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Sedimentological characterizations of Recent sediments from the Teesta River, Bangladesh: implication for sediment transportation and depositional conditions

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Abstract

The Teesta River originates from the Higher Himalayas, flows through India and Bangladesh and transports huge sediments to the Brahmaputra-Jamuna River. Geomorphologically, the Teesta River shows braided in nature with different types of bars and floodplains. This study incorporates both the exposed sands from river banks and bars as well as subsurface borehole samples of the Teesta River with the aim of sedimentological characterization of these sediments which further assist to understand their history of transportation and deposition. The sand deposits of the Teesta River can be categorized into seven distinct lithofacies: trough cross-stratified sand (S_t), planar cross-stratified sand (S_p), massive sand (S_m), ripple cross-laminated sand (S_r), parallel laminated sand (S_h), massive clay (F_m) and laminated clay (F_l), which grouped into multiple fining-upward sequences, indicating periodic decrease in flow velocities as well as shifting of channels and bars. The sand deposits from channels and bars show mostly unimodal in nature which suggests unidirectional current flow, although evidence of minor redistribution by chute channels has been observed. The textural characteristics of these Teesta River sands consist of fine to medium grained, moderately well sorted to well sorted, dominantly positively skewed and leptokurtic to mesokurtic in nature. These sands are dominantly bedload deposits and have been transported predominantly by saltation process with subordinate suspension process, while traction processes are limited mainly in the upper reaches of the river. Various bivariate diagrams indicate that these sediments were deposited in low to medium level of energy conditions.

Keywords: Teesta River, braided river, sedimentary processes, lithofacies

Introduction

The Teesta River is a major tributary of the Brahmaputra-Jamuna River system which carries huge amount of sediments from the Himalayan orogen. These clastic sediments preserve the clues of their provenances and nature of transportation as well as depositional processes within the basin. Textural properties and their associated

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parameters are the essential indicators of sedimentary environments and interacting processes (BLOTT 2001; EDWARDS 2001; HAKRO *et al*. 2021). Grain size analysis of clastic sediments is used over the years to classify sediments, to distinguish different depositional environments (FOLK & WARD 1957; MASON & FOLK 1958; FRIEDMAN 1961, 1967, 1979; KANHAIYA *et al*. 2017), and to establish the transportation processes and depositional conditions (PASSEGA 1957, 1964; PASSEGA & BYRAMJEE 1969; LUDWIKOWSKA-KEDZIA 2000; SING *et al*. 2007). In addition, facies analysis is a fundamental sedimentologial approach to reconstruct any depositional system where specific group of processes are functioned to provide resultant sedimentary sequence.

In recent years, major rivers of Bangladesh have extensively studied in sedimentological, geochemical and economic aspects, for examples, the Bahmaputra-Jamuna River (JASY *et al*. 2010; ABEDEN *et al*. 2018; RAHMAN *et al*. 2020), the Ganges-Padma River (ALI *et al*. 2019; ISLAM *et al*. 2022), and the Meghna River (HOSSAIN 2019; RAHMAN *et al*. 2022). In addition, recent sediments of the Atrai River that is a tributary of Ganges-Padma River are studied to delineate the provenance rocks of the sediments as well as the current hydrodynamic conditions of the river (SAYEM *et al*. 2021). BISWAS *et al*. (2018) studied the heavy mineral potentiality of bar sediments from the Teesta River. Besides, SAHA *et al*. (2021) have recognized only the lithofacies-types of the Teesta sediments exposed along the river banks and bars. However, the present study on Teesta River sediments, includes both the textural and lithofacies analysis, aims to explore the hydrodynamic conditions of the river during sediment deposition particularly: (1) the shifting pattern of braided channels, bars and floodplain with time; and (2) the sediment load-types and their transportation mechanisms. For these purposes, the 110 km reach of the Teesta River from Bangladesh – India border to the confluence with the Jamuna River have been studied (Fig. 1).

Geological Settings

The Teesta River which is originated from the Pahunuri glacier in Sikkim (India), is a major tributary of the Brahmaputra River. The Pahunuri glacier is located in the Higher Himalaya from which the river traverses the Lesser Himalaya, Sub-Himalaya and Teesta Mega fan in its upstream region, whereas in the downstream, the river progress along the area of Old Himalayan Piedmont Plain, Dinajpur Slope and Rangpur Saddle in its course. Tectonically, the downstream part of the Teesta River lies within the Stable Shelf province (Geotectonic Province 1) of the Bengal Basin, follows the Teesta lineament (Fig. 1a).

