i S_i}} \right\} \qquad \text{………………..3}$$

2.2.2 Weighting factor

Borselli et al. (2008) developed the weighting factor W to simulate the impedance to runoff and sediment fluxes caused by local land use characteristics and soil surface characteristics. The weighting factor W may be found in the upslope and downslope components of IC. The C-factor of RUSLE models (Wischmeier & Smith, 1978) was applied by Borselli et al., 2008 as the weighting factor W. When the soil is more susceptible to erosion, the C-factor, which is connected to vegetation cover and management, reaches its highest value, and it approaches zero when the soil is more protected. However, the W should be obtained from surface properties that affect runoff processes and sediment fluxes within a watershed or a hill slope. Here, the surface roughness index (Upadhyay et al., 2020) is an important impedance to sediment and runoff fluxes. First, the single-flow (D8) direction technique or IC was replaced with the D-Infinity algorithm (Tarboton, 2013), which produced more realistic flow patterns and improved delimitation of the contributing area. Second, the C-factor of USLE-RUSLE models in the original index was replaced with the W-factor produced using the roughness index RI (Cavalli & Marchi, 2008; Cavalli et al., 2013). As a result, a roughness index (RI) has been considered, being a local indicator of topographic surface roughness, as the weighting factor W. Here, the residual topography's standard deviation at a scale of a few meters is used to estimate the roughness index. The following is the definition of the roughness index:

$$RI= \sqrt{\frac{\sum_{i=1}^{12.5\times 12.5}(xi-xm)^2}{12.5\times12.5}} \qquad \text{..................4}$$

Where 900 is the number of processing cells within the 12.5 × 12.5 cells moving window, xi is the value of one residual topography cell inside the moving window, and xm is the mean of the values of the 900 cells. The weighting factor is stated in the following way:

$$W= 1-\left(\frac{RI}{RImax}\right) \qquad \text{..................5}$$

$Where,\ RImax$ is the maximum value of the Roughness index. Based on the RI, the W calculation produces a skewed distribution of values crammed into a weighting factor of 1 with a very small variance range. To increase the geographical variability of W, the authors proposed normalizing the natural logarithm of roughness.

3. Results

3.1 Spatial Pattern of the Morphometric Attributes

There is a lot of variation in channel slope (Figure 3) in the upper Ranikhola basin. The northeastern and western portion of the basin is characterized by a very steep slope, ranging from 35 to 70 degrees, and the slope from the centre to the north and west has a moderate to gentle slope (Figure 4), ranging from 10 to 25 degrees, respectively. The capital of Sikkim state is in this region, which has a moderately

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sloping landscape from the centre section to the south. The stream power index (Figure 3) map illustrates the spatial variations of the stream power along the river channels from upstream to downstream. The stream power varies from very high in the main channel to very low in its tributaries due to the accumulation of water from tributaries.

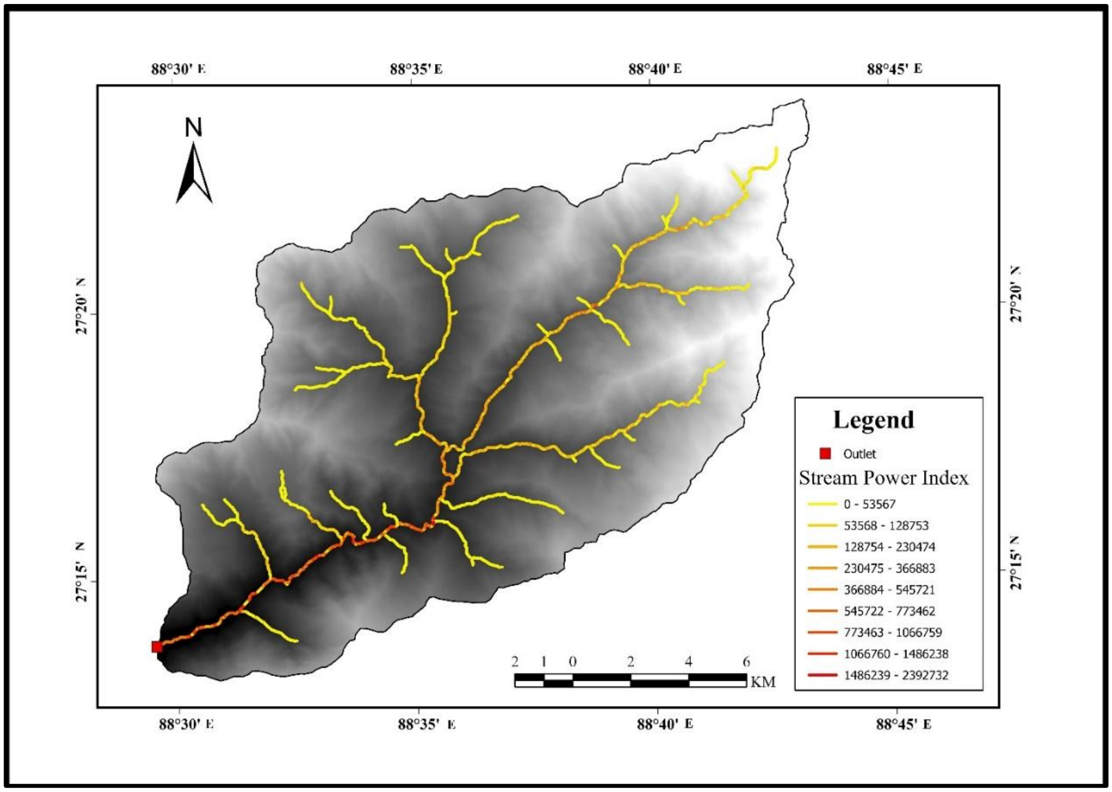

Figure 3 Spatial distribution of stream power along the Ranikhola River and its tributaries.

