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Preliminary assessment of the suspended sediment dynamics in the Sikkim–Darjeeling Himalayan river

Paweł Prokop*

Department of Geoenvironmental Research, Institute of Geography and Spatial Organisation, Polish Academy of Sciences, Jana 22, 31-018 Kraków, Poland

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A B S T R A C T

The Sikkim–Darjeeling Himalaya region receives the highest amount of rainfall along the whole southern Himalayan margin and is known for the occurrence of extreme hydrometeorological and geomorphological events. The massive amounts of water and sediment transported each year through the mountain part of the Teesta River drainage system (~8,150 km^2)——the largest river in the region——have been severely impacted by dam construction in recent decades. The aim of the current study was to determine, for the first time in this part of the Himalaya region, the dynamics of suspended sediment transfer at a number of points distributed through the mountainous part of the Teesta River catchment prior to dam construction and preliminarily assess the impact of dam operations on the suspended sediment. Sediment sources were identified using a database of landslide inventories from 1965 to 2019, combined with visual interpretation of satellite imagery from the U.S. Corona programme and Google Earth. Hydrological and sediment data up to the second half of the 1990s were used to reconstruct the discharge and suspended sediment dynamics before direct human intervention in the river channels. The beginning and end of the construction of the reservoirs was determined by analyzing satellite images. The impact of dam operations on the suspended sediment was compiled from the available literature. The results of the current study indicate that the primary sources of sediment are landslides caused by the interaction of rainfall and road undercutting of slopes as well as channel erosion. During extreme rainfall events, the influence of deforested areas in the mobilization and delivery of sediment to the river network increases. The current analysis reveals that reconstruction of the suspended sediment dynamics should take into account the course of extreme events responsible for supplying material to the river network, as well as the long-term remobilization of already deposited sediment in the river channel. It was found that the mean suspended sediment load (SSL) following extreme rainfall, flooding, and landslides in the Teesta River catchment can be up to four times higher than its average values for the same catchment unaffected by such an event, and the effects can be observed for more than a decade afterwards. Under these conditions, the mean suspended sediment yield can reach 12,000 and up to 20,000 t/(km^2·y) in individual years, which is among the highest in the Himalaya region and, indeed, the world. The construction of 13 dams in the last 30 years has disrupted the hydrological regime and sediment transport in the Teesta River catchment along 70% of its main course and largest tributaries, and this has resulted in the selective retention of coarser material in the reservoirs and a reduction in the SSL in the Himalayan piedmont. The high density of the dams suggests that further transport of suspended sediment will depend on the efficiency of the water and sediment management at the reservoirs, which may be affected by irregular natural extreme events.

1. Introduction

In the Himalaya region, tectonics, topography, and rainfall facilitate the supply and transfer of massive amounts of water and sediment through river network systems to their piedmonts (Bookhagen & Burbank, 2006, 2010; Godard et al., 2014; Prokop & Płoskonka, 2014). Vegetation density modulates the relations between rainfall, topography, and sediment transport in these highly active young mountains (Olen et al., 2016). Human activities can further intensify or reduce the delivery and transfer of sediment through deforestation, road building, settlement development, and

* Corresponding author.
E-mail address: pawel@zg.pan.krakow.pl (P. Prokop).

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the construction of dams across rivers (Chong et al., 2021b; Gupta et al., 2012; Li et al., 2021; Panta et al., 2023). Most of these factors controlling the sediment fluxes are characterized by large variabilities, which are also reflected in a large spatiotemporal variability of suspended sediment dynamics (Bhattacharjee et al., 2022).

Various factors have also been attributed a decisive role in the sediment supply to the river network in the Himalaya region. Bookhagen et al. (2005) found an increased sediment load in streams in the arid part of the north-western Himalaya region during a year with enhanced annual rainfall. By contrast, the densely vegetated lower parts of this region did not show increased denudation rates. Andermann et al. (2012a) suggested, for the Nepal Himalaya, that material transport in the rivers depends on the hillslope sediment supply, which is controlled not by extreme rainfall events, but by moderate ones with a high recurrence interval. Godard et al. (2014) proposed a dominance of tectonics over rainfall in Himalayan region denudation. Prokop et al. (2020) pointed out that the deforestation of small catchments along the margin of the Eastern Himalaya had significantly increased the sediment loads in the river channels in their piedmonts. Bhattacharjee et al. (2022) indicated that the sediment load in Himalayan catchments is susceptible to changes in vegetation cover and topographic steepness on time scales of up to 100 years. However, only general information on the suspended sediment load (SSL) has been presented for the Eastern Himalaya region, drained by the Brahmaputra and its tributaries.

The Sikkim–Darjeeling Himalaya region, as a part of the Eastern Himalaya, receives the highest annual rainfall (up to 6,000 mm) and the most frequent heavy rains (up to 600 mm/d) along the whole southern Himalayan margin (Bookhagen, 2010; Soja & Starkel, 2007). The catchment of the Teesta River (~8,150 km^2), the main river draining this part of the Himalaya region, is known for the occurrence of extreme hydrometeorological and geomorphological events. The rainfall of about 1,000 mm over three days in October 1968 caused a 20-m-high flood wave in this catchment (Dhar & Nandargi, 2003; Starkel, 1972). This was the highest level for any river in India in the previous 70 years. Measured data have indicated that the Teesta River has one of the highest suspended sediment yields (SSYs) in the Himalaya region, exceeding 12,000 t/(km^2·y) (Tejwani, 1986) and large variations in its maximum annual discharge of between 2,000 and 10,000 m^3/s at the outlet from the Himalaya (Gosh, 1983).

Unfortunately, studies on the suspended sediment in the Eastern Himalayan rivers are constrained due to an inadequate gauge network, the poor availability of data in the open domain, and hydrological alterations caused by dam construction or extreme hydrometeorological events (Bhattacharjee et al., 2022; Dhar & Nandargi, 2003; Ghosh & Chakraborty, 2022). Thus, most of the research on the Teesta River catchment has focused on the sources of the sediment supply. Starkel (1972) observed enhanced hillslope erosion and increased suspended sediment flux in the Teesta River catchment during the 1968 extreme rainfall and flood event. Infrequent extreme rainfall events, the low resistance of the lithology to weathering, and 70%–80% deforestation of the catchment have been found to be of the greatest importance in the supply of material to the river network. By contrast, Froehlich and Walling (2007), used the cesium-137 (^{137}Cs) radionuclide method to investigate overbank sedimentation rates along the Teesta River, and suggested that mass movement and gully erosion are the main suspended sediment sources in the catchment, while the role of land use is less important. A number of authors have recognized that landslides in the rugged topography of the Teesta River catchment are common and mobilize significant amounts of material that is delivered directly into the main Teesta River channel as well as through much smaller tributaries (Gupta et al., 2022; Starkel et al., 2017).