The Teesta is a single sinuous graded stream in the Himalaya terrain and cut through the Darjeeling ridge in a narrow and deep George and, therefore, provide the best cross section of the eastern Himalayas (MUKHOPADHAYA 1982). The river becomes braided with sandy-gravel bars bifurcate multiple channels when it enters the plains of West Bengal, i.e., the Old Himalayan Piedmont Plain which is formed with colluvial and alluvial sediments deposited by rivers or streams at the foothill of Himalaya (RASHID 1979). The Teesta floodplain stretches between the Old Himalayan Piedmont Plain in the west and the N-S flowing Brahmaputra in the east. It has low drainage density and features a terrain ranging from medium to very high relief (PRAMANIK 2016). Changes in relief causes high stream gradient and thus the river shows braided nature in its downstream part before drain into the Brahmaputra River. The river has the highest sediment yield (98.40 cum/ha/yr.) among all Himalayan rivers (AGARWAL & NARAIN 1991).

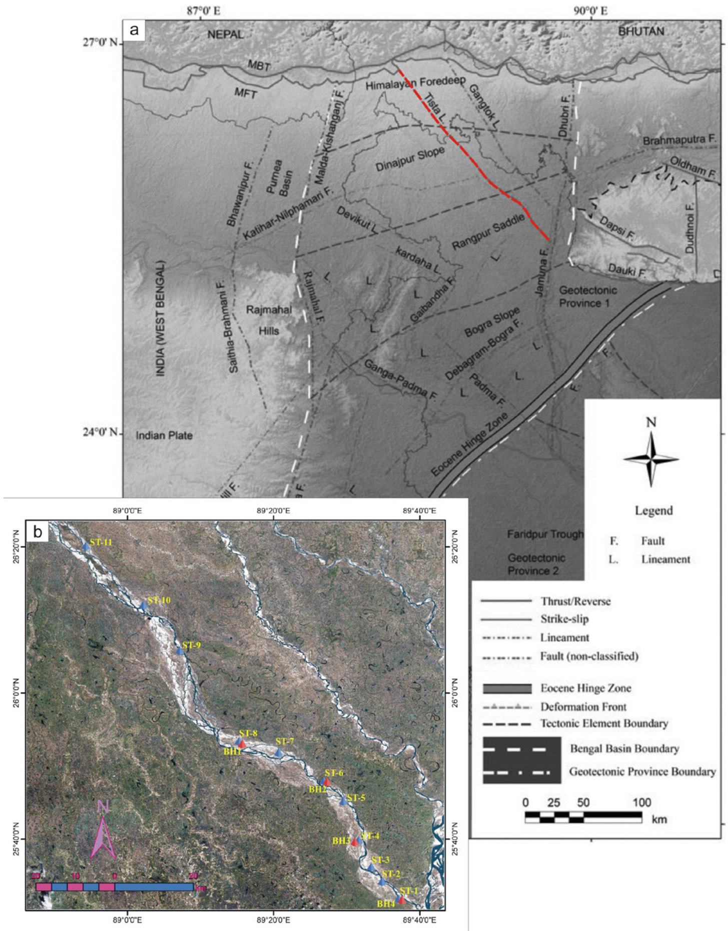

Fig. 1. (a) The tectonic map of the Geotectonic Province 1 of the Bengal Basin and its surroundings (after HOSSAIN *et al.* 2019). The Teesta River follows the Teesta lineament of the Stable Shelf area (marked in red dashed line). (b) The google earth image of the Teesta River showing the braided pattern. Surface sampling locations (St-1 to St-11) and borehole locations (BH1 to BH4) are shown in this image.

Geomorphology

The characteristic geomorphic features of the Teesta River are the channels, different types of bars and floodplain (Fig. 2). The braided nature of the Teesta River is shown as a result of the significant reduction in slope in the immediate foreland of the Himalayas (PRAMANIK 2016). Notably, the construction of the Gajoldoba and other barrages has played a substantial role in shaping the downstream braiding patterns and altering the river's flow (PAL & PANI 2016). The river continues its braided nature in Bangladesh part due to high slope gradient of the north-western part of the Bengal Basin as well as seasonal variation of water discharges. Therefore, chute channels are common in the river system (Fig. 2). When the river flow is sluggish, different types of bars are developed, for examples, longitudinal bars, transverse bars and lateral bars which are highly variable in shape and size (Fig. 2). The longitudinal bars are most common types of sand bars which are elongate along the axis of the channel. Some longitudinal bars are coalesced each other and divided the channel (Fig. 2). On the other hand, lateral bars that are developed in very low energy conditions, are attached to the bank (Fig. 2). The widely spreading transverse bars within channels are also found in the Teesta River.