3.2 Slope, Stream Power Index and Flow Length

Here, slope, Stream power index and flow path are considered as major attributes for the analysis of IC (Baker et al., 2004; Cavalli et al., 2013; Najafia et. al., 2021). The slope has a significant influence on sediment distribution in a particular region, and the various physical processes act in response to slope types, resulting in various geomorphological features or landforms (Parker & Bendix, 2006). The steeper the slope, the more runoff will be produced, accelerate up, and gain energy, creating erosion and, subsequently, more downward cutting into the channel. The Stream Power Index (SPI) quantifies the erosive capacity of moving water using the size of the contributing area and local slope (Mishra et. al., 2019). The slope and the stream power are related (Figures 3 and 5) because if the slope inclination increases, the stream power also increases and vice versa. However, it also depends on the channel width and length due to flow accumulation in narrow channels and divergence in wider channels. The flow length of a stream steadily increases with increasing distance from the source, which indicates the likelihood of sediment-laden runoff entering the stream and decreases with distance. Flow lengths in streams indicate that streams may be able to reduce the distance of runoff loaded with sediment and must travel from a hill slope to a stream by changing the direction of transmission when considering that stream as the route for the forward transmission of sediment-loaded runoff.

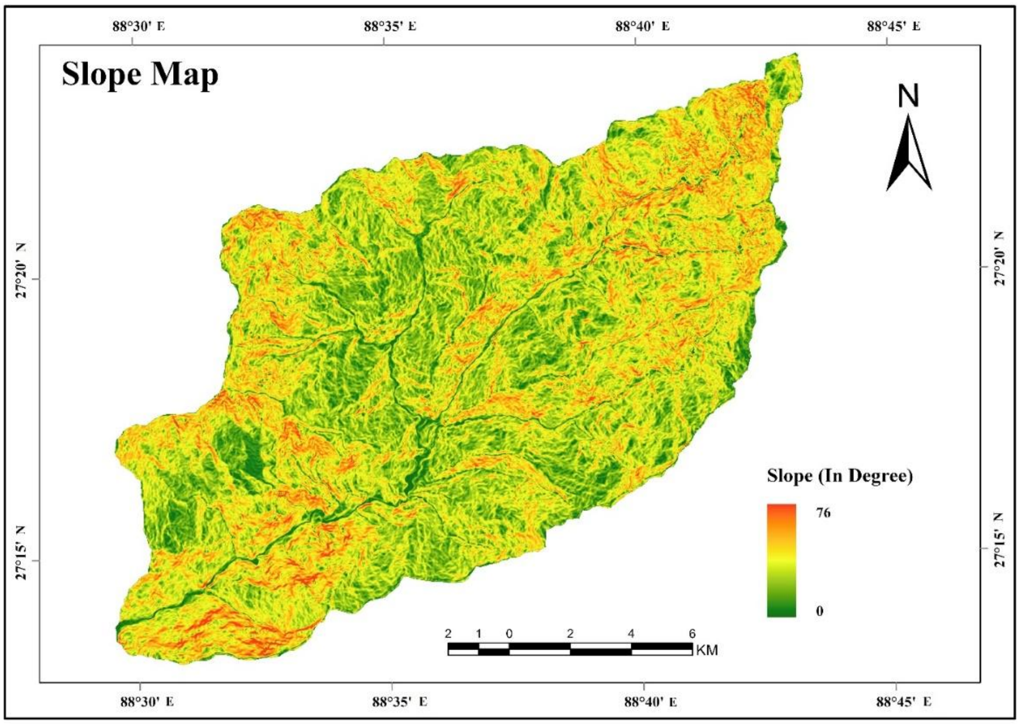

Figure 4 Spatial distribution of surface Slope in the Ranikhola river basin.

3.3 Spatial distribution of channel along the elevation

The main river and its tributaries in the upstream area have high altitudes ranging between 1409 to 2383 m above m.s.l, which resulted in the steep channel slope. It is seen that where the stream channel acts as a sediment-laden runoff sink (Borselli et al., 2008), the stream significantly reduces the distance between higher hill slopes and the stream junction, but on the other hand, its impact on runoff length gradually diminishes as its reach extends. The influence of a stream on the connectivity of sediment and the region to which debris from the higher hill slope contributed rapidly declines as one moves further away from the other stream.

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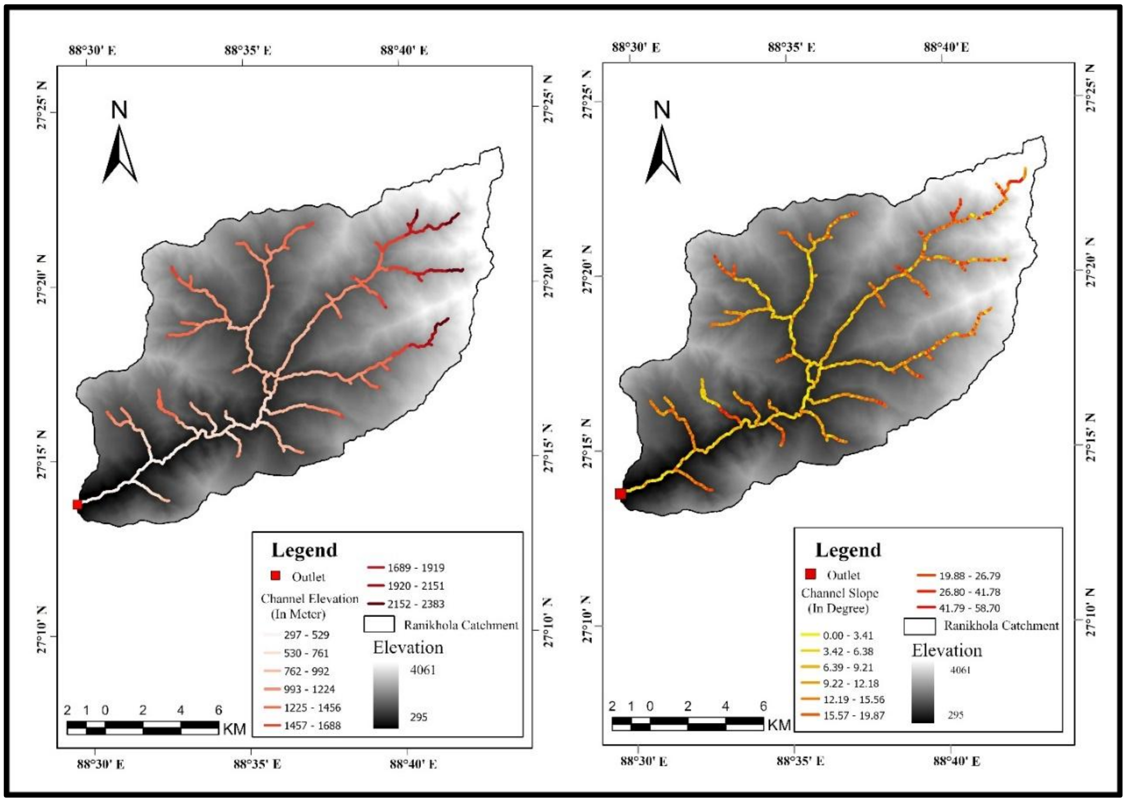

Figure 5 Elevation and slope map along the channel and depicts the variation of slope and elevation along the river channel.