However, none of the previous studies have provided specific long-term data on the discharge and suspended sediment. Reconstruction of the past fluvial processes is difficult in the context of the influence of recent anthropogenic regulations on the river system. In the last few decades, the discharge and sediment transport in the Teesta River catchment have been seriously affected by dam construction (Ghosh & Chakraborty, 2022; Sanyal, 2017). A total of 12 dams (> 25 MW) are currently in operation, with a further one under construction in the mountainous part of the catchment (Bhatt et al., 2017; Rahaman & Abdullah-Al-Mamun, 2020). This means that there is a dam every 15 km along this stretch of river compared with an average of one dam every 32 km along the rivers covering the other Himalayan catchments (Grumbine & Pandit, 2013). In addition, the Teesta River catchment will have the highest density of dams globally if all the proposed dams are constructed in the future.

The aim of the current study was to determine the dynamics of the sediment transfer at a number of points distributed across the Teesta River catchment in the Sikkim–Darjeeling Himalaya region. More specifically, the objectives included: (i) identifying the major sources of sediment; (ii) reconstructing the suspended sediment dynamics, including the effects of extreme rainfall and floods prior to direct human intervention along the Teesta River and its tributaries (i.e., dam construction); (iii) characterizing the period of dam construction and its potential impact on the suspended sediment dynamics; and (iv) preliminarily assessing the functioning of the dams on the suspended sediment.

2. Material and methods

2.1. Study area

The Teesta River and its main tributary, the Rangit River (boundary river between the Sikkim and Darjeeling Himalaya), originate from the glaciers in the northern Sikkim (Fig. 1). The Teesta River descends from ~7,000 to around 150 m a.s.l. over a distance of ~180 km and, leaving the Himalaya region, passes through the Indo–Gangetic Plain to join the Brahmaputra in Bangladesh. In its mountainous section, the Teesta River valley cuts through schists and gneisses, creating a deep incision bringing the river channel in direct contact with steep slopes with little accommodation space for sediment deposition and high transport capacities. In such tectonically active terrain, earthquakes and rainfall initiate landslides that deliver large amounts of material to the river channels (Gupta et al., 2022; Martha et al., 2015).

The precipitation distribution across the catchment is strongly influenced by the orographic effect, resulting in a decrease in annual precipitation from 3,500 mm at the southern margin to below 1,000 mm at the highest elevations in the north and northwest (Bookhagen & Burbank, 2006; Prokop & Walanus, 2017). Up to 80% of the annual amount of precipitation falls during the summer monsoon season in June–September in the southern and middle part of the catchment. At the highest elevations, precipitation in the form of snow falls the whole year round. The total area under glacier cover is estimated to be around 425 km^2 (Bajracharya & Shrestha, 2011). The contribution of snow and glacier melt to the annual discharge has been calculated to be about 10% (Bookhagen & Burbank, 2010). River feed from the glaciers as they melt overlaps with the feed from the summer monsoon rainfall, and along the main Himalayan river course, and the Teesta is a river with a year-round flow.

Topography and climate influence the variation in vegetation with elevation. Tropical, subtropical, and temperate forests

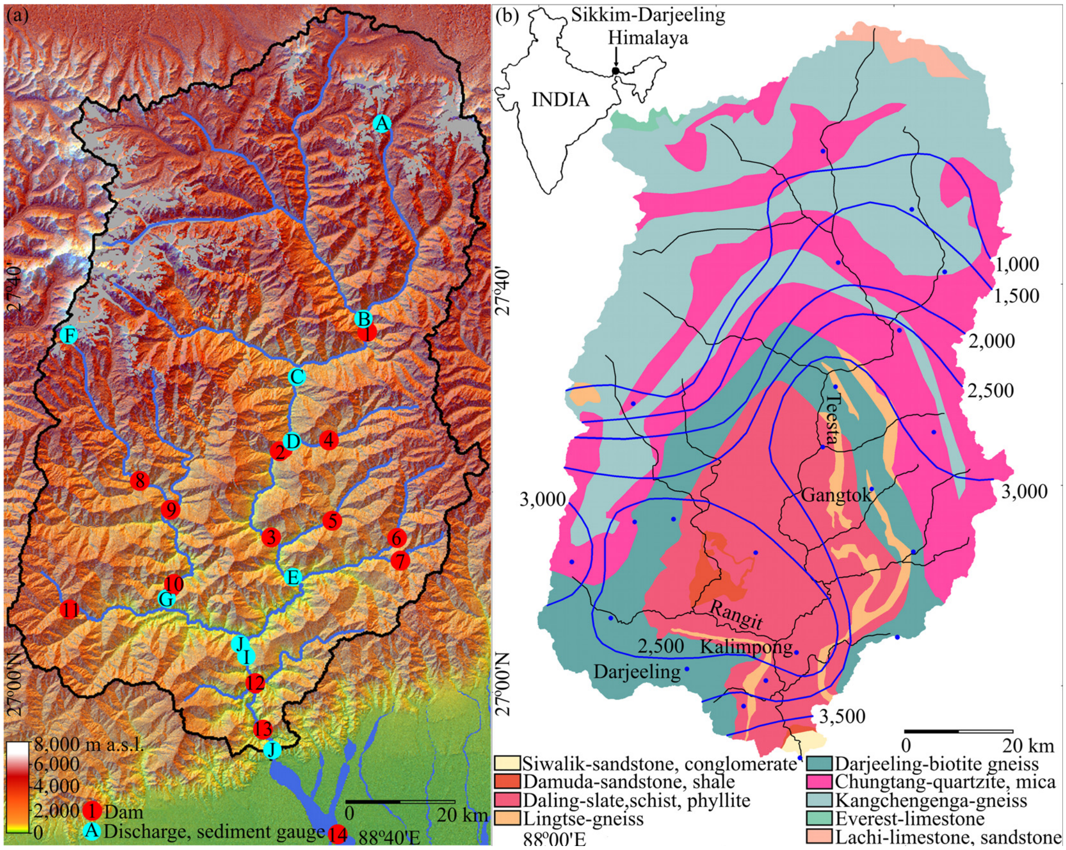

Fig. 1. Study area. (a) Topography: glacier coverage (light grey) (after ICIMOD, 2011), (b) geology (after Acharyya, 1975, 1980) and isohyets with mean annual rainfall (mm). Dams: 1 – Teesta Stage III, 2 – Teesta Stage V, 3 – Teesta Stage VI; 4 – Dikchu, 5 – Rongnichu, 6 – Rolep, 7 – Chuzachen, 8 – Tashiding, 9 – Rangit III, 10 – Jorethang, 11 – Ramman II, 12 – Teesta Low Dam III, 13 – Teesta Low Dam IV, and 14 – Gazaldoba Barrage. Discharge and sediment gauging sites: A – Changme Khangpu, B – Chungthang, C – Sanklang, D – Dikchu, E – Khanitar, F – East Rathong, G – Naya Bazar, H – Peshok, I – Teesta Bazar, and J – Coronation Bridge.

