Role of tributaries in shaping the middle course of the Himalayan River Teesta after the 1968 extreme floods

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Extremely high precipitation is characteristic of the frontal zone of the Himalaya. In this article we study tributaries which supply huge sediment loads to the Teesta river in the Darjeeling Himalaya, India and significantly affect transportation regime downstream the junction of the Great Rangit with the main river. The material supply is also conditioned by 70–80% deforestation of the catchment. Will the deepening of the Teesta river and its tributaries follow tectonic movements? Or will the Teesta follow smaller streams that drain the fringe of the Himalaya, and then will the huge foreland cones penetrate the mountain interiors? These questions are important, especially in the context of construction of dams and water reservoirs along the Teesta river and its tributaries.

Keywords: Dams and reservoirs, extreme floods, high precipitation, river channels, role of tributaries.

TRIBUTARIES may be related to the main river depending upon the size of their catchments, stages of evolution of mountain relief reflected in the depth of the valleys, width of the valleys floors, channel gradients, channel substrate, steepness of slopes, etc.[1–4]. The geologic structure and human impact also play a significant role in these relations. The transformation takes place mainly during extreme events characterized by high discharges with a tendency to hyperconcentrated flows and even debris flows[5–7].

In this article we demonstrate that tributaries which supply huge river load can significantly affect the transportation regime downstream the junction with the main river.

We considered the lower section of the mountain reach of the Teesta river draining almost the whole Sikkim Himalaya, India (this section has been under study by us since 1968, see refs 8, 9). The mountain catchment is 8051 sq. km, 95% of which forms the upper catchment ending at the junction with the greatest right tributary – the Great Rangit river. From that point to the outlet from the Himalaya (52 km long section), the Teesta valley has a narrow, canyon-like appearance, with straight or sinuous sections and with several incised meanders downstream. Sediment supply from other small creeks draining narrow or wider belts (3–15 km) on both sides of the Teesta valley is relatively small. In contrast to the Teesta, Great Rangit drains, besides the southern slope of Kangchenjunga glaciated massive, a wide belt of the deforested marginal zone of the Himalaya invaded by extreme rainfall (40 km extending in W–E direction). Therefore, during huge floods, the Rangit can compete with the Teesta river discharge, and especially with sediment load at the junction of both the rivers; and both the rivers combined register an increase in water level rise and discharge oscillations (Figure 1).

Environment of the middle course of the Teesta river system

Geology

The Darjeeling Hills form a great synclinorium built of Precambrian and Paleozoic metamorphic rocks thrust over on a narrow Siwalik zone of Neogene and Lower Quaternary sandstones building the edge of the Himalaya[10]. A lower unit of the great syncline is formed of

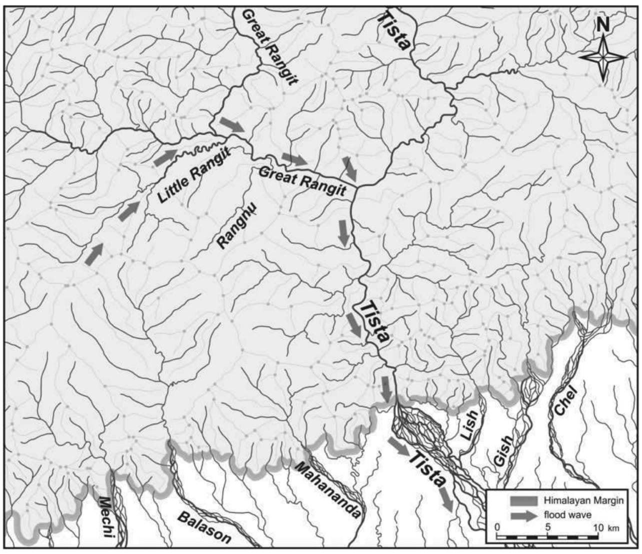

Figure 1. Map of Darjeeling Himalaya, India.

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Damuda quartzites, hard sandstones and carbonaceous shales as well as of less-resistant phylities and schists belonging to the Dailing series that rest over the Damuda series. The Darjeeling gneisess appears at some distance from the Teesta valley, because just at the axis of the Teesta, transversal rises occur and beds are inclined towards W–E instead to N–S. This controls mass movements on the sides of the Teesta valley.

