Human role in shaping the hydromorphology of Himalayan rivers: study of the Tista River in Darjeeling Himalaya

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The aim of the present study is to evaluate the hydromorphological state (the degree of naturalness and anthropogenic transformation) of Himalayan rivers and to determine the role of human activity in shaping their hydromorphology. The study was conducted in the valley of the Tista River in Darjeeling Himalaya. The field research was carried out in selected channel sections with and without noticeable human interference. The assessment of the hydromorphological state was conducted on the basis of the River Habitat Survey method. The analysis of research results shows that the habitat quality of the river sections with noticeable human interference is not significantly different from that in the sections without noticeable anthropogenic pressure.

Keywords: Darjeeling Himalaya, hydromorphology, human impact, River Habit Survey method, Tista River.

HYDROMORPHOLOGY describes the geomorphology and hydrology of a river system, their interactions, and their arrangement and variability in space and time[1]. It is expressed through the diverse morphological elements and hydrodynamic features of a river. Hydromorphology is characterized by the spatial complexity of a channel, which is caused by processes occurring in many interrelated scales in river connectivity. This works in three dimensions – longitudinal, lateral and vertical – and by dynamism, which shapes channel form and connectivity[2]. It has an impact on river ecology and is one of the most important factors shaping the habitat conditions of a river; therefore, it influences biodiversity and the functioning of a river's ecosystem[1,2].

Noticeable changes in the hydromorphology of rivers and streams are one of the results of human activity in mountain areas. According to Wohl[3], human impact on mountain streams may result from activities undertaken in a stream channel that directly alter the channel geometry, the dynamics of water and sediment movement, contaminants in the stream, and aquatic and riparian communities. Human impact can also result from activities within the watershed that indirectly affect streams by altering the movement of water, sediment and contaminants into the channel. Human activities that directly change river habitat involve flow regulation, channel fragmentation with hydraulic structures, riverbank stabilization and exploitation of aggregates. Elosegi *et al.*[2] state that human activity transforms natural environment into a more homogenous one, with less diversity.

Evaluation of the ecological quality of the Himalayan rivers has been included in recent studies on the subject matter[4–6]. Although human role in transforming mountain environment of the Himalaya has been widely studied[7–11], changes in the hydromorphology of Himalayan rivers caused by human activity are not extensively documented. The present study attempts to characterize the hydromorphology of the Tista River (a right tributary of the Brahmaputra) in Darjeeling Himalaya. The aim of the present study is to demonstrate similarities and differences in river hydromorphology between sections permanently transformed by humans and those without permanent hydromorphological transformations.

The analysis was focused on extreme hydrological and geomorphological phenomena (precipitation, erosion and accumulation in river channels, mass movements) and on the contemporary evolution of form both in Darjeeling Himalaya and in its foreland[12–18].

Study area

The study was conducted in the valley of the Tista River in the Darjeeling Himalaya. The investigated area encompassed a 33 km section between Sikkim Bridge and Sevok Bridge (Figures 1–3). The Tista River is a right tributary of the Brahmaputra with draining mountain area of approximately 8600 km^2. It originates in the Pauhunri massif (7127 m amsl). The total length of the mountain section of the river amounts to 182 km (ref. 18). The Tista is characterized by a complex hydrological regime. The river is fed not only by precipitation, but also by melting glaciers and snow as well as groundwater[13]. Mean annual precipitation in the mountain area of the

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drainage basin of the Tista from 1963 to 2001 equalled 2218 mm, with 78% of the precipitation falling during the monsoon season[17]. Maximal river flow registered on 4 October 1968 in Tista Bazaar was estimated at 18,150 $m^3 s^{-1}$ (refs 14, 19). It was caused by the highest reported precipitation in this region, which exceeded 500 mm over 3 days. The minimal flows during the dry season drop below 20 $m^3 s^{-1}$ (refs 16, 18). The water level during high water stages usually rises by 5–6 m in relation to the medium water level, and the corresponding flows range from 1800 $m^3 s^{-1}$ to 2500 $m^3 s^{-1}$ (refs 14, 19). The highest rise of water level was registered in 1968, and equalled 26 m (ref. 18).