predominate up to an altitude of 3,600 m, above which the vegetation is alpine (FSI, 2011). Since the 19th century, part of the forest has been protected and under forest management. The rest of the Himalayan part of the Teesta River catchment, on the other hand, has been progressively deforested for the establishment of tea plantations and terraced farming, and the development of buildings, roads, and bridges (Kijowska-Strugała et al., 2022; Wiejaczka et al., 2014). At the end of the 20th century, the Himalayan part of the Teesta River catchment began the intensive development of hydroelectric projects that continue to date.

2.2. Data analysis

The monthly rainfall dataset from 22 stations for the period 1951–2010 was obtained from the National Data Centre of the Indian Meteorological Department. Missing rainfall values were filled in using correlations of monthly data with neighboring stations and a network of tea gardens that make their own rainfall measurements.

The sources of sediment in the Teesta River catchment were identified using the landslide inventory database from Geological Survey of India (GSI, 2022) for the period 1965–2019. Landslides initiated by rainfall, rainfall and fluvial activity, rainfall and anthropogenic activity, and earthquakes were identified. The role of extreme rainfall and dam construction in sediment mobilization and delivery to the river network was determined based on visual interpretation of high resolution (< 3 m) U.S. Corona satellite imagery from 1967 to 1968 and Google Earth imagery from 2006 to 2020. The analysis was supplemented by a literature review of field studies on sediment sources in the Teesta River catchment (Froehlich & Walling, 2007; Starkel, 1972).

Table 1
Period of measurements and source of discharge and suspended sediment data in the Teesta River catchment. The location of gauging sites is shown in Fig. 1.

Label	Gauging site	River	Discharge (years)	Suspended sediment (years)	Source
A	Changme Khangpu	Teesta	1979–85[a]	1979–85[a]	Puri, 1999
B	Chungthang	Teesta	1976–95	1983–97	CWC; CISMHE, 2007
C	Sanklang	Teesta	1989–95	1992–97	CWC; CISMHE, 2007
D	Dikchu	Teesta	1984–93	1986–97	CWC; CISMHE, 2007
E	Khanitar	Teesta	1980–94	1995–97	CWC; CISMHE, 2007
F	East Rathong	Rangit	2013–15[b]	2013–15[b]	Kumar et al., 2020; Sharma et al., 2022
G	Naya Bazar	Rangit	1971–82	1970–74	Irrigation and Waterways, 1986, 1999
H	Peshok	Peshok	1989–92	1989–92	Soja and Patel, 2000
I	Teesta Bazar	Teesta	1971–82	1970–74	Irrigation and Waterways, 1986, 1999
J	Coronation Bridge	Teesta	1971–82	1970–74 and 1981–82	Irrigation and Waterways, 1986, 1999

[a] July–September only.
[b] June–September only.

The hydrological and sedimentological data were collected from the Central Water Commission (CWC) in India, from reports and published papers (Table 1). Glacial catchments have calculated discharges, suspended sediment concentrations (SSCs), and SSLs for months and/or seasons (Kumar et al., 2020; Puri, 1999; Sharma et al., 2022). Daily data on discharge, SSLs and SSCs, as well as the calculations made by Soja and Patel (2000), were used for the Peshok River catchment. For the Naya Bazar, Teesta Bazar, and Coronation Bridge gauging sites, the SSL was calculated by multiplying the daily SSC by the daily discharge (Irrigation & Waterways, 1986, 1989). For the Chungthang, Sanklang, Dikchu, and Khanitar gauging sites, the already calculated monthly discharge and SSL were acquired from the CWC and the CISHME (2007).

These data cover a period from the 1970s to the second half of the 1990s——that is, before direct human intervention in the river channel of the Teesta River and its tributaries in the Himalaya region. Measurements of the glaciated catchments covered the summer monsoon season for a period of 3–5 years. Analyses of the suspended sediment from other parts of the Himalaya region indicated that the measurement periods were sufficient for estimating the dynamics of the suspended sediment in a catchment such as that for the Teesta River (Andermann et al., 2012a; Bhattacharjee et al., 2022).

Information on the beginning and end of the construction of the reservoirs was acquired by analyzing high-resolution Corona, Landsat, Spot, Indian Remote Sensing (IRS), and Google Earth satellite images. The preliminary impact of the dams on the suspended sediment was compiled from the available literature.

3. Results and discussion

3.1. Major sediment sources in the Teesta River catchment

The Teesta River catchment in the Himalayas is characterized by varying topography, tectonics, lithology, and precipitation overlain by human activities. Therefore, sediment sources are diverse both spatially and temporally. The positive correlation between suspended sediment load, air temperature, precipitation, and discharge indicates that glacial erosion and snowmelt in recently degraded areas are critical to sediment production in the northern part of the Teesta River catchment (Bookhagen & Burbank, 2010; Puri, 1999; Sharma et al., 2022). This area also is the least human-transformed part of the catchment. In contrast, mass movements, particularly landslides, are a significant source of sediment delivery to rivers in the rest of the catchment (Froehlich & Walling, 2007; Lukram & Tandon, 2022; Starkel, 1972; Starkel et al., 2017).

The analysis revealed that of the 4,358 inventoried landslides in the Teesta River catchment, 95% of landslides were triggered by rainfall and only 5% were the result of earthquakes (GSI, 2022, Fig. 2). Among all landslides triggered by rainfall, 44% are the result of rainfall alone, 12% are the result of the interaction of rainfall and fluvial activity—most commonly the undercutting of the toe of a landslide by a river, and 44% are the result of rainfall and human activity—most commonly the undercutting of slopes by a road. This confirms the observations of Froehlich and Walling (2007) that much of the sediment is mobilized from the landslides and roads in the Himalayan Teesta River catchment. The important role of landslides in sediment delivery to the river network also is evidenced by their spatial distribution. Landslides triggered solely by rainfall dominate the southern part of the Teesta River catchment which receives the highest annual rainfall and is affected by extreme rainfall events (Figs. 1 and 2). The extent of highest annual rainfall coincides simultaneously with the occurrence of deeply weathered phyllites, schists, and Darjeeling gneisses, which favor the formation of mass movements (Acharyya, 1975, 1980). Many landslides also are concentrated along the course of the Teesta River and its main tributaries (Lukram & Tandon, 2022), which are often followed by roads. These landslides usually deliver sediment directly into river channels.