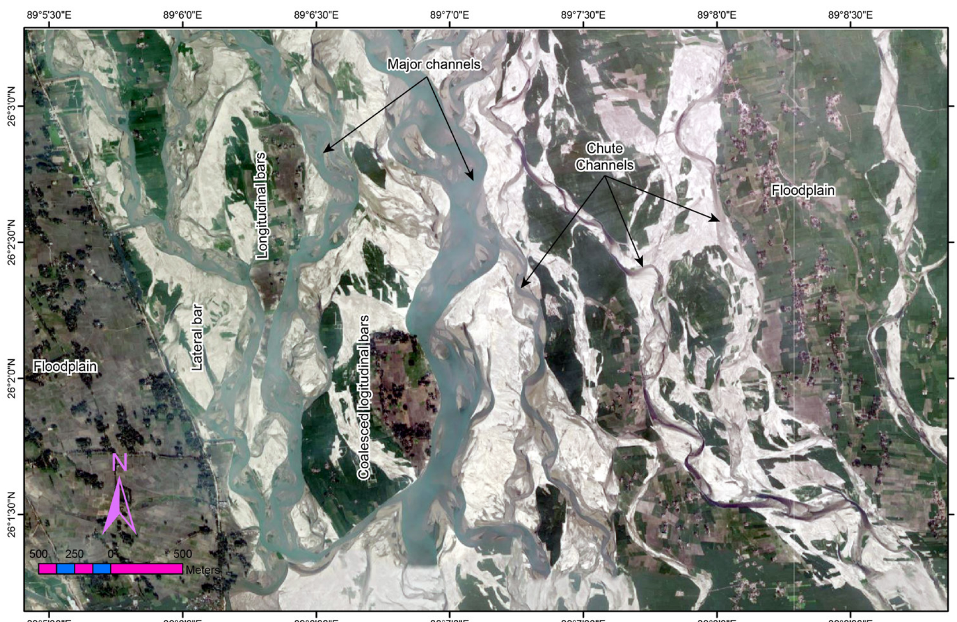

Fig. 2. Fluvial geomorphological features of the Teesta River showing channels, different types of bars and floodplain.