Relief

The Darjeeling Hills rise abruptly (from 150 to 1200 m amsl) over the sub-Himalayan depression as a tectonically active sharp edge. The pattern of ridges is connected with the pattern of valleys which are 700–1500 m deep. East of the Teesta river, the streams drain a wide belt of mountains (Gish, Chel, Jaldaka). The Teesta, which is 200 km long in the mountains, drains most of Sikkim Himalaya. On the west side, the condition is different. The Darjeeling Hills are separated from the inner Sikkim Himalaya by a latitudinal W–E tributary of the Teesta, i.e. the Great Rangit which drains not only the slopes of the Kangchenjunga massif (8586 m amsl), but also the northern slope of the Darjeeling Hills. Therefore, only the southern side is drained directly to plains by the Balasan and Mahananda rivers. Due to such a valley pattern, the other tributaries (like Kalijhora) are relatively small.

Along the Teesta and Rangit rivers, we observed flattened ridges of about 900–1000 m relative height; the lower one, was only 200–300 m (refs 8, 11). With that lower level are probably connected huge boulders[12] and gravels cover next terrace (Rangamati surface)[13]. The incised meanders of the Teesta were connected with the last phase of uplift[9].

Precipitation/rainfall regime

Precipitation occurs during four months (June–September) and fluctuates between 4000 and 6000 mm at the margin of mountains as well as 1000 and 2000 mm near the Great Rangit valley[8,9,14]. A decline in precipitation towards the mountain interior is common in the Himalaya; a dense network of rain gauges (every 2–4 km) at the tea plantations helps identify a leading role of a slope exposure in rainfall formation (elevation is less relevant), especially the large decrease in precipitation after passing the second ridge (Figure 2). Therefore, the tributaries of the Great Rangit get double precipitation from the south. This is especially dangerous during the 2–3 days continuous rainfall, e.g. during 2–4 October 1968, when 1091 mm rainfall (up to 200 mm in last 4 h) was recorded. Combined effects of several downpours with 2–3 h of rainfall up to 500 mm (mainly local) may lead to more substantial geomorphic outcomes.

The sandy–silty soil resting over metamorphic rocks facilitates infiltration and then formation of mudflows and debris flows, especially on tea plantations and other cultivated areas. After the catastrophic rainfall in October 1968, 20–30% of cultivated tea bushes were removed[8]. Most of them were delivered to river channels.

Hydrological regime

The upper Teesta catchment is supplied with water originating from rainfall during summer season, and also due

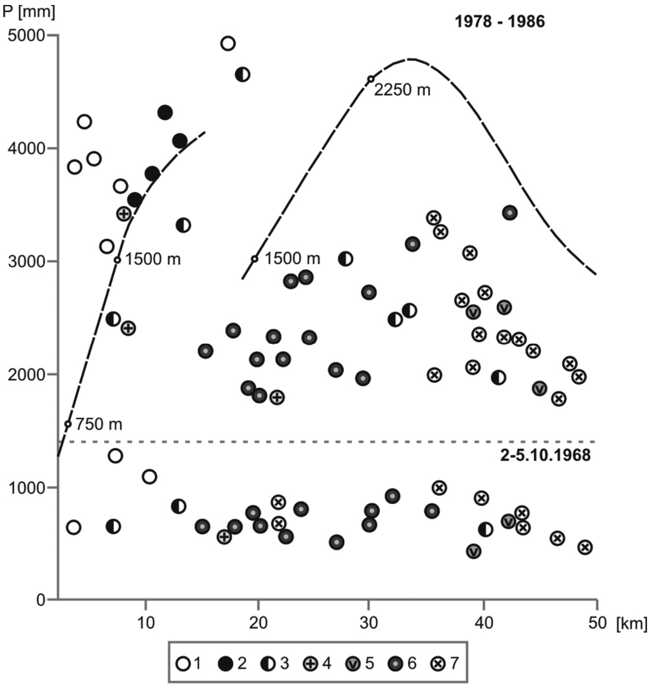

Figure 2. Rainfall totals in 1978–1986 and during continuous rain in 1968 with the growing distance from the mountain front (0–50 km), (after ref. 9). 1, Southern marginal slope; 2, Ridges on southern margin; 3, Other locations on ridges; 4, Northern slopes in southern margin; 5, W and E exposed slopes; 6, S exposed slopes in the interior; 7, N exposed slopes in the interior.