In the analysed mountain section, the width of the channel in the valley of the Tista ranges from 100 to 200 m. The course of the valley is either straight or winding; at the edge of the Himalaya, it has a shape of a narrow and deep canyon. Old terraces can be found high on the slopes of the river valley (approximately 60 m), and are covered with permanent vegetation. Low terraces located near the channel are often washed, and are covered with sand during annual high water states. On the channel bottom of the Tista, visible rock basements indicate the processes of channel deepening[15]. In the convex parts of meanders, bars composed of loose rock material comprising grains of different fractions (from sand to large post-flood boulders) are developed. The concave parts of the bends are present in the places where the exposed rocks creating high walls. Characteristic morphological elements in the valley bottom of the Tista River are alluvial fans developed by side tributaries[14,15]. The slopes of the valley of the Tista are shaped by landslide processes, which are especially active during intensive precipitation and high water flows during monsoon season[12,16,20]. Moreover, intensive transformation of channel morphology takes place during high water states[13,14,19].

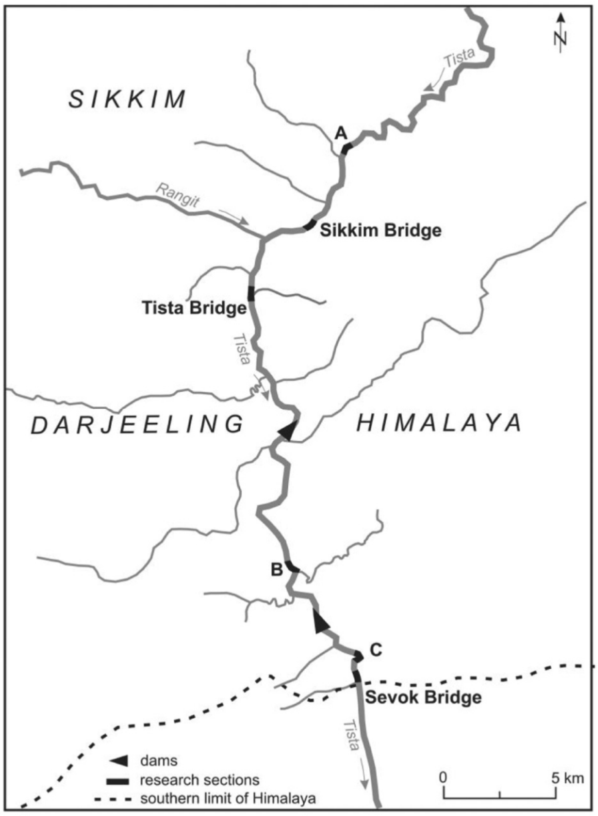

Figure 1. Study area.

Aim and methodology of the study

The aim of the study is to evaluate the hydromorphological state of the Tista River (the degree of naturalness and anthropogenic transformation) and to determine the role of human activity in shaping the hydromorphology of Himalayan rivers. Field research was conducted in December 2012. It involved the assessment of the hydromorphological state of the mountain reaches of the river between Sikkim Bridge and Sevok Bridge. The study was carried out in six selected research sections measuring 500 m that comprised three channel sections without noticeable human interference (called A, B, and C for the purpose of the analysis) and three channel sections noticeably transformed by humans (Sikkim Bridge, Tista Bridge and Sevok Bridge). The research sections without noticeable human interference in the analysed part of the river were distributed irregularly because of restricted access to the channel (steep valley slopes covered with jungle vegetation), and because a considerable part of the valley of the Tista was flooded due to a rise in water level caused by one of the dams (a second dam, located downstream, was under construction). The choice of the sections characterized by a noticeable transformation of channel morphology was based on significant degree of anthropogenic pressure expected in the parts of the river located near bridges.

The assessment of the hydromorphological state was conducted on the basis of the British river habitat survey (RHS) method. The collected data were used to compare the quality of hydromorphological state and river habitat in the sections with and without noticeable human interference.

The RHS method was developed at the beginning of the 1990s by the Environment Agency, UK. It is the most popular method of evaluating the hydromorphological state of rivers used in Europe[21–26].