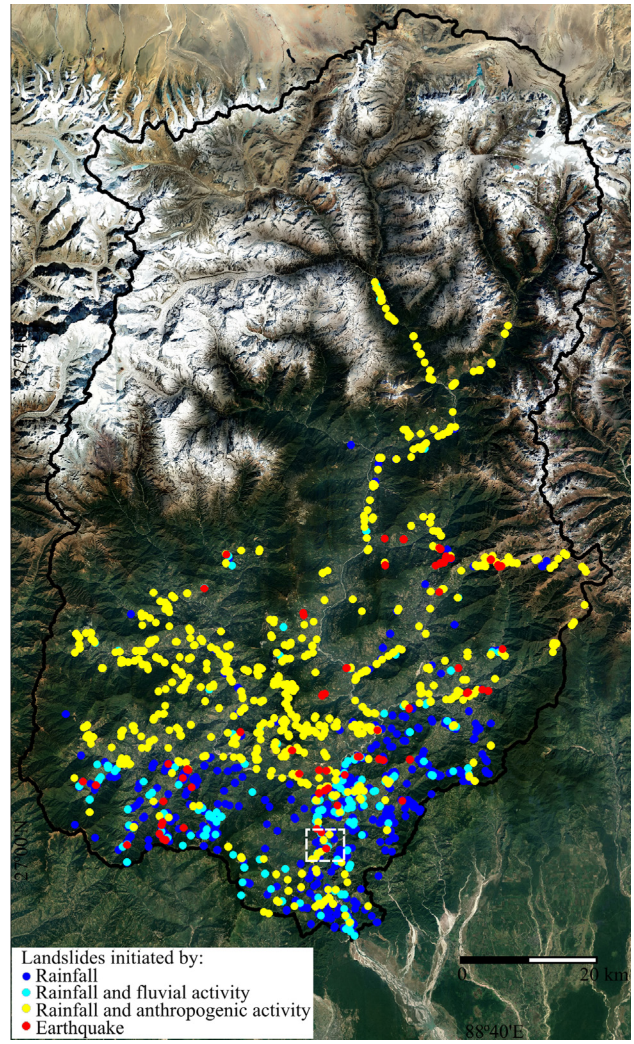

Fig. 2. Landslides as the major sources of sediment in the Teesta River catchment (author's compilation based on GSI (2022) landslide inventory and Google Earth satellite image from 2022). The area in the white dashed square is analyzed in detail in Fig. 3.

A comparison of the U.S. Corona satellite image fragments in the area most affected by the extreme rainfall event of October 1968, supported by direct field observations (Starkel, 1972), allows for a detailed analysis of the role of rare extreme events in the mobilization and delivery of sediment to rivers (Fig. 3). An extreme rainfall of about 1,000 mm in three days covered the southern part of the Teesta River catchment up to the Rangit River (Abbi et al., 1970). Approximately 20,000 landslides were generated as a result of the rainfall (Ives, 1970). Landslides affected 20%–25% of agricultural land and only 2% of forested areas (Starkel, 1972). The rate of soil erosion on agricultural land exceeded the rate of erosion within forests by one to two orders of magnitude. The delivery of sediment to the Teesta River by landslides, roads, and local streams has resulted in the Teesta's riverbed changing in places from a single-threaded to a braided pattern.

An analysis of the same area in a 2006 Google Earth image (Fig. 3(c)) indicates that the Teesta River bed has returned to a single channel, and construction has begun on the Teesta Low Dam