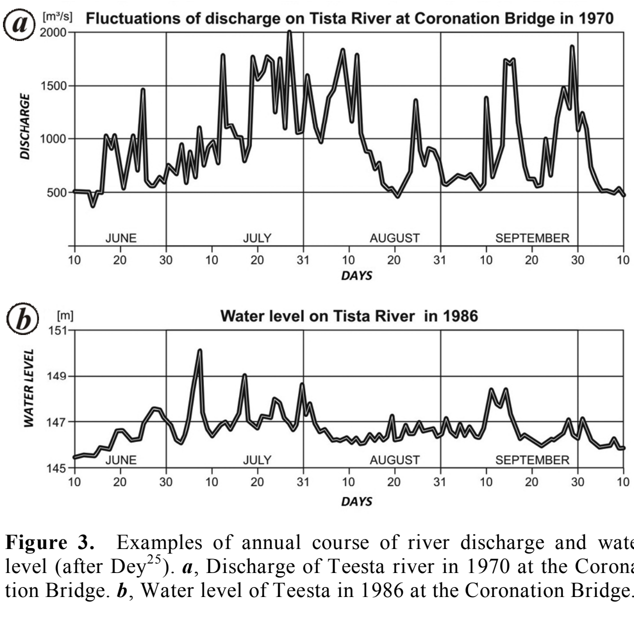

Figure 3. Examples of annual course of river discharge and water level (after Dey[25]). ***a***, Discharge of Teesta river in 1970 at the Coronation Bridge. ***b***, Water level of Teesta in 1986 at the Coronation Bridge.

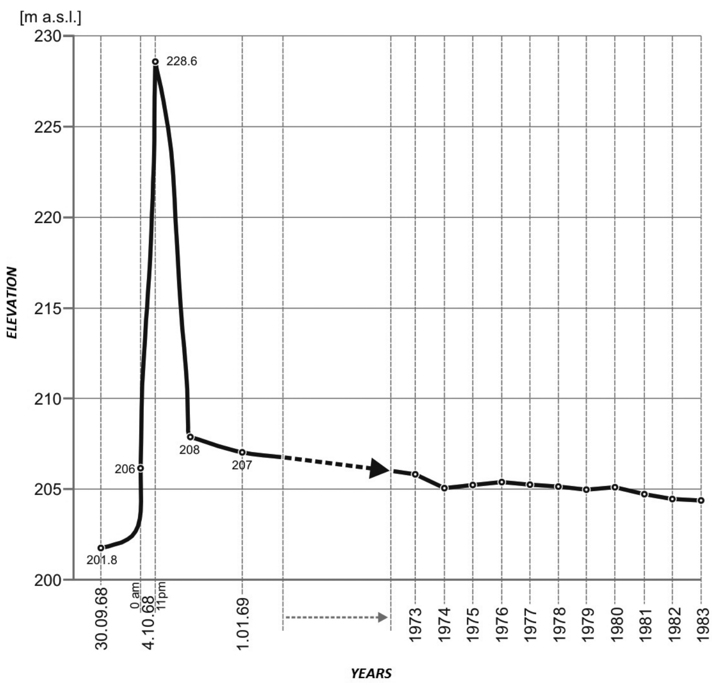

Figure 4. Fluctuations of Teesta river water level at the Coronation Bridge before, during and after the floods 4 October 1968 (after Starkel[16]).