The guidelines for research utilizing the RHS method can be found in the studies carried out by Raven *et al.*[27] and the Environment Agency, UK[28]. Studies based on the RHS method are conducted in two stages in a 500 m river section. The first stage involves a description of the basic morphological features of a channel and riverbanks in ten control profiles located at 50 m intervals. This stage also involves assessing riverbank and channel bottom substrates,

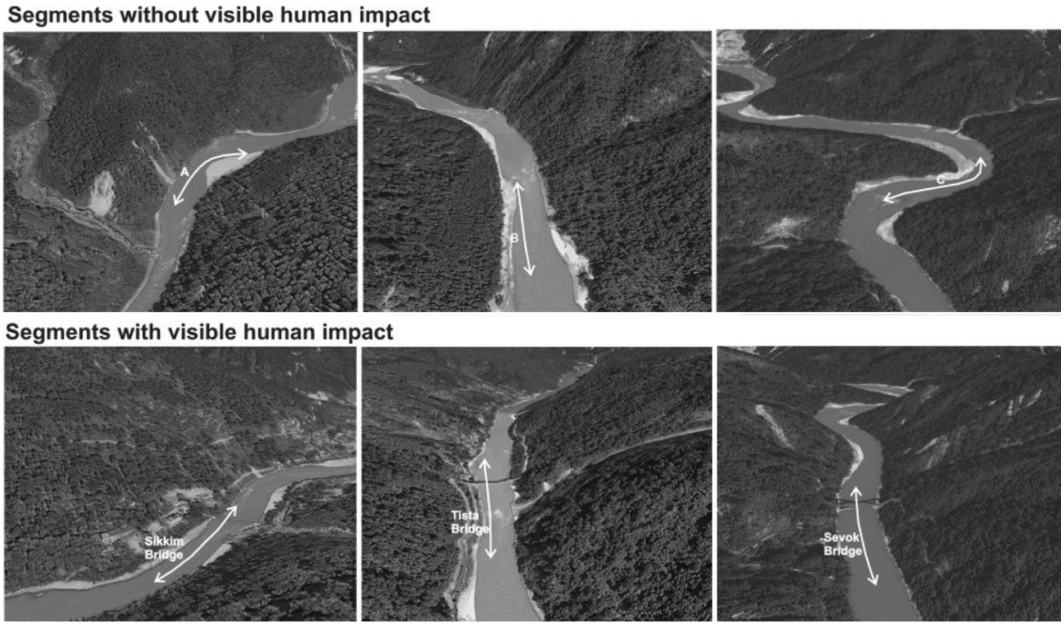

Figure 2. Research sections in the aerial photograph of the Tista River (source: *Google Earth*).

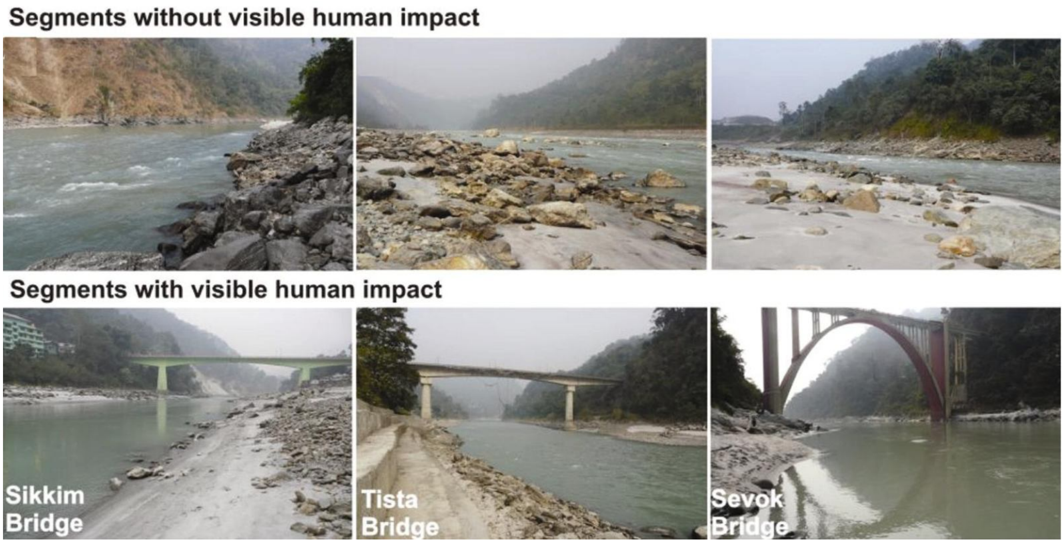

Figure 3. Research sections of the Tista River (photograph: Ł. Wiejaczka).