3.4 Spatial patterns of sediment connectivity (IC $_{Channel}$)

An analysis of the spatial distribution of IC in the Ranikhola catchment was conducted using the connectivity index described above, with an emphasis on connectivity between hill slopes and catchment outflow (IC outlet), and hill slopes and major rivers and lakes (IC channel). Identification of the channels is necessary because the purpose of the study is to analyse the longitudinal connectivity between the channels. Figure 6 shows the spatial distribution of IC along the channel. The maximum, minimum and average values of IC have been shown in Table 2. There is also a wide dispersion of IC values around 3.92. The values of the IC vary from +1.16 (high) to -7.67 (low). Table 1 depicts the statistical information for the IC $_{Channel}$ values with highlighted geographic in/non-homogeneities. High values are seen in the main channels and lower values are mostly seen far from the main channel.

Table 2 Statistics of the IC channel and IC outlet in the Ranikhola sub-watershed

Parameter	Minimum	Maximum	Mean	SD
IC Channel	-7.68	1.6	-3.935	0.771
IC Outlet	-9.21	2.14	-6.62	0.59

Source: Compiled by authors

Note: SD-Standard deviation

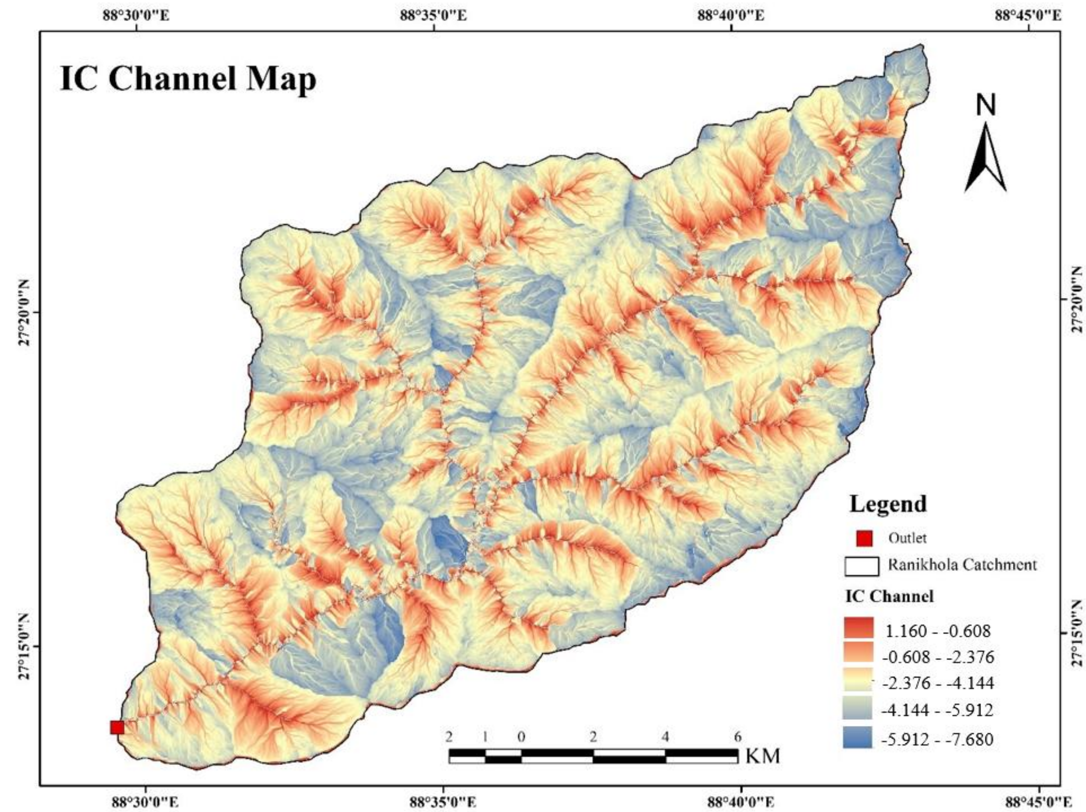

Figure 6 Distribution pattern of IC values in the channel network map of the Ranikhola catchment

These variations may indicate spatial variability in flow continuity that is associated with changes in longitudinal connectivity. In other situations, lower values are also found across the hill slopes, indicating a potential stream flow. The upper reach of the Ranikhola has a high IC value along the main channel, but the middle part exhibits a low value, according to the IC $_{\text{Channel}}$ map. On the other hand, a rapid break in the slope at the confluence point leads to high IC $_{\text{Channel}}$ values in this upper area. Land Use and Land Cover (LULC) changes significantly influence sediment connectivity by altering hydrological pathways and sediment transport dynamics (Anand et al., 2021; Kayitesi

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et al., 2022; de Oliveira Serrão et al., 2022; Adi et al., 2023). In river basins like Ranikhola, upslope LULC modifications can disrupt the confluence path, leading to erosion and sediment yield changes that influence the connectivity pattern. Glacier melting in the summer season carries gravel, pebbles, boulders, and other material also carried downstream by the flowing river. It is common to see high IC channel values on hill slopes sloping to the northeast or east of an axial river running across the southwest or western end of the basin. Finally, the lower portion is made up of the combined effects of the top and middle portions of the catchment. Steep and moderate slopes are mostly composed of hard rock, which is responsible for low IC values in the lower and middle valleys. The main channel in this part dominantly passes through the mountains and crosses a limited number of moderately flat valleys, resulting in moderate to low $IC_{channel}$ values. Based on the result, the IC -5.24 is the highest percentage of the overall catchment area. Approximately 70% of the whole catchment area covers the maximum IC value that is beneath the slope of 20 degrees. Anthropogenic activities observed across the watershed, such as road and building construction, terrace or contour farming, and settlement, all in combination or singularly affect the connectivity (Figure 9) prospects.