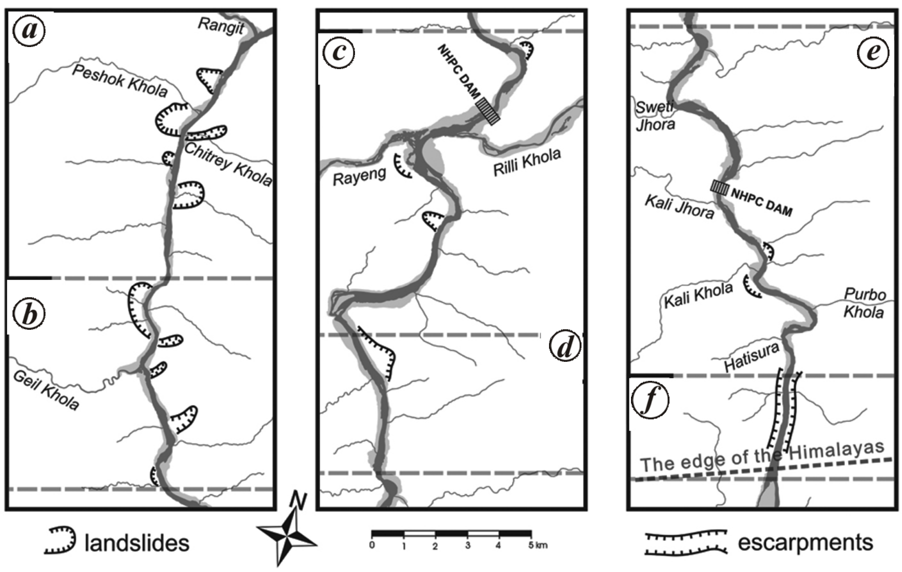

Figure 5. Sections of Teesta river valley from junction with the Great Rangit to outlet of the Himalaya. ***a–f***, Sections of the Teesta channel. ***a***, ***d***, ***f***, Straight; ***b***, Sinuous; ***c***, Meandering; ***e***, Sinuous/meandering.

to snow and glaciers melting; 78% of the supply is associated with the summer monsoon[15]. Each summer, over a dozen oscillations of discharge are registered that are as high as 2000–2500 $m^3 s^{-1}$ at Teesta Bazar (Anderson Bridge) and the water level rises by 3–6 m with respect to the minimum (Figure 3). This was evidenced by the absence of vegetation cover and exposure of bare rocks up to this height, as well as the presence of sandy bars or marks of lower flood extents[9].

During the last 150 years, rainfall exceeding 2–3 days was registered three times (in 1899, 1950 and 1968), that exceeded 1000 mm and resulted in discharges reaching 18,000 $m^3 s^{-1}$. The water marks of 1968, in the form of a torn-off vegetation cover (including trees), were noticed up to a height of about 15 m on steep, undercut slopes along the Teesta and the lower Great Rangit rivers for several years. Prior to the floods, the water level registered in Teesta Bazar was 202.8 m amsl, while after the

Table 1. Parameters of the middle course of 835 the Teesta valley

Sections	Length of river	Length of valley	Width of channel (m) Average	Maximum	Minimum	Width of bars (m) Average	Maximum	Minimum	Width of valley floor (m) Average	Maximum	Minimum	Sinuosity
A	8250	7909	69.1	135	27	29.2	117	6	160	250	140	1.04
B	7200	6519	66.3	133	34	28.8	134	5	150	340	100	1.10
C	15,200	10,438	86.5	213	25	47.1	237	3	270	600	130	1.46
D	5410	4917	85.7	132	29	34.5	126	5	180	230	120	1.10
E	14,350	10,727	75.6	167	36	37.4	200	1	250	670	110	1.34
F	1660	1630	93.7	158	64	–	–	–	120	390	90	1.02
G	8400	8091	85.3	156	23	102.5	523	4	–	–	–	1.04
Total	60,470	50,135	79.5	213	23	46.6	523	1	188.3	670	90	1.21

Figure 6. Outlet of the Teesta river from the Himalaya forming deep canyon (photograph taken in 2011).

Figure 7. Shifting channel and bars in the great incised meander of the Teesta river (section C and D upstream of the Kalijhora).

floods on 4 October 1968, the water level reached 228.6 m amsl. Thus, the water level rose by 26 m and bed-load transport (combined likely with material supply from slopes) resulted in river floor accretion by 5 m (Figure 4). In the following years, the river channel was deepened by washing out finer particles[14,16].

Teesta valley and sources of sediment load supply

The Teesta valley between the mouth of the Great Rangit and the outlet from the mountains, along the 52 km passage, comprises alternating straight, sinuous and meandering sections (Figure 5) with a sinuosity index of 1.02–1.46 (Table 1).

A 90–670 m wide valley floor is accompanied either by steep slopes dissected by forested troughs and by landslides, or by ridges parallel to the river course that are sometimes undercut. The valley floor is occupied by the 23–213 m wide Teesta channel with sidebars that are wider in the meandering reaches or near the mouths of larger tributaries (Table 1). The straighter sections as well as the bends have steeper gradients and riffles. The over 2 km long mountain outlet section, forming a notable rectilinear 50–100 m deep canyon cut down in more resistant beds (Figure 6), suggests an intensive uplift of the discussed zone and contrasts with surfaces of two fans: one widening to 5 km and attributed to a braided channel, and the second one being higher with an edge rising 10–15 m.