natural elements and modifications of riverbanks and channel bottom, type of flow, riverbank and channel vegetation structure and land use in the river valley in the proximity of a channel (in a strip no longer than 5 m). A synthetic description of an entire research section is made during the second stage. This includes different morphological forms and transformations that were not registered during the previous stage (description of a valley, channel dimensions, number of hydraulic structures). Studies based on the RHS method enable approximately 400 parameters to be collected that characterize the hydromorphological conditions of a river section. The obtained material can be used to calculate the synthetic habitat quality assessment (HQA) and habitat modification score (HMS) indices. These are the result of many individual basic parameters, and allow us to conduct a numerical evaluation of the hydromorphological features of a river. Using the HQA index of naturalness, the diversity of natural channel and valley elements can be assessed. The evaluation comprises the following elements: physical channel dimensions, riverbank features, channel vegetation types, bank-face vegetation structure, shrubs and land use within 50 m of a riverbank. These elements are assessed at a given point, the summation of which facilitates categorization of the studied section. The HMS index of habitat modification is calculated on the basis of information about the type and number of hydraulic structures, riverbank reinforcements, changes in a channel profile and disturbances in the hydrographic conditions of a valley. A river is characterized by the best habitat conditions when the values of the HQA index are high and those of the HMS index are low.

The terminology used in the RHS method represents a considerable simplification of the terms used in various areas of natural and technical sciences. To avoid terminological ambiguities, the meaning of the potentially confusing terms used in the article has been explicitly clarified in the analytical part of the study. A detailed description of the RHS terminology has been included in the study by Raven *et al.*[27] and the Environment Agency, UK[28], which provides the basic literature for anyone interested in this method.

In the present study, the quantitative characteristics of the hydromorphological state of the Tista River are presented as a percentage share of individual cross profiles (located every 50 m in a 500 m section), where given natural and anthropogenic elements were observed in the overall number of profiles in the entire research section. The characteristics of the channel bottom were provided in relation to 10 cross profiles. In the case of riverbanks, the total number of observation points equalled 20 (10 on the left and 10 on the right riverbank in a given section of the river).

Analysis of the results

Hydromorphological state of the Tista River in sections without noticeable anthropogenic pressure

Riverbanks are mostly composed of exposed bedrock in the analysed sections of the Tista River without noticeable human influence. Its presence was observed in 25–50% of all cross profiles in individual research sections. The riverbanks composed of exposed bedrock form very steep or even vertical walls that reach around 100 m above the valley bottom. The riverbank substrate also includes boulders, i.e. the fraction with diameter ≥ 256 mm (from 15% to 55% of the profiles), as well as loose rock material comprising fractions with a diameter smaller than the boulders, i.e. 64–256 mm (cobbles) and 2–64 mm (gravel and sand; Table 1). The natural morphological riverbank elements of the Tista recorded in all research sections comprised accumulation forms, i.e. vast unvegetated side bars (10–50% of profiles) and point bars (understood as side bars developed in bends of channels characterized by a winding or meandering course) observed only in section C (45% of profiles). These elements constituted a significant part of the cross profile of the riverbank and were formed from the aforementioned loose rock material, from sand to boulders. There were no anthropogenic riverbank and channel bottom transformations, i.e. artificial reinforcements and reprofiling in the studied section of the Tista River.

The channel bottom of the Tista River is composed of diverse material. In section B, cobbles (80%) were significantly dominant compared to boulders and sand. On the other hand, in sections A and C boulders (50% of profiles in each of the sections) were dominant compared cobbles, pebbles and gravel (2–16 mm), and sand (<2 mm). Exposed boulders, a commonly present natural morphological

Table 1. Hydromorphological state of the Tista River in sections without noticeable human interference

	Section A	Section B	Section C
Bank material			
Bedrock	40	50	25
Boulders	35	15	55
Gravel/sand	25	10	5
Cobbles	0	25	15
Bank modification			
None	100	100	100
Natural bank features			
None	75	50	45
Unvegetated side bar	25	50	10
Unvegetated point bar	0	0	45
Channel substrate			
Bedrocks	50	10	50
Cobbles	30	80	0
Pebbles/gravels	0	0	10
Sand	20	10	40
Flow type			
Unbroken standing waves	30	50	70
Broken standing waves	30	0	0
Rippled	40	50	0
Smooth	0	0	30
Channel modification			
None	100	100	100
Channel features			
None	60	40	20
Exposed boulders	40	60	60
Unvegetated midchannel bar	20	30	20
Land-use within 5 m of bank top			
None	0	0	30
Suburban development	50	0	20
Broadleaf woodland	40	100	50
Tall herbs/grasses	10	0	0
Bank top vegetation structure			
None	0	0	0
Simple	10	5	5
Uniform	15	55	35
Complex	75	40	60
Bank face vegetation structure			
None	10	50	70
Simple	10	25	10
Uniform	35	25	0
Complex	45	0	20