The assessment of IC has been conducted concerning the rivers, which results in a different pattern of connectivity in this basin. The IC channels map (Figure 6) shows that the areas closer to the main channel have high IC values (1.160 to -0.608), while sub-catchments and steep hill slopes have low values (-5.912 to -7.680). The sediment delivery rate may be significantly increased when distances along the river channel are short (Fryirs & Brierley, 2001; Lane et al., 2007; Wang et al., 2024). This river features mostly debris flow processes that have lower values of IC because bedload dominates the stream, while hilly terrain has higher IC values among basin channels. It is due to this extended leafy shape of the basin that the hill slopes are typically steep, and the catchment outlet is very unevenly connected. The steep gradient along the river thus makes it easier for sediment transportation. In contrast, the catchment's elongated structure increases the length of the sediment travel route of the finger strip channels, which aids in separating the upper area's hill slopes from the catchment outlet. The Stream channels served as primary routes for moving material down to hill slopes and had far more connectivity than the tributaries of rivers shown in the diagram. As the stream approaches the foot of the hill slope, its connectivity significantly increases, and this increase is depicted in Figure 6 where IC values are ranged. In addition to having high IC, the most dynamic sediment changes also occur at these locations. So far, the nature of connectivity is concerned, most erosion is occurring within the stream channel bed and boundary because concentration flow has more erosive force than sheet flow. As the channel extends further downslope, the flow power builds up, causing greater erosion. Stream power along the main channel is extremely high because of the enhanced discharge capacities from the contributory tributaries to flow downhill and gain energy to travel downstream. The main channel hence excessively cuts through the downhill with enriched and increased energy, which affects connectivity. Evidence of sheet erosion could be seen in one area in the top section. Even though the IC at such sites can be rather high, figure 7 revealed that most of the deposition took place close to the channel at the lower section of the hill slope. Deposition is more sparsely dispersed with a strong site means resistive to erosion or as opposed to erosion, which is scattered along the channel with a more continuous pattern.

3.5 Spatial patterns of sediment connectivity (IC $_{Outlet}$)

The pattern of connectivity for the entire basin has been evaluated using the IC, highlighting the connectivity concerning the catchment outlet and showing the different types of sediment connectivity over the basin. It is evident from the IC $_{Outlet}$ that the upper Ranikhola region has a low IC value (i.e. -9.21), while the lower reach of the main channel receives a high value (i.e. 2.14). There is a striking difference between the IC channel map and the outlet map for the Ranikhola basin. Several areas of the basin have moderate to high slopes that are highly connected to its outlet. The catchment outlet becomes increasingly close to the middle and lower parts of the basin, as the river flows downstream until it reaches maximum proximity to the catchment outlet. According to the map of the IC outlet, the lower part of the catchment has high values regarding sediment transport, which indicates that gullies and deep channels in the upper catchment have the potential to contribute more delivery of sediment to the IC outlet (Figure 7).

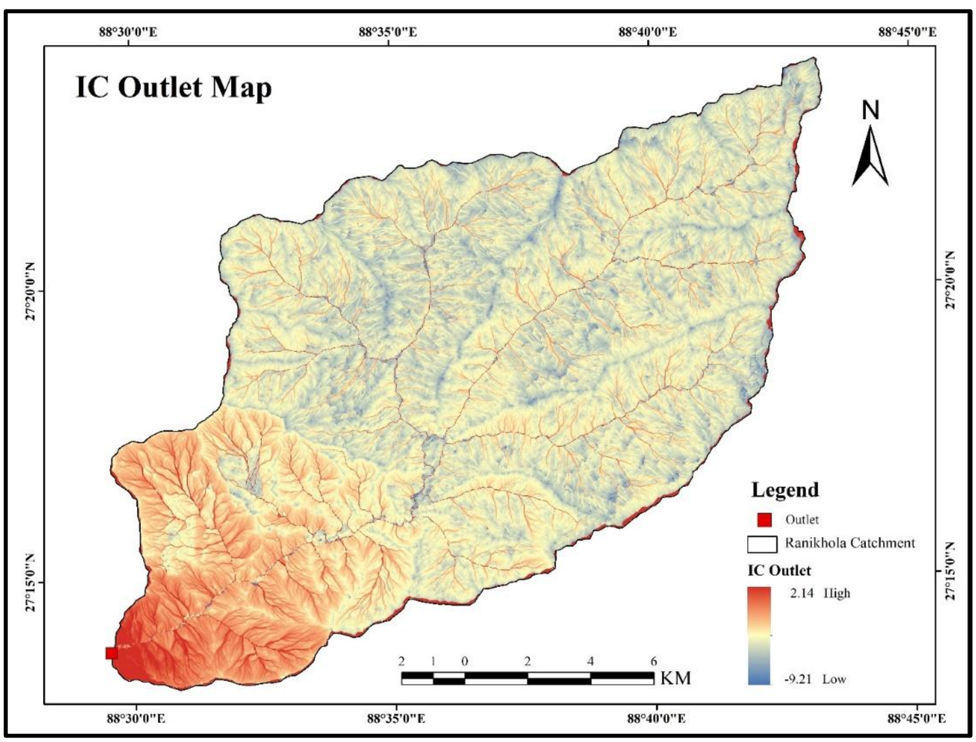

Figure 7 IC $_{outlet}$ map of Ranikhola Catchment

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Incised channels and heavily sloping terrain are only capable of producing a lower index value (Grant & Swanson, 1995; Geach et al., 2017). The upper portion of the channel has a convex slope that washes away all the material that erodes over the basin landscape. It is then deposited in the lower portion near the outlet of the channel as a result of the hydraulic action of the stream. Only a few minor locations close to the mainstream and the lakeside exhibited higher values of IC, which are predominant in the upper portion of the basin. While steep-sided slopes are present at the highest altitudes, the previous glacial and current periglacial processes in this area produce typically high slopes. Because of this, even if the absence of vegetation cover and the presence of dense, loose debris enhance erosion, only a tiny amount of sediment is delivered to the lakes and the main channel and this material are largely delivered via processes producing colluvial debris. An example of this can be seen at the upper lake's inlet, where there is no fully formed fan at all due to the lack of vegetation cover. There is almost an exact match between the abrupt changes in slope shown on the slope map of the channels of the tributaries and the change in the value of IC outlet from high to low associated with them. Although the elongated shape of these basins separates the upslope from the downslope area by distant channel, the distance and the amount of time it takes to reach the outlet of the basin are longer; however, the steeper river reaches are usually associated with narrow valleys that allow tributary valleys to be directly coupled up with the main river channel with contributing sediments.