The source of material transported by the Teesta river from the Rangit junction originates from the upper catchment of the Teesta (5503 sq. km) and of its tributary – the Great Rangit (2086 sq. km). In the Teesta river, upstream of the junction, gravels of 10–20 cm in size predominate, while downstream large boulders (of diameter over 50 cm or even reaching 2 m) are frequent.

Moving downstream, larger tributaries (catchment area 50–200 sq. km) are less numerous and generally supply finer sediments (like, for example, the Kalijhora stream) which are distributed by the Teesta as exemplified by the aggradational sections (Figure 7). A detailed analysis of alluvia of the gravel bars and the lower 4 m high terrace of the Teesta river upstream of the Kalijhora outlet was performed at the beginning of 1993 (ref. 17). It showed a predominance of cobbles 20–40 cm in size and larger boulders originating likely from the extreme floods of 1968.

Other sources of material supply are rockslides and landslides. Several types of landslides can be distinguished – all together covering 20–30% of the slopes. Below Teesta Bazar, a steep slope, across which is the main road to Sikkim, is built of metamorphic schists that slide down in whole packets to the river. At the opposite steep slope, about 3 km downstream, a trough-like landslide, being permanently undercut by the river, expands and removes patches of forests (Figure 8). In 1968, along the Teesta river a series of large landslides (each several hectares in area) occurred[8]. These landslides are still rejuvenating and provide coarse material to the steep Peshok cone descending down to the Teesta channel upstream of Teesta Bazar.

The third source of material supply is a direct lateral erosion of the Teesta river. The erosion affects solid rocks as well as older alluvia and colluvia. Roles of various types of landslides have been discussed above. Many of them are coupled with erosion. At the meander bends, e.g. downstream of Kalijhora, large boulders were washed out of the banks, while the 6–8 m high terrace which formed during the 1968 floods was reworked in the following years that affected grain-size composition of younger gravel bars[17].

Role of the Great Rangit in supply of material

The Great Rangit with catchment area 2086 sq. km drains not only the southern slope of the Kangchenjunga range but also the northern slope of the Darjeeling foothills, which are characterized by higher annual precipitation and a range of catastrophic precipitation. Especially high precipitation in October 1968 was observed in the catchment of the Little Rangit, being 16.5 km long and 75 sq. km in area[8].

Before discussing the mechanism of accumulation and formation of a mini delta at the outlet of the Great Rangit (Figure 9), one should consider the magnitude of erosion and accumulation in the Little Rangit sub-catchment, where almost 1000 mm of rainfall occurred during 52 h. Besides several mud flows, debris flows and numerous larger landslides, the channel with bars widened from 25–50 to 80–200 m as well as bridge-buttressed Little Rangit river deposited 10 m thick sediments with boulders of 1–2 m diameter were observed. The huge material supply from the Little Rangit to the Great Rangit during the extreme floods resulted in an 'accumulation choke'.

The Great Rangit in its lower course transports similar boulders that provide evidence of at least hyperconcentrated flow. The above was registered in the photo of the Great Rangit from the late 19th century (Figure 10). Normal floods are not capable to mobilize so coarse sediment. It should be emphasized that similar catastrophic rainfalls were recorded three times (in 1899, 1950 and 1968). Therefore, transportation in forms of hyperconcentrated flows and debris flows in the deforested part

Figure 8. Landslide on the steep Teesta valley sides near junction with the Great Rangit (photograph taken in 2014).

Figure 10. Course debris transported by the Great Rangit. Photograph taken in the late 19th century (source: archives of Das studio, Darjeeling).

Figure 9. Junction of the Great Rangit with the Teesta river forming a small delta (November 2014).

Figure 11. Debris flow in the upper section valley of the Posam creek formed after the catastrophic rainfall in October 1968 (photograph taken in December 1968 during the heaviest rainfall).