element of the channel bottom of the Tista, were observed in all three sections. They were transported from the upstream river sections as well as by side tributaries during high water states in the monsoon season, and were registered in 40–60% of profiles. The natural elements of the bottom also include unvegetated middle-channel bars (20–30% of profiles), exposed during low flows in the dry season. Human activity concerning the channel bottom substrate of the river involves the exploitation of this substrate by local communities.

In the RHS method, nine flow types can be distinguished on the basis of the characteristics of the surface of flowing water, velocity and direction of a current, and the influence of flow on the channel bottom substrate. In the Tista River, unbroken standing waves are the basic flow type, and were observed in 30–70% of profiles in all research sections (according to the RHS method, it is a turbulent flow with short waves characterized by glazed crests). The frequent occurrence of unbroken standing waves is caused by the presence of boulders and cobbles in the channel bottom, as well as by a considerable increase in gradient of the channel in some of its parts. In sections A and B, rippled flow type was also present (the surface of water develops characteristic 1 cm high wavelets that travel along a river). Additionally, the study registered broken standing waves (a turbulent flow with foamy water and breaking wave crests – 'white water') and smooth flow (a slow and laminar flow, which does not disturb the water surface; Table 1).

In a 5 m long stripe from the banktops (in the RHS method, defined as an area adjacent to the edge of a riverbank and transforming into a 1 m floodplain), broadleaf forests were the predominant form of land use in the analysed research sections of the Tista River (40–100% of control profiles). In section A, the land use along the left banktop comprised infrastructure, i.e. a road built along its entire length.

The RHS method classifies the vegetation structure of a riverbank based on four categories (complex, simple and uniform vegetation structure and bare earth). The components correspond to vegetation types that influence the formation of the vertical structure of a riverbank. In the RHS method, vegetation structure is determined separately for a banktop and for a bank-face (the area between the edge of a riverbank and a water level in a channel). The banktops of the researched sections were covered mostly by simple (i.e. two or three vegetation types, including scrubs and trees) and complex vegetation structure (four or more types). The bank-faces of the Tista River in sections A–C were characterized by a significantly greater diversification of vegetation structure, which ranged from uniform to complex. In sections B and C, large areas of bare earth were observed on the bank-faces, which resulted from the presence of point bars and side bars formed during every monsoon season.

Hydromorphological state of the Tista River in sections with noticeable anthropogenic pressure

The modifications concerning the morphology of a considerable part of riverbanks are a major form of anthropogenic pressure in the analysed sections of the channel of the Tista River (Sikkim Bridge, Tista Bridge and Sevok Bridge). Reinforcements with concrete wall and re-profiling of riverbanks were observed in all three studied research sections; however, the degree of human interference was diverse (Table 2). The highest number of

Table 2. Hydromorphological state of the Tista River in sections with noticeable human interference

	Sikkim Bridge	Tista Bridge	Sevok Bridge
Bank material			
Bedrock	20	50	90
Boulders	5	0	0
Gravel/sand	55	0	0
Concrete walls	20	50	10
Bank modification			
None	55	50	80
Reinforced	45	50	20
Resectioned	45	50	20
Natural bank features			
None	25	0	75
Unvegetated point bar	75	100	25
Channel substrate			
Boulders	50	80	0
Pebbles/gravels	0	0	30
Sand	50	20	70
Flow type			
Unbroken standing waves	0	70	0
Rippled	20	30	0
Smooth	80	0	100
Channel modification			
None	100	100	100
Channel features			
None	50	60	30
Exposed boulders	50	40	20
Unvegetated midchannel bar	0	0	10
Bedrock	0	0	40
Land-use within 5 m of bank top			
Suburban development	100	65	80
Broadleaf woodland	0	35	20
Bank top vegetation structure			
None	30	0	0
Simple	10	35	10
Uniform	45	15	10
Complex	15	35	80
Bank face vegetation structure			
None	15	50	0
Simple	35	10	5
Uniform	35	40	40
Complex	15	0	55