4. Discussion

4.1 Controlling Factors and their relation to Sediment Connectivity

The findings revealed that the sediment connectivity varied by the slope patterns, vegetation distribution, human activities and so on. However, some places are rugged and remote so field validation could have been more feasible. The IC showed a spatial pattern of connectivity that is reasonably consistent with our field-based investigations throughout the catchment. Figure 8 explains the changes to the process of landforms that disrupt sediment transfer (Cavalli et al., 2013; Lopez-Vicente et al., 2013; Jing et al., 2022) within the catchments and the impact of surface structures on sediment flux. As a result of its steeply inclined slopes, the sediment supply from the top of the basin is significantly enhanced. In contrast, the lower part of the basin has channelized sediment paths and high slope profiles linked by high (Figure 5) and moderately connected sediment pathways. There are a few examples where bare surfaces have minimal infiltration rates, except for river networks, but this is due to the mass compaction of the underlying surface, which leads to more surplus overland flow than in undisturbed hill slope environments caused by infiltration (Jancewicz et al., 2019).

Consequently, the IC will be able to accurately reflect the geographical pattern of sediment connections under river impact of infiltration more effectively. That is why the IC Channel values decrease with distance from both sides of rivers that are used as a path for sediment to flow when calculating IC values because rivers are used as a path for sediment to flow (Torresani et al., 2021). The IC Channel values tend to decrease as you move further away from the riverbanks. This is because rivers act as natural pathways for sediment transport. When calculating IC values, the proximity to rivers is a significant factor since these water bodies facilitate the movement and deposition of sediment. Consequently, the sediment concentration—and thus the IC values—are higher near the riverbanks and diminish with increasing distance from the rivers (Torresani et al., 2021). Since the water flows along the steep slope of the river, there is a small amount of moisture. On the other hand, once the channel extends further, the IC_{Outlet} value dramatically drops, which is not seen in the case of the $IC_{Channel}$. Since materials from runoff, overland flow, and erosion are deposited together (Shown in the IC Outlet map Figure 7) at the outlet in the case of the IC_{Outlet}, the sediment connection is enhanced at the downstream part. In particular, the degree and pattern of connectivity within the watershed were directly affected by the spatial arrangement of targets (streams). Due to the target geographic composition and a more different drainage system within the basin, the scenarios showed a distinct pattern of medium-high and high IC values within the study area, given the dispersion of the river network. The calculated IC for both channel and outlet, the field investigation process can be compared to show the importance of each process in visualizing watershed connectivity based on these measurements and site-specific information using connectivity maps and field surveys. By calculating Internal Catchment (IC) values for channels and outlets and conducting field surveys, we can compare these processes to visualize watershed connectivity. Connectivity maps created from IC values and field data highlight how different areas within the watershed are connected. This comprehensive approach helps identify key areas affecting sediment transport and water flow, aiding in effective watershed management and conservation efforts. The geographic models of IC obtained in this watershed-scale work are generally consistent with the landscape features and connectivity mapping observed in the field. However, this index is confusing at a more local scale because it is based on a simple surface structure. Due to similar slopes and relatively high roughness, many upper slopes of the basin have high $IC_{Channel}$ values that are relatively similar across the basin. However, field mapping shows that these upland areas' sediment formation capacity and activity levels vary considerably across the basin.

The Kanchenjunga gneiss rock group found in the upper basin is quite resistant to erosion, and much of the material created in these areas by occasional rock-fall and landslides remains on the slopes of the hills. This rock is found in the Teesta Mountain area of the Darjeeling-Sikkim Himalaya and is more complex than hardly soft. In general, the rock structure consists of a variety of carbonate, meta-quartzite, calc-silicate within admixed impurities of limestone, and mafic gneisses as well as parageneses composed of migmatite quartz-feldspathic paragneiss, gneisses composed of metapelitic garnets, cordierite, and orthogneisses made up of augend crystals (Saha, 2020). Both sides of the watershed of the study area contain rocks from the Lingtse Gneiss group. The area has low erodible rocks, so there is less possibility that materials

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from the hillsides will enter the channel network despite low slope angles and somewhat moderate connection levels in this region. As a heterogeneous rock, Lingtse Gneiss presents layers of biotite and ilmenite, forming melanite bands, and bands of quartz and feldspar, forming leucocratic (Ray et al., 2011) rock structures. Around the cleaved Lingtse Gneiss grades, coarse garnet bands are sometimes observed along the gneissic band. The Daling group of rock formations (Figure 1 b), which covers high areal coverage within the catchment, is located in the middle and lower parts of the basin and is shown as the dominant source of load supply. This Daling Group covers flaky quartzites, meta-greywacke, and metapelite with a small mafic dyke and still shows shallow marine, passive edge platformal association (Saha, 2013). The composition of such rocks is highly detachable and disintegrative due to the disproportionate expansion-contraction variability of the composing rocks, especially the Daling group, during winter and summer. This area is affected by landslide incidences (frequency of 2 incidences each year as per field investigation) because of its rugged mountainous host topography and excessive rainfall amounting to more than 3000 mm in years (Sharma & Kumar, 2015). In addition, the landform diversity and the catchment area's diverse geology trigger variable erosion and deposition rates. Excessive range of loads starting from coarser particulate matters to erratics of mean load diameter size of 6 to 7 feet (6 ft, meaningly medium to bigger monolithic deposits) and commonly found coarse to very coarse boulders (~ 6.56 m length ~13.12 m length) facilitate sand entrapment within the river bed. Sediment storage and sink distribution, as well as the efficiency of the reworking process in the catchment (Fryirs & Brierley, 2001; Souza et al., 2016), all get disturbed, and interrupting the operating cycle of fluvial processes due to sudden landfalls was very common here.