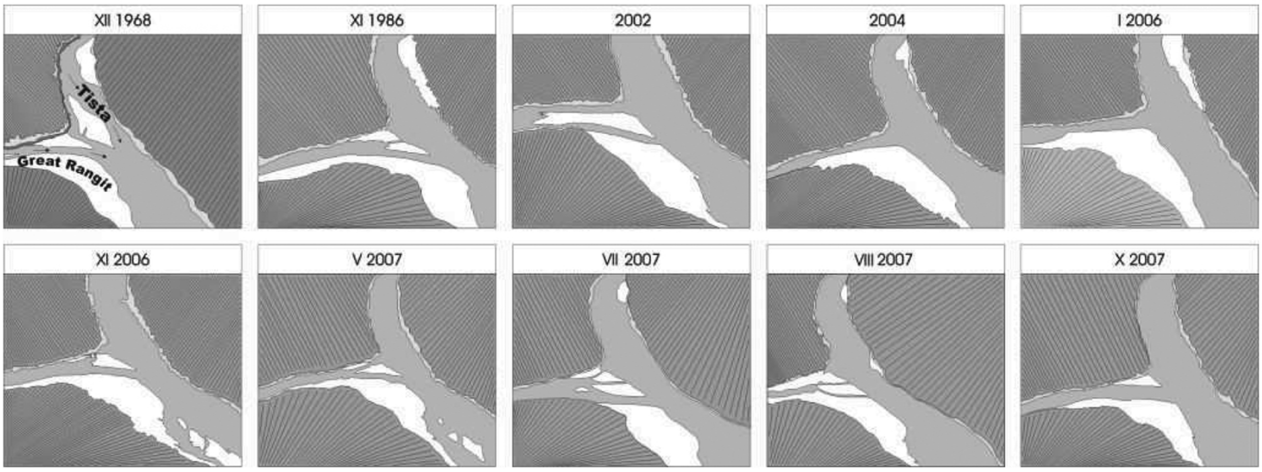

Figure 12. Junction of the Great Rangit with Teesta river during various years and seasons.

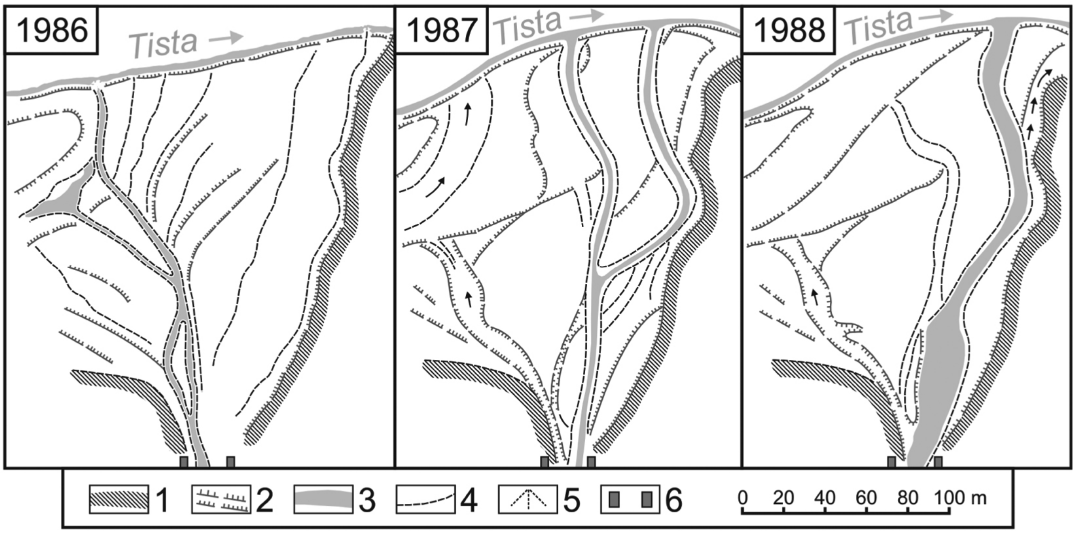

Figure 13. Kalijhora alluvial fan changing its surface when surveyed during 1986, 1987 and 1988 (after Starkel and Basu[9]). 1, Steep slopes; 2, Edges; 3, River (water); 4, Small paleochannels; 5, Small fans and 6, Bridge.

of the catchment was likely initiated in mid-19th century by clearing forests and setting up tea plantations. Location features and tea plantation setting similar to those of the Little Rangit are also found in the catchment of Rangnu, a next right tributary of the Great Rangit (area of 61 sq. km). In 1968 a debris flow, transporting boulders up to 6–8 m long, travelled over the floor of tributary valleys (Figure 11).

Material from the tributaries gets to the Teesta river which changes and attenuates the transportation capacity. Indeed, in its narrow valley water level rises more often and for a longer duration (but generally lower) which undermines coarse material of the Rangit and deposits on it sandy sediment of an overbank facies. The photo of December 1968 taken just after the huge flood shows how the alluvia carried away by the Rangit push the Teesta current to the left hand side. A very large, 18–20 m wave of October 1968 deposited ca. 1.5 m of sediment on the surface of the higher cone (ca. 4 m high). The deposited sediment was ^{137}Cs dated[18]. Later on, deposition has never reached such a high level which is delimited also by a sod cover.