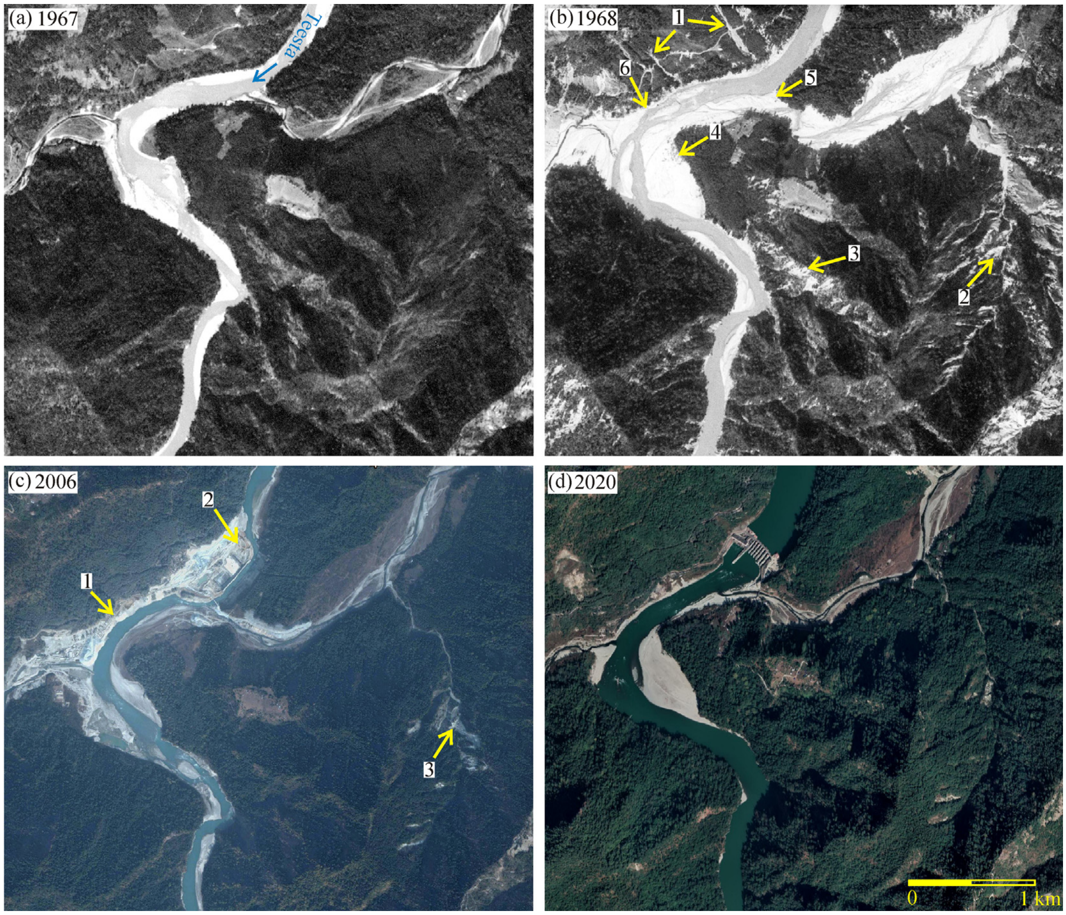

Fig. 3. Impact of an extreme rainfall event and dam construction on sediment delivery to the river network in the Teesta River catchment. (a) Teesta River in 1967 with normal monsoon rainfall. (b) Teesta River after the extreme rainfall of October 1968: 1 – landslides on a slope undercut by a road; 2 – initiation of landslides in a forest; 3 – intensive surface erosion in deforested/agricultural areas; 4 – erosion of river banks due to flooding; 5 – delivery of sediment to the Teesta River channel by local streams; and 6 – transformation of the Teesta riverbed from a single-thread to a braided pattern. (c) The beginnings of the construction of Teesta Low Dam III in 2006. 1 – supply of sediment from the Teesta River banks and tributaries deforested during construction of the dam; 2 – construction works in the Teesta riverbed with temporary narrowing and shifting of the channel; and 3 – active landslides initiated by the 1968 extreme rainfall. (d) Teesta River with the Teesta Low Dam III in operation in 2020. The expansion of vegetation on the river banks and the stabilization of landslides can be seen. The filling of the Teesta River channel with the backwater of the Teesta Low Dam IV Reservoir located 13 km downstream is evident.

III. The riverbanks are devoid of vegetation due to the construction work, which is a source of sediment over a distance of about 1.5 km. Direct work in the riverbed led to a temporary narrowing of the river, a change in its course, and an additional supply of sediment visible in the riverbed below the construction site. Landslides in the forest that were initiated by the heavy rainfall in 1968 are still active. In the 2020 Google Earth image (Fig. 3(d)), the Teesta River channel above the operating Teesta Low Dam III is filled with water, and below this dam, the Teesta Low Dam IV Reservoir backwater affects this reach. Most of the landslides in the forest, which were initiated by the extreme rainfall in 1968, are now revegetated.

3.2. Discharge and suspended sediment prior to dam construction

3.2.1. Discharge

Discharge is one of the most important factors controlling suspended sediment transport in a river channel. In the small glaciated catchments of the Sikkim Himalaya region, discharge is limited to the spring and summer, reaching, on average, only a few cubic metres per second during these seasons (Table 2) (Kumar et al., 2020; Puri, 1999). This discharge is associated with increases in insolation and temperature causing the melting of snow and glacial ice (Bookhagen & Burbank, 2010). Overall, along the main mountain course of the Teesta River, the mean annual discharge increases linearly with an increase in drainage area (Fig. 4). However, in the Darjeeling Himalaya region, between the Teesta Bazar and Coronation Bridge gauging stations, the discharge shows no differences with an increase in drainage area. In small catchments of up to 10 km^2, such as the Peshok River in the Darjeeling Himalaya, no discharge is recorded during the winter and early spring seasons (Soja & Patel, 2000). During the extreme rainfall event in 1968, the discharge on the Teesta River at Teesta Bazar and Coronation Bridge reached 16,330 to 17,300 m^3/s, respectively (WAPCOS, 2003). These are the highest values recorded on this river in the history of its measurement.

During the year, the highest discharges are in the months of July and August, reflecting the highest rainfall in these months. While the proportion of summer monsoon rainfall to the annual rainfall decreases from over 80% to 50% with increasing distance from the southern Himalayan margin in the Teesta River catchment, the proportion of discharge during the summer monsoon is less than the rainfall and also decreases from about 70% to 60% along the same N–S gradient. This phase shift between the rainfall and river discharge, as well as the lack of discharge increase with drainage area increase in the Darjeeling Himalaya region (Fig. 5), indicates the passage of the water into a deep fractured basement aquifer that also is a feature of the neighboring Nepal Himalaya region (Andermann et al., 2012b).

Table 2
Mean annual discharge and suspended sediment load in the Teesta River catchment. Seasonal values are presented for glaciated catchments (Changme Khangpu and East Rathong). The two values for Coronation Bridge represent the periods 1970–1974 and 1980–1981, respectively.

Label	Gauging site	Drainage area (km^2)	Mean annual discharge (m^3/s)	Suspended sediment load (Mt/y)
A	Changme Khangpu	4.5	2.2	0.002
B	Chungthang	2,792	137	1.265
C	Sanklang	3,839	249	7.984
D	Dikchu	4,260	304	9.908
E	Khanitar	4,874	367	11.516
F	East Rathong	19.8	6.4	0.007
G	Naya Bazar	1,393	171	4.558
H	Peshok	9.8	0.3	0.008
I	Teesta Bazar	7,714	563	27.706
J	Coronation Bridge	8,147	537	99.038, 24.286

3.2.2. Suspended sediment concentration

The mean SSC in the glaciated catchments is 0.1 g/L during the monsoon season (Sharma et al., 2022). The mean annual SSC along the main course of the Teesta River generally does not exceed 1 g/L. The highest monthly averages of SSC reach 7 g/L, with the daily averages showing a range of variability between 0.1 and 35 g/L. In the small catchments of up to 10 km^2, such as the Peshok River in the Darjeeling Himalaya region, the mean annual SSC was calculated to be 0.2 g/L, the highest monthly mean value was 3.3 g/L, with the daily measured values ranging from 0.0 to 12.6 g/L (Soja & Patel, 2000). The exceptions are years like 1968, when extreme rainfall initiated a flood wave up to 20 m high that removed the vegetation from the banks along the main course of the Teesta River between Teesta Bazar and Coronation Bridge (Starkel, 1972). The landslides this event triggered delivered sediment directly to the channel, raising the bed by 5–7 m in places. In effect, daily SSC values of up to 177 g/L were measured between the Teesta Bazar and Coronation Bridge gauging sites in 1970–1974.

During the year, in the glaciated catchments, the maximum SSCs occur in July, when the temperatures and solar radiation are at their highest (Sharma et al., 2022). In the rest of the Teesta River catchment, the SSC maxima occur in June, coinciding with the high rainfall at the start of the monsoon season.