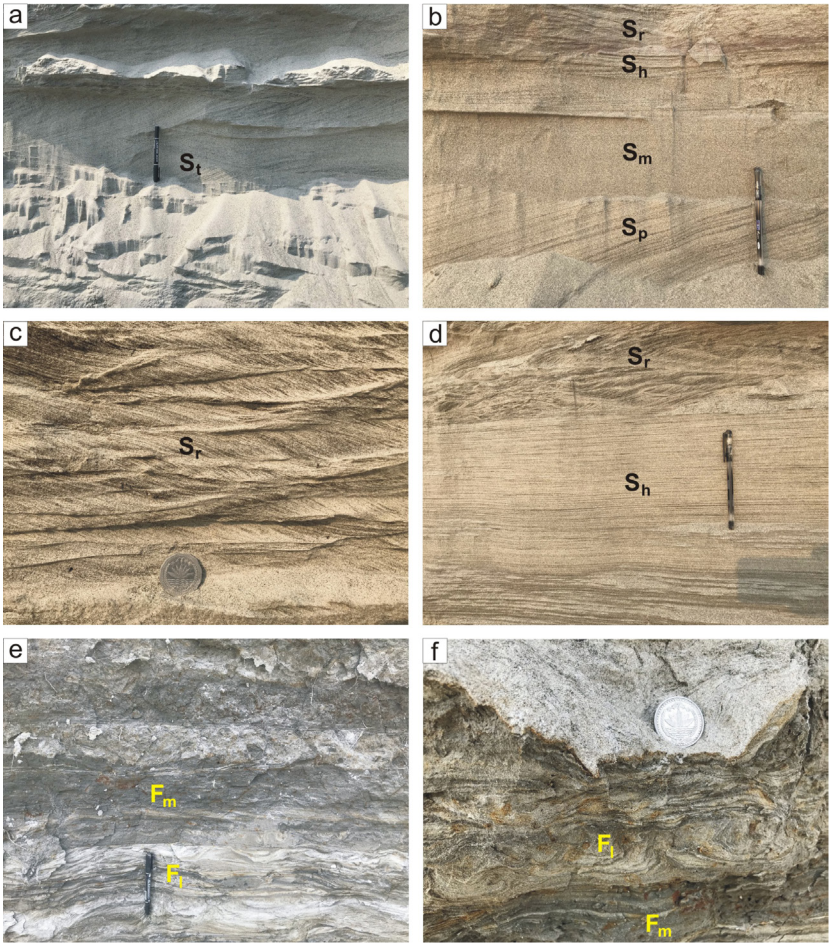

Fig. 3. Photographs showing lithofacies as observed along the cut banks of the Teesta River. (a) Trough cross-stratified sands (S_t) at the Teesta River river bank (ST-7). (b) Five lithofaceis at cut bank of the ST-1 which can be clearly distinguished from each other. They are planar cross-stratified sands (S_p), massive sands (S_m), parallel laminated sands (S_h) and ripple cross-laminated sands (S_r). (c) Ripple cross-laminated sands (S_r) at the ST-3. (d) Ripple cross-laminated sands (S_r) is overlaid the parallel laminated sands (S_h) at cut bank of the ST-3; (e) Massive clay (F_m) and laminated clay (F_l) lithofacies at the ST-7 (f) Laminated clay (F_l) at the ST-7 shows the deformation structure (convolute bedding).

Methodology

For this study, both borehole and exposed samples were collected. Four boreholes (BH1 to BH4) were drilled on the exposed bars of the Teesta River (Fig. 1). The field work was carried out along the Teesta River from upstream to downstream directions to define the sedimentary facies. Detailed sedimentological loggings were performed at suitable outcrops along the river banks and bars. Each lithofacies were described and interpreted in terms of lithology, i.e., color, texture, sedimentary structures, etc. Samples were collected at regular intervals to cover all lithofacies types. The facies associations were identified and interpreted based on the tempo-spatial relationship and similarity of the lithofacies described with regard to diagnostic sedimentary characteristics.

A total of 39 representative samples were selected for particle size analysis, of which 28 are the borehole samples collected from four boreholes at intervals of 5 meters, ranging from the surface to a depth of 30 meters. To classify the various grain sizes, a standard sieving method with 1.0 φ interval was followed as per Folk & Ward (1957). The statistical parameters such as graphic mean, inclusive graphic standard deviation, inclusive graphic skewness and inclusive graphic kurtosis were also calculated according to Folk & Ward (1957).

Result

Facies analysis

A summary of lithofacies that are found in the Teesta River sediments and their interpretations is presented in Table 1. The nomenclature and coding of the observed lithofacies are according to Miall (1978). The nature of major lithofacies is sandy with subordinate thin mud layers. The sand lithofacies is further categorized based on sedimentary structures.

Table 1. Summary table of lithofacies identified in the Recent sedimentary deposits of the Teesta River, Bangladesh.

Facies code	Facies name	Thickness (cm)	Description	Interpretation
S_t	Trough cross-stratified sands (Fig. 3a)	8-60 (Average 20)	Fine to medium fine grained, moderately sorted sands with occasional pebbles; troughs are well defined by curved surfaces and foresets are tangential to the curved bedding surfaces; the bottom of the facies is occasionally erosional.	Developed due to migration of sandy dunes (lower flow regime condition).
Sp	Planar cross-stratified sands (Fig. 3b)	15-70 (Average 35)	Fine to medium grained well sorted sands; low to moderate angle foresets (30° to <10°) are continuous across the width of the outcrop, sometimes bottom surfaces are erosional.	Formed due to rapid advance of sandy bars towards current flow direction.
S_r	Ripple cross-laminated sands (Fig. 3b - d)	7-65 (Average 25)	Fine to medium grained, well sorted sands; ripple-laminated; climbing ripples are very common, presents a clear view of completely preserved lee side and partially or completely eroded stoss side.	Deposited in lower flow regime condition where moderate flow velocity allowed the migration of ripples; characterized by rapid sedimentation from suspension.

Facies code	Facies name	Thick-ness (cm)	Description	Interpretation
S_h	Parallel laminated sands (Fig. 3b, d)	20-90 (Average 40)	Fine to medium sands, well sorted; finely laminated.	Deposited in upper flow regime condition when water flow velocity was very high.
S_m	Massive sands (Fig. 3b)	20-130 (Average 70)	Fine to coarse grained, poorly sorted sands without any prominent sedimentary structure.	Rapid sedimentation of sands probably due to high supply of sediment and/or rapid decrease in flow