Photos taken during various years indicate some similarities in supply of sediments after different monsoon seasons (Figure 12). Five photos taken from November 2006 till October 2007 show a sequence of the changes: prior to the monsoon, during the monsoon and just after that period (Figure 12). In November 2006, the huge bar was formed, resembling a delta, which was dissected by two stream arms. A similar stage was in May 2007. Last observations from 2013 show that small floods on the Teesta river, apart from the large wave from the Rangit river, make the gravel bars to be accreted with deposits of the overbank phase. The flood of May–July of 2007 shows the Rangit to build a new delta dissected by two-three arms (Figure 12). In October 2007, when the material supply from the Rangit ceased, one channel maintained.

Function of the Kalijhora in sediment load supply

The Kalijhora stream, a tributary on the right of the Teesta river, is 10.6 km long and its catchment area is 20 sq. km. The differences in heights are from 250 to 1750 m amsl. The Kalijhora stream drains the marginal part of the Darjeeling Hills, which are characterized by the highest precipitation of the order of 4000–6000 mm. This marginal part is built of less-resistant members of metamorphic rocks. Therefore, in the load transported by the stream gravel grain sizes predominate. Also convectional downpours occur more often here at the fringe of first rises of the Himalaya. In the extent of large fans, channel avulsions after downpours were registered every year during 1985–1988 (Figures 13 and 14)[9,19]. The other flood events occurring in the Teesta river, easily undermine the fan that shifts the river channel. Large portion of a sand grain-sized fraction (40%) is marked 3–4 km downstream the Teesta in the section analysed by Wiejaczka *et al.*[20]. However, it cannot be excluded that an abrupt increase in the sand fraction is related to earth works associated with the building of a dam above the Kalijhora mouth that started prior to taking measurements (in 2012).

Conclusion and discussion

Various factors can affect the role of the tributaries in the formation of hydrological regime and load transportation in a large mountain river – like the Teesta river – that is at a distance from a nival zone with mountain glaciers. Simultaneously downstream of the junction with the Rangit dominante permanent uplift at the foreland of the subducting mountain foredeep. Erosion predominates this canyon reach at the mountain edge. Upstream, deposition associated mainly with hyperconcentrated flow and debris flows is observed. This load material transported through the Great Rangit channel originates from catchments on the right of the Little Rangit and Rangnu as well as from landsliding over valley sides.

This is the area of extremely high precipitation characteristic of the frontal, barrier zone of high mountains[8,21,22]. The Great Rangit channel is the main route of supply of huge boulders that were observed in the valleys of the Little Rangit, Posam and Rangnu just after the extreme floods of October 1968 (ref. 8). The material supply to the channel was also conditioned by 70–80% deforestation of the catchment – this is the centre of Darjeeling Tea Plantations. The tea plantation has been in operation for over 150 years – the period when extreme precipitation and flood events occurred at least three times in 1899, 1950 and 1968. During all such events, a similar transport through the Great Rangit likely occurred. Figure 10 supports this view.

The input of the coarse load resulted in accretion of the channel floors, which, as indicated by repeated observations, are being gradually lowered due to removal of finer material[9,14]. So, will the deepening of the Teesta and its tributaries follow tectonic movements? Or will the Teesta follow smaller streams that directly drain the fringe of the Himalaya and then will their huge foreland cones penetrate mountain interiors like in the case of the Reti, Gish, etc.[23,24].

Meanwhile, 10 years ago, the task of building dams and hydropower plants in the entire Teesta catchment has started. Two dams and reservoirs have already been built in the discussed section between the mouths of the Rangit and Kalijhora. Transportation of the material load down the river had been hindered, but was the supply of material stopped? Will not new heavy downpours occur over the Rangit catchment? Indeed, it is almost 50 years since the last catastrophe occurred. Should not one think about preventive measures prior to a new flood wave being formed in the region of tea plantations? Hydrologists traditionally start setting protection measures and water control structures in the source areas of the catchments and gradually progressing downstream. In the meantime in the Himalaya, rainfall is the most copious at the fringe of the mountains.

Figure 14. Wide alluvial fan at the outlet of the Kalijhora creek (photograph taken in 1987).

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