3.2.3. Suspended sediment load

In the small glaciated catchments, the mean SSL varies between 0.002 and 0.007 Mt in the monsoon season (Table 2) (Puri, 1999; Sharma et al., 2022). Along the main course of the Teesta River, the SSL increases linearly with an increase in drainage area (Fig. 6). This indicates a steady supply of fine sediment available for transfer (Smith & Dragovich, 2009). Local factors, such as rainfall and the low weathering resistance of the local gneisses, slates, and schists, results in the Rangit River——a major tributary of the Teesta River——in Naya Bazar having almost four times more the SSL from a catchment area half the size, compared to the Chungthang gauging site.

Sharp increases in the mean SSL to 28 and 99 Mt/y at Teesta Bazar and Coronation Bridge, respectively, were measured in the Darjeeling Himalaya region in 1970–1974 as a result of the extreme rainfall in 1968. This event changed the SSL–drainage area relation from a linear to a power relation in the Teesta River catchment. As a consequence, in the lower part of the catchment, the annual SSL increased faster than the drainage area (the exponent in the power equation had a value greater than 1) for more than a decade. This resulted from the deposition of a large amount of sediment in the Teesta River channel and its gradual transport down the catchment by remobilization. At Coronation Bridge, at the outlet of the Teesta River from the Himalaya region, the SSL varied over a large range, from 44 to 168 Mt/y, between 1970 and 1974. These values are, on average, four times higher than the average in the early 1980s, when the riverbed returned to its pre-1968 levels (Froehlich & Starkel, 1987). A similar several-fold increase in sediment load has also been recorded in the Western Himalaya region during flash floods or in years with abnormally high monsoon rains (Bookhagen et al., 2005; Dobhal et al., 2013; Wulf et al., 2012). On a spatial scale, this extreme event confirms that the Darjeeling Himalaya margin is the most vulnerable to the effects of high rainfall, which include erosion and landslides within the Teesta River catchment (Prokop & Walanus, 2017).

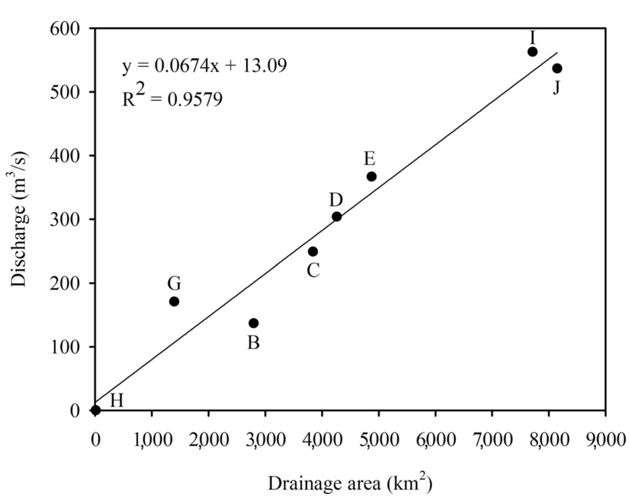

Fig. 4. Relation between drainage area and mean annual discharge for the Teesta River catchment before the period of dam construction. Glaciated catchments excluded (see Tables 1 and 2).

3.2.4. Suspended sediment yield

The SSY, like the discharge and SSL, generally increases with an increase in drainage area along the main course of the Teesta River, but shows greater variability, from 450 t/(km^2·y) in Changhtung, through 2,000 t/(km^2·y) in the middle part of the Teesta River catchment to almost 3,000 t/(km^2·y) at Coronation Bridge, at the outlet of the Teesta River from the Himalaya region. The highest mean SSYs at the site——in excess of 12,100 t/(km^2·y)——were recorded in 1970–1974 as a result of the 1968 extreme rainfall event. In one of the individual years in this period, the SSY reached 20,000 t/(km^2·y). These values are the highest in the Himalaya region and, indeed, in the world (Cohen et al., 2022). On the largest tributary——the Rangit River——and in the small catchments of up to 10 km^2, like the Peshok River, the SSY may be locally higher than on the main river. This confirms previous observations that peaks in the SSY may occur anywhere within the catchment up to 20 km^2 (Chaplot & Poesen, 2012).

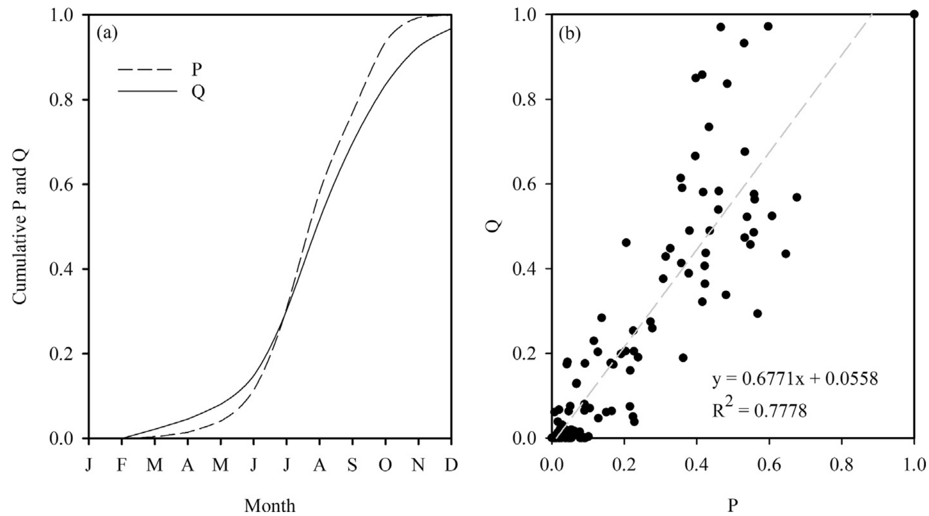

Fig. 5. Precipitation and discharge for the lower part of the Teesta River catchment in the Darjeeling Himalaya region for 1971–1980. (a) Cumulative plot of mean monthly precipitation (*P*) and mean monthly river discharge (*Q*) for the lower Teesta River catchment between Teesta Bazar and Coronation Bridge (normalized by the respective maxima) illustrating the temporal phase shift due to transient groundwater storage. (b) Relation between *P* and *Q* revealing the dependency of *Q* on *P* (both normalized by the respective maxima) (note: R^2 is the coefficient of determination for the linera regression relation between *Q* and *P*).