Sand particles are the dominant load products, and the very low amount of organic matter significantly promotes erosion and concomitant slide (nearly 40.5–81.06% incidents) due to the low tensile strength of loose sand (0.05 to .15 MPa; 240-260 Kcl per m ^{2}field investigation 2023 February), which indicates more vulnerability to further erosion (Kusre et al., 2018). Within this zone, the IC index is volatile, i.e. nominal to suddenly increasing in nature. High IC values are found on steeper hill slopes, and low IC values on comparatively flat alluvial terrace deposits. This is consistent with the overall connectivity traits observed in the field, where highland slopes are connected to tributary channels, which indicates chances of more sediment influx. However, this relationship disintegrates when the river is incised through the fan deposits, decreasing possibilities for reworking. The slope angles are steeper (46-76 degrees) over the highly erodible rocks, but the degree of lateral connectivity among them is significantly higher, so it is more likely that material may enter the channel network due to the slopes averagely more than 30-45 degrees, regardless of slope angles. Due to steeply sloping rocks with less organic matter in the soil (less than 0.23- 0.35%, Laboratory Investigation), overland flows with high operative actions normally intensify landslides (Mishra et al., 2021; Sharma et al., 2013). Based on the analysis of the channel course, the changes were observed in the IC C_{hannel}. Due to its narrower valley, the river

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channel is readily filled up by loads and, at a few sites, closer to the sediment source zones. However, due to the persistence of the floodplain, the downstream portion of the bed slope is heavily infested by bed armouring. The IC Outlet's sediment retention is very high because sediment particles are effectively carried downstream with the water flow, indicating strong sediment connectivity (Figure 7). The study revealed a perfect allometric progression of downslope sediment supply over the channel network pattern starting from its high catchment to the extreme downslope segment and defined the vivacity of the channel as being an active tributary of Teesta major with sufficient load supply. It also opened up new avenues for further sediment supply and quantification studies, especially for classified rivers like Teesta. Where the river slope is steep throughout its course, the flow of material transport for long distances helps accumulate and improve connectivity. Therefore, it is very likely that the steepness of the downstream catchment will produce significant amounts of sediment. Attainment of the high elevation and considerably high river bed slopes are the major driving forces of huge load accumulation in short duration, and less of the slope factors near river outlet points are responsible for higher sediment connections.

4.2 Validation of Sediment Connectivity outputs with field investigations

Various geomorphological processes are observed across mountain regions of the Ranikhola River basin, influencing the movement, transportation, and deposition of sediments along cascade routes and downslope the basin outlets as visible at different locations viz. Bhusuk, Ranipool, and Rongpo have signatures of sediment load entrapments within the heterogeneous imbrications of in-channel liths (imbricating angularity:40-65^{o}). In most of the upper and middle parts of the basin, sediment paths are strongly linked and interrupted by debris flows within the channels (Figure 8). In this way, debris flows are considered essential paths for transferring sediment in mountainous areas and a critical component in connecting to the slope-channel system that runs along hill slopes for maximum cases. The long and steeply inclined slope profiles with narrow channels are shown (Figure 5) in the upper part of the basin and small parts of the middle basins and are associated with well-connected sediment pathways; however, sediment delivery from the upper section is greatly influenced by the long and steeply inclined slopes (Figures 5 & 6). The high indexes in the high-hanging valleys in the upper area are closely related to the talus slopes and the rock walls (Figure 8c).

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Figure 8 Field photographs of sediment supply zone in the upper catchment of Ranikhola Basin (a) loose debris on the extensively flat and smooth-slopping surface at Upper Ranikhola Basin (b) debris flow along the main channel in the upper part of the basin (c) loose debris on the steep slope at Nathula road (d) V-shaped valley and huge debris accumulation along the left bank of Ranikhola River

In this river catchment, it is demonstrated that the geomorphological characteristics of the watershed and human-induced changes to the land surface significantly impact connectivity. Long flow channels, high slope gradients, and catchment layouts all supported the occurrences of several sediment transporting channels (Liu 1998). Erosion and sediment transport depend on geological structures, including rock types and fault lines. Due to high-relief topography and frequent tectonic activity, landslides and soil erosions are major sediment sources. The rivers and streams are steep and fast-flowing, allowing silt deposition downstream. The geology, including readily erodible rocks, boosts river sediment output. Additionally, geological formations intersecting river networks promote sediment deposition and accumulation, impacting sediment connectivity regularities. Road building, deforestation, and urbanization modify sediment flows. These operations may enhance erosion and sediment movement, breaking sediment connectivity. Thus, there has been an increment in the decoupling behaviour between the hill slope and downstream areas, as seen by analysing IC values, where the carried sediment begins to be deposited in the downstream areas because of the declining nature of average slopes along the hill slope. Aside from agriculture and urban growth, there has been no other human interference with the environment in the Ranikhola catchment since the natural circumstances do not permit more intensive land use. However, across the catchment, the human effect on connectivity was seen. The villages of the Ranikhola catchment were found to have little effect on connectivity, but

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anthropogenic influence (Figure 9) is more pronounced regarding the road network. Roads are significant in a different timeframe than most other buffers (Brown et al., 2017; Persichillo et al., 2018) since they are readily spanned and altered.

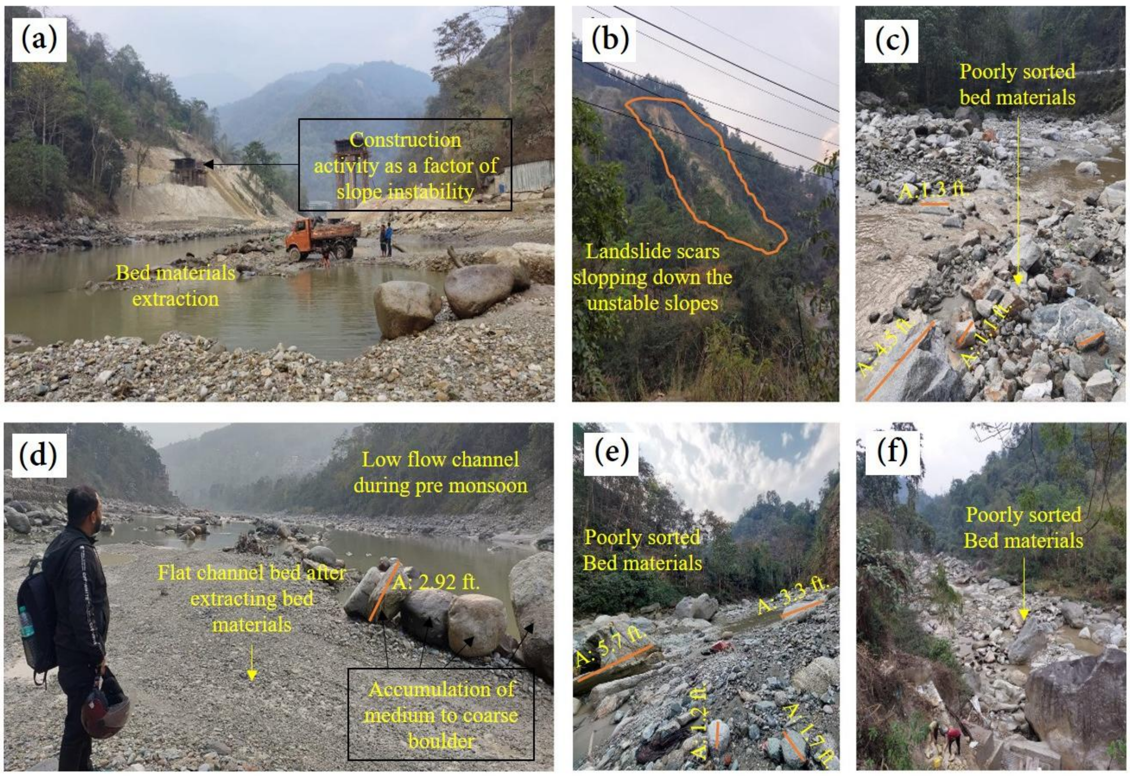

Figure 9 Field photographs showing the sediment connectivity of Ranikhola River and the anthropogenic activity evident of human interference as forceful slope-instability ventures (a) un-scientific bed loads extraction of channel bed materials at Simthang causing loss of sediment influx to continue allometric maintenance of channel network (b) landslide prone site on the channel bank and valley wall at Sangkhola sourcing glided debris materials and their attritional-fracturing to induct more sediments of future (c) large stationary pebbles are settled down to the main channel of Ranikhola River and waiting for a heavy flux (d) the main channel passing though the flatbed topography (e) Poorly sorted bed materials (Coarse pebble to coarse boulder) at down section of Rorochu river confluence with Ranikhola (f) accumulation of pebble, cobble, boulder and slide-erratics as bed materials on river bed at Mangthang

Steep roadways frequently act as a preferred route for water and silt in the upstream region because of the high slope and height, which alter as elevation changes. As most roads offer a surface that is mainly straight and smooth, they may even speed up the water flow and shift tilt downhill (Sivakumar & Ghosh 2021). According to earlier studies, roads, mainly those directly connected to the channel network, can serve as an additional channel for sediment to flow (Jing et al., 2022). This demonstrates a

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road's potential to improve connectivity on a wide scale by providing an alternate flow path for sediment. In addition to temporarily retaining sediment, glaciers and glacial lakes also allow for massive sediment discharge during the retreat stages. A significant volume of sand is transferred because of the ice sheet melting since the upper portion of this basin is entirely covered by a glacier that melted throughout the summer. However, the Index of Connectivity does not take the glacier or snow cover parameter as an input parameter that may affect the seasonal transfer of sediment and impact the sediment connectivity (Costa & Schuster, 1988; Morche et al., 2007; Frattini et al., 2016; Heckmanna et al., 2018). Thus, it is easier to understand and more practical to define a process-based form of connectivity rather than a structural model of connectivity in understanding how systems work and interact over time. That process-based connectivity is more accessible to implement.

The IC values could be more accurate using precise and high-resolution input data based on catchment-specific connectivity influencing parameters, such as topography, slope, runoff, and sediment availability (Rainato et al., 2017). There are similarities between their flow and connectivity patterns as debris flows tend to travel in predefined incisions, whereas, on the other hand, they tend to influence and shape landscape appearance to create connectivity between them (Schopper et al., 2019). Since it considers the physical characteristics of the catchment, such as surface features like structural components and the spatial interactions among these functional aspects by modelling the erosion, deposition, and transport processes, this index enables us to integrate functional and structural elements (Najafi et al., 2021). The channel's size, shape, and gradient and the amount of rainfall a basin receives throughout the year determine how connected its catchment is (Rainato et al., 2017; Ferguson et al., 2006) and in the case of Ranikhola, it is highly connected to regulate load through the slopes. As a result, sediment from the hill slopes within the basin moves from the basin's slopes to the outlet once the sediment enters the channel to complete the upstream-downstream connection. In case of other studies than this study area, considerable differences between the calculated estimates of $IC_{\text{channel or outlet}}$ and the field measurements for example quantity of supply of sediment through connections or channel links in such mountain catchments indicate some variables and other factors like size of load and gravity responses being dominant divers, and opposing the role of topography.