modifications was found in the Tista Bridge section, where the right riverbank was reinforced with a concrete wall along its entire length. A smaller degree of riverbank modification was observed in the Sikkim Bridge section, where the reinforcements and reprofiling were only occasionally present in the top part of the left bank. The Sevok Bridge section was characterized by the smallest degree of modification of riverbank morphology, and reinforcements and reprofiling were only observed in two profiles. In this section, exposed bedrock, reported in 90% of profiles, is a natural riverbank reinforcement. In the Sikkim Bridge section, loose fraction (gravel and sand) predominates in the riverbanks. Along the entire length of the Tista Bridge section, the left riverbank of the Tista is composed of exposed bedrock. In the right riverbank in this section, the study reported the presence of a concrete wall, which reinforces the riverbanks. Concrete walls are also present in the Sikkim Bridge and the Tista Bridge sections (20% and 10% respectively). The only natural morphological riverbank elements in the analysed sections comprised unvegetated side bars (25–100% of profiles).

The channel bottom of the Tista River in the Sikkim Bridge and Tista Bridge sections was mostly composed of boulders (50% and 80% respectively), which predominated over sand. In the Sevok Bridge section, sand (70%) dominated over cobbles and gravel. In the Sikkim Bridge and Sevok Bridge sections, smooth flow (70% and 100% of profiles respectively) was the dominant flow type. In the Tista Bridge, it was unbroken standing waves that predominated (70% of profiles). In the Sikkim Bridge and Tista Bridge, rippled flow was occasionally reported. Natural morphological bottom elements mainly included exposed boulders (20–50% of the profiles). In the Sevok Bridge section, exposed bedrock (40% of the profiles) and barely visible unvegetated middle-channel bar (10% of the profiles) were also present. In the studied sections, no modifications of the channel bottom of the Tista were reported.

In a 5 m strip from the banktops, the dominant form of land use comprises infrastructure (65–100% profiles) such as roads, residential buildings and outbuildings. Additionally, in the Tista Bridge and Sevok Bridge sections, the study registered the presence of broadleaf woodlands. Both the banktops and bank-faces were covered with considerably diverse vegetation structure, which ranged from uniform to complex (Table 2). The study also reported cross profiles characterized by the lack of riverbank vegetation, caused by riverbank reinforcements, exposed bedrock and bars that constitute a significant part of the riverbank cross profile.

Analysis of the HQA and HMS indices

The HQA index values, which indicate the degree of diversification of natural hydromorphological elements in the river habitat, calculated for the individual research sections without noticeable human interference (sections A–C) are similar and fall within a narrow range of 46–51 (Figure 4). According to the classification by Walker *et al.*[29] for British rivers (no existing classification of the analysed indices concerns only mountain rivers characterized by noticeably different hydromorphology in comparison to lowland rivers), the quality of the river habitat in the studied sections of the Tista River with regard to diversification of natural elements can be categorized as sufficient (Table 3). The obtained value of the HQA index in the studied sections was determined by the diversification of material and natural elements of the channel bottom as well as by water flow types. Riverbank vegetation structure and land use, i.e. broadleaf woodlands located in the proximity of the channel, are other factors influencing the quality of the river habitat of the Tista.

In the Sikkim Bridge and Sevok Bridge sections with noticeable human interference, the values of the HQA index equalled 43 and 45 respectively. According to the classification by Walker *et al.*[29], the quality of these sections can be considered as sufficient, similar to the sections without noticeable anthropogenic pressure. On the other hand, the Tista Bridge section was characterized by smaller diversification of the natural hydromorphological elements of the habitat (39) in comparison to the aforementioned sections, and the quality can be categorized as low.

The values of the HMS index, which indicates the degree of anthropogenic changes in the river hydromorphology, calculated for the sections A–C, which were not influenced by humans, equalled zero; this indicates that the river habitat is almost natural[29]. On the other hand, the Sikkim Bridge and Tista Bridge sections, with modifications in the morphology of riverbanks, i.e. reinforcements and reprofiling, are characterized by the greatest changes in the hydromorphology related to human interference in the habitat. The river habitat in these sections can be considered as significantly changed (the values of the HMS index equalled 29 and 34 respectively). The Sevok Bridge, where the HMS value equalled 9, was characterized by the least modified river habitat of the Tista, which is the result of the smaller transformation of riverbank morphology in comparison to the Sikkim Bridge and Tista Bridge sections.