3.3. Dam construction and its potential impact on the suspended sediment dynamics

The deeply incised Teesta River, which descends over a considerable elevation in a relatively short distance, has great potential for hydroelectric-power generation. The first plans for dam construction appeared as early as the 1940s, but it was not until the mid-1970s that a dam was built in the Himalayan piedmont, and from the 1990s onwards, intensive dam building began in the Himalayan part, which continues to this day (Basu & Pattanaik, 1982; Rahaman & Abdullah-Al-Mamun, 2020).

Currently, along the main course of the Teesta River, five reservoirs form a cascade, their total capacity comprising 95% of the capacity of all the retention reservoirs (81 million m^3) built in the mountainous part of the catchment (Fig. 7; Table 3). The remaining eight smaller reservoirs are located in the Sikkim Himalaya region on tributaries of the Teesta River. The construction of these reservoirs has disrupted the hydrological regime and sediment transport in the Teesta River catchment along 70% of its main course and largest tributaries.

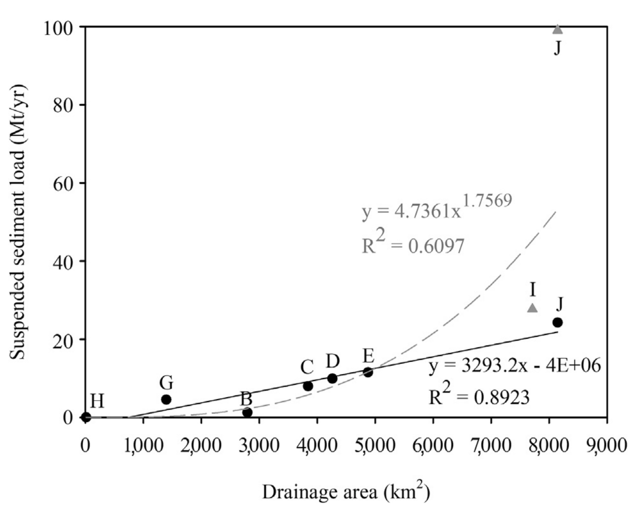

Fig. 6. Relation between drainage area and mean annual suspended sediment load for the Teesta River catchment before the period of dam construction. Glacierized catchments excluded. Linear relation (black continuous line) and equation for gauging sites (black circle) mainly for the 1980s and 1990s, not affected by extreme rainfall in 1968. Power relationship (grey dashed line) and equation including data from Teesta Bazar and Coronation Bridge (grey triangle) gauging sites for the period 1970–1974 following the extreme rainfall in 1968 (see Tables 1 and 2) (note: letters denote the gauging stations shown in Fig. 1).

Based on the analysis of satellite imagery, it was concluded that the construction period of the dams in the mountainous part of the Teesta River catchment has already exceeded 30 years. The average construction time for a dam lasted seven years, and varied between three and 15 years. The construction of the dam has affected the supply and transport of suspended sediment in contrasting ways (Brandt, 2000; Campos & Pedrollo, 2023; Dethier et al., 2022; Ghosh & Chakraborty, 2022; Starkel et al., 2017). The beginning of the construction itself has affected the stability of the slopes and has mobilized material during mining of the riverbeds, which involved the delivery of additional suspended sediment to the channels. Once a reservoir is filled with water, it modifies the seasonal pattern of flow variability and acts as a selective trap for sediment, potentially changing its granulometric composition downstream (Banadkooki et al., 2020; Chong et al., 2021a; MoayeriKashani et al., 2016). In addition, from 1998 onwards, the mean annual discharge of the Teesta River, after completion of the Gazaldoba Barrage, decreased by about 100 m^3/s due to the diversion of water (including sediment) through the Teesta–Mahananda Link Canal for irrigation purposes outside the Teesta River catchment in the Himalayan piedmont (Ghosh, 2014).

3.4. Preliminary assessment of the impact of dam operations on suspended sediment

The cascade of dams, the long, and not yet completed, construction time of the reservoirs, and the overlap of the start of construction of one reservoir with the end of the construction of another, have complicated the assessment of the changes in the suspended sediment dynamics in the Teesta River catchment. In the upper part of the catchment, in the Sikkim Himalaya region, the reservoir capacity has been reduced due to storage effects in the small reservoirs on the Teesta River tributaries, such as Rangit III, by 2.3%––that is, by 0.3% per year––between 2000 and 2006 (Grover

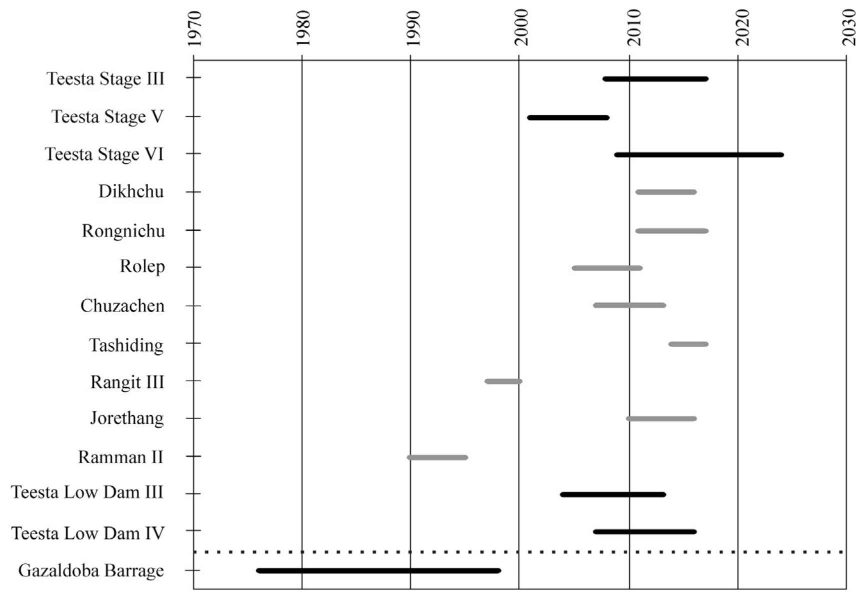

Fig. 7. Construction of dams (years) in the Teesta River catchment on an N–S cross-section showing dams constructed along the main course of the Teesta River (black line), dams constructed on tributaries of the Teesta River (grey line), and the boundary between the Himalaya region and the foreland (dotted line).

et al., 2005; Sen, 2014). However, an extreme flood that occurred on July 11, 2006, peaking at 1,405 m^3/s and with a sediment concentration of 51.5 g/L, was able to damage the turbines and generators at the Rangit III Dam (Sen, 2014). This extreme event stopped energy production for several months, leading to permanent changes in the operation procedures of the spillway gates and sediment management at the dam. It was also found that the mean annual sediment load estimated during the project design was 2.7 Mt, but that the sediment load recorded since 2006–2007 actually ranged between 3.8 and 17.3 Mt.