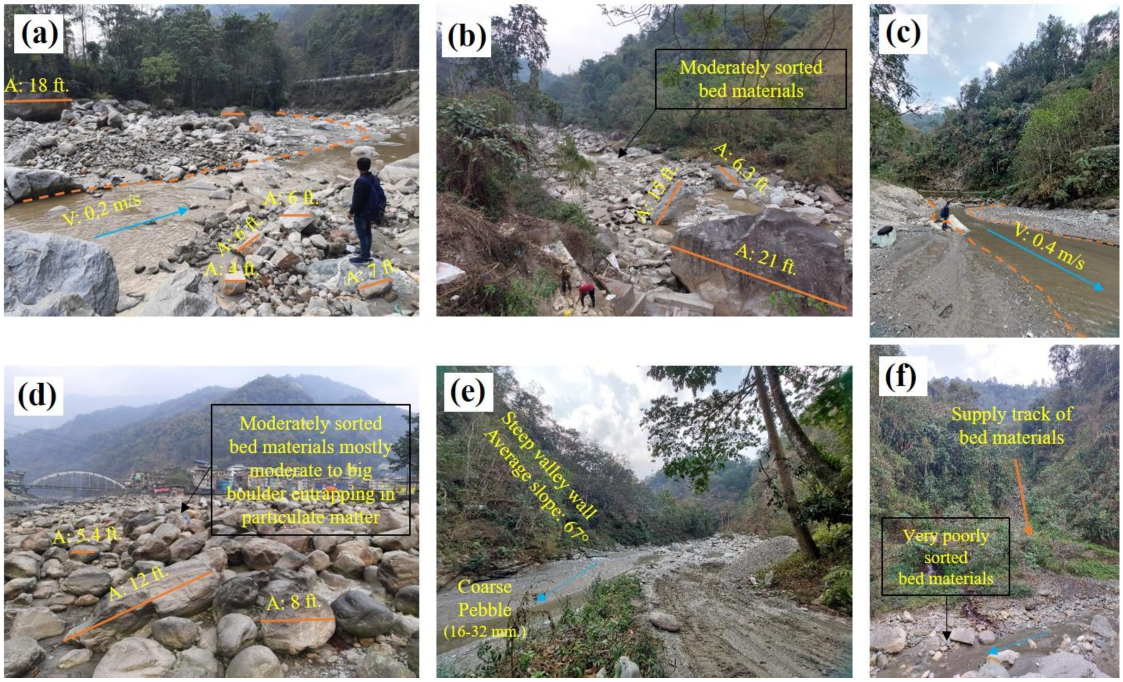

Figure 10 Field photographs showing the nature of channel and bed condition of Ranikhola River (a) Poorly sorted channel bed materials (long axis ranges between 21ft to 0.6 ft.) at Martam (b) Low flow regime within the channel at high altitude of eastern Himalaya evidencing poorly sorted bed materials i.e. boulders and hummocky rocky slabs alike vestiges of last glacial residues (c) low flow channel condition with a fine pebble to very coarse pebble during pre-monsoon at Sangkhola (d) Accumulation of fine or small boulder to very coarse boulder (Wentworth's scale) at Singtam indicating of high flow competency causing clastic frictions facilitating sedimentogenesis (e) bed materials extraction site of River Ranikhola at Namli (f) Debris flow path as a source of channel bed materials near Martam [Note: A-length of the long axis of the bed material; V is Flow velocity]

This study showed that the geographical patterns of the IC index at the catchment-wide level, which was determined in this study, are conformal to the landscape features observed evident through fieldwork investigations. There were numerous instances when access to data and information was restricted or impossible, such as in the upper reaches of the Ranikhola River, where it was possible to quickly calculate metrics related to the IC index using freely available data, which is highly beneficial here. In the IC map, Figure 6 shows that, in the upstream part of the basin, higher connectivity of this sector to the major channels concerning sediment movement suggests more continuous flows. There are abandoned high-elevation (between 3500 – 4000 m.) hilly terraces in this catchment area. These findings suggest that terrace abandonment may significantly have increased erosion susceptibility and transport sediments further

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downstream and debris from the hill slopes to the channels by river flows (Figure 8), as these terraces may have been abandoned for some time.

On the other hand, several landslides in this region are caused by thaw-induced landslides, occasional rock falls, and rockslides within exposed bedrock zones. A large amount of sediment may be supplied to the channel network by such activity of hill slopes, and there is a moderate amount of lateral and longitudinal connections. In addition, one might be able to determine which of the reaches receive a significant amount of sediment through the contribution of the fluxes as well as the consistency of the fluxes, which may be used for estimating the overall pattern of linking (Figure 6) by analyzing the generated map thoroughly. Once initiated, debris flows will follow a specific course until they arrive at a deposition site. For the IC, the chosen target in this study, either the catchment outflow or the leading channel network, has proper connectivity along a prospective flow path, which determines a large part. Otherwise, gravitationally mobilized material is deposited when a significant gradient breaks inside the broader channels. Higher IC values reflect this, especially in the area near the catchment's bottom surface, i.e., in the upper part of the study area, where minor streams with somewhat steep-sided hill slopes are highly linked with the main channel. There are several fundamental issues in the current study about sediment influxing factors. It has also been described in some recent research, and this is one of the most crucial issues that will need to be addressed soon to allow all the different definitions to come to a common understanding. According to the study's results, the development of landscape can be an outcome of dynamic connectivity links within a given catchment and identifying areas of load detentions for watershed management activities over time with the fluviatile landscape development of the catchment.

5. Conclusion

This study analyses the spatial distribution of sediment connectivity in the Ranikhola catchment, Sikkim. The basin is characterized by a steep and dissected topography, which impacts the mobilization of sediments from hill slopes to the channel and then along the channel to the outflow of the basin. By applying the connectivity index to a wide variety of scenarios regarding sediment supply, sediment couplings and de-couplings between hill slopes and channels and lakes, authors arrived at an overall pattern of connectivity that is substantiated by field visits on the effectiveness of sediment transfer mechanisms in the catchment. To fully understand sediment delivery in dynamic contexts, conducting field investigations to provide supplementary data from which to compute sediment connectivity is indispensable. As a result of fieldwork, validation shows that the connectivity patterns projected by the IC calculations accurately matched the actual sediment connectivity patterns in this mountain basin. An IC map has been generated by combining structural and functional characteristics into the map that produces preferred sediment transfer paths using a flow accumulation algorithm that combines such features. This map type often shows strong connectivity patterns with the main

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river and lacks material storage structures. Nonetheless, there is a wide range in the connectivity of the catchment, with certain portions exhibiting distinctly different characteristics. The study eliminates the numerous activities occurring in other landscape segments that are not directly connected to the river since connectivity emphasizes the interaction between catchments and rivers. While it is critical to point out that the Ranikhola basin is highly dynamic in terms of sediment production and transfer, it is also significant to note that the basin is composed mainly of low-quality sediments. Based on the significant relationship between the values of IC and coherent field evidence between the hill slopes and the main channel, which has been seen, it is evident that spatial variation of the IC enhances the segmentation of a catchment into some sectors characterized by comparable patterns of connectivity. Furthermore, the uplands also have quite a significant impact not only on long-term drainage channels but also on sediment movement downstream and the stability of eroded sediments. The identification of regions with uniform sediment connectivity patterns shows a comparable topographic influence on susceptibility to sediment delivery, which further provides objective grounds for evaluating the potential effects of land use changes and may help with the objective selection of the type and placement of structures for limiting sediment transport given river restorations. The present study evaluated the sediment dynamics within the basin based on structural sediment dynamics. However, it would be advantageous to investigate the temporal variability of sediment connectivity within the basin because of variabilities in landslides, rainfall, and periglacial process dynamics due to the increasing anthropogenic influence on this region. As a result, the sediment management plans could be improved and created more effectively by discovering new sources for sediment formation and paving the way for new mobilization pathways.

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Declarations

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper and no other third party interferences, so far their knowledge and belief.

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