Discussion and conclusion

The assessment of the hydromorphological state of the Tista River showed that the river sections without noticeable human interference are characterized by sufficient habitat quality, which results from the presence of different morphological elements in the channel, water flow type, and from the diverse riverbank vegetation structure.

Table 3. Category of the river due to habitat modification score (HMS) and habitat quality assessment (HQA) values

Type of habitat	HMS value	Quality of habitat	HQA value (%)
Almost natural	0–2	Very high	80–100
Slightly changed	3–8	High	60–80
Little changed	9–20	Sufficient	40–60
Much changed	21–44	Low	20–40
Highly changed	≥ 45	Very low	0–20

Source: Walker *et al.*[29].

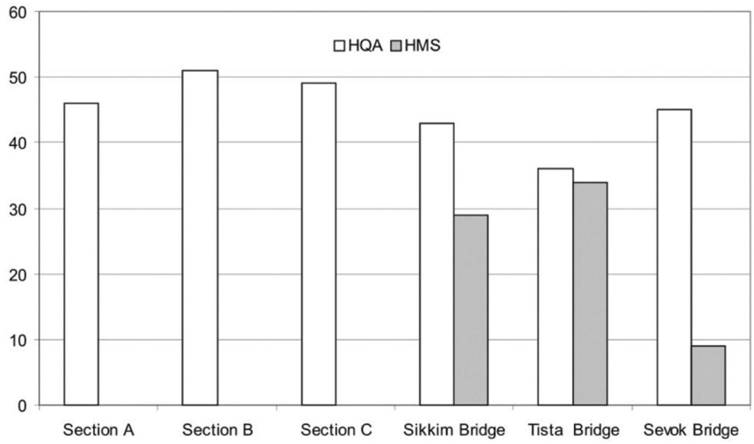

Figure 4. Values of the habitat quality assessment (HQA) and habitat modification score (HMS) indices calculated for the individual research sections of the Tista River.

The broadleaf woodlands observed in the proximity of the channel are an important factor in determining the river habitat quality. Distinctive features of the channel hydromorphology of the Tista River comprise high rock walls forming the channel banks, as well as side and point bars characterized by large dimensions (length and width) developed due to the accumulation of material transported during high water states in the rainy season. The bars are formed mainly from considerably smoothed, loose rock material that comprises grains of different fractions (from sand to boulders). Similar to other Himalayan rivers, large post-flood boulders with a diameter up to a few metres were present in the channel of the Tista River. During low water states, middle-channel bars develop. The side, point and middle-channel bars were covered with bare earth. No water vegetation was observed in the channel of the Tista. In the river sections without riverbank and channel bottom modifications, exploitation of fluvial material by the local community is the only form of anthropogenic pressure. The decrease of the fluvial material observed during dry season is compensated by the delivery of debris during high water states in the monsoon season.

The analysed sections of the Tista River with noticeable human interference, i.e. riverbank modifications, are characterized by small or considerable modifications of the river habitat. The modifications that involve concrete walls or riverbank reprofiling occur in the long channel sections, and their function is to protect road infrastructure and buildings from river erosion (the road serves as the main communication route between West Bengal and Sikkim). Despite a large human impact on riverbank morphology, the studied channel sections of the Tista are characterized by a considerably large amount and diversification of natural morphological elements (boulders, side bars and exposed bedrock). As a result, the river habitat quality is not significantly different from the habitat quality in the sections without noticeable anthropogenic pressure, and can be categorized as low or sufficient. Additionally, exploitation of gravel during the dry season is observed in many places.

Two reservoirs between Kalijhora and Tista Bazar that are under construction will be another important factor leading to the modification in the morphology of the mountain section of the Tista. The construction of the reservoirs will cause the disappearance of the hydromorphological features of the valley that are characteristic for the river, and will result in the development of conditions typical for standing waters. The operation of reservoir complex will most likely have an influence on the natural hydrodynamics of the channel and on the fluvial processes. Below the reservoirs, it can be expected that the erosion of the channel bottom caused by the outflow of water without river debris will increase. Intense accumulation of the material transported by the Tista River will take place in the reservoirs. The local community that exploits the fluvial material in the area of the reservoir, having no access to the channel, as it is currently under water, has begun exploiting gravel in terraces located high above the channel. It should be assumed that, after some time, this will cause permanent changes in the morphology of the high parts of the valley, and it will also lead to other land-forming processes (e.g. landslides).

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