In the case of the large dams on the main Teesta River course, such as the Teesta Stage V, within the first year after commissioning (in 2009), the reduction in live capacity was 10.3% (Joshi et al., 2018). Subsequently, due to the application of sediment management techniques, such as flushing and sluicing, there was only a 3.8% reduction in the live capacity over the next seven years——that is, 0.5% per year. As a result, much of the sediment already deposited in the reservoir has been remobilized and transported downstream. This indicates that, in individual years, the SSL below the large dams can vary significantly, depending on the sediment management technique introduced for the dam or modified during its functioning.

In the lower part of the Teesta River catchment, in the Darjeeling Himalaya region, Fields et al. (2021) predicted, based on pre- and post-dam digital elevation models and bathymetric measurements, that up to 71% of the Teesta Low Dam III Reservoir area may be showing visible sediment bar formation during intervals of low water levels until 2031. For the shallower Teesta Low Dam IV Reservoir, up to 88% of the reservoir area may show visible sediment bars by 2027. This will be the effect of the deposition of sediment in the reservoirs, due to the reduced sediment carrying capacity of the main Teesta River as well as the sediment supply from landslides and small tributaries.

In the foothills of the Sikkim–Darjeeling Himalaya region (at Domohani, located 27 km downstream from the Gazoldoba Barrage), after the several dams were built, there was a large decrease in the average SSY, from 3,400 t/($km^2 \cdot y$) in 1999–2009 to 1,300 t/($km^2 \cdot y$) in 2010–2014 (Sanyal, 2017). In the same area, downstream from the Gazoldoba Barrage, Ghosh and Chakraborty (2022) found massive sediment generation during the dam

Table 3
Reservoirs in the Teesta River catchment (based on CWC, 2018; Ghosh & Chakraborty, 2021; and the author's own analysis of satellite images). The Teesta Stage VI Reservoir is expected to be operational in 2024 (note: the reservoir numbers correspond to the locations shown in Fig. 1. Full data were not available for the Ramman II Reservoir).

No.	Reservoir	River	Period of construction	Dam height (m)	Reservoir capacity (million m^3)	Power capacity (MW)
1	Tessta Stage III	Teesta	2008–2017	60.0	5.08	1,200.0
2	Tessta Stage V	Teesta	2001–2008	88.6	13.25	510.0
3	Tessta Stage VI	Teesta	2009–2024	26.5	3.18	500.0
4	Dikhchu	Dikhchu	2011–2016	36.0	0.33	96.0
5	Rongnichu	Rongnichu	2012–2017	12.6	0.36	96.0
6	Rolep	Rangpo	2005–2011	45.0	0.35	72.0
7	Chuzachen	Rangpochu	2007–2013	48.0	1.28	110.0
8	Tashiding	Rathongchu	2014–2017	12.0	0.05	97.0
9	Rangit III	Rangit	1997–2000	47.0	1.18	60.0
10	Jorethang	Rangit	2010–2016	17.0	0.67	96.0
11	Ramman II	Ramman	1990–1996	–	–	51.0
12	Teesta Low Dam III	Teesta	2004–2013	32.5	18.36	132.0
13	Teesta Low Dam IV	Teesta	2007–2016	45.0	37.00	160.0
14	Gazaldoba Barrage	Teesta	1976–1998	11.0	7.72	67.5

construction period and an overall reduction in the sediment grain size in the Teesta River channel for the same period, and, thereafter, when several upstream dams and the Gazoldoba Barrage were fully operational.

An analysis of the spatial distribution of the gauging stations and the functioning of the dams in the Teesta River catchment indicated that the most reliable results for the impact of the dams on the general suspended sediment dynamics in the Himalayan part of the Teesta River catchment would be those provided by long-term measurements of discharge and suspended sediment from the gauging station at Coronation Bridge. This type of long-term analysis can separate the impact of extreme events from years with normal monsoon rainfall, as well as from the anthropogenic/dam-construction impact. Furthermore, an analysis of sediment from the riverbed above the Gazoldoba Barrage (i.e., before the diversion of water and sediment outside the Teesta River catchment) could also be very valuable.

4. Conclusions

This first study of the Eastern Himalaya region has enhanced the understanding of the fine-sediment dynamics over a range of temporal and spatial scales within the large Teesta River catchment. The results indicate that a reconstruction of the suspended sediment dynamics of the past should take into account the extreme hydrometeorological and geomorphological events responsible for supplying material to the river network as well as the long-term remobilization of already deposited sediment in the river channel. The primary sources of sediment are landslides caused by the interaction of rainfall and road undercutting of slopes as well as channel erosion. During extreme rainfall events, the influence of deforested areas in the mobilization and delivery of sediment to the river network increases. The mean SSL following an extreme event, such as that of 1968, can be up to four times higher than its average value for the same catchment unaffected by such an event, and its effects can be observed for more than a decade afterwards. In the Teesta River catchment, these values were the highest in the entire Himalaya region and, indeed, among the highest in the world. The 1968 event also revealed that the Darjeeling Himalayan margin is the most vulnerable to the effects of extreme rainfall, and this could change the relation between the SSL and the drainage area from a linear to a power relation. This was also confirmed by the SSY, which was lower in the Sikkim Himalaya region than the Darjeeling Himalaya region in those years not affected by extreme events.

The impact of the dams on the suspended sediment was difficult to assess due to their long and ongoing construction, the overlap between the beginning of new reservoir construction and the end of construction of another reservoir, and the coverage of most of the Himalayan Teesta River catchment by the cascading dam system, as well as the water and sediment transfer outside this catchment in its piedmont. The results to date indicate that there has been a reduction in the SSL downstream of the dams and a selective retention of coarser material in the reservoirs. The high density of the dams suggests that further transport of suspended sediment will depend on the efficiency of water and sediment management at the reservoirs, which may also be affected by irregular natural extreme events.

An analysis of the spatial distribution of the gauging stations and dams in the Teesta River catchment indicated that the most reliable results on the impact of the dams on the overall suspended sediment dynamics in the Himalayan part of the Teesta River catchment would be provided by long-term measurements of discharge and suspended sediment from near the Teesta River outlet from the Himalaya region, but before the water and sediment are diverted out of the Teesta River catchment. This type of long-term analysis would separate the impact of extreme events from those years with normal monsoon rainfall, as well as from the anthropogenic/dam-construction impact on the sediment dynamics.

Declaration of competing 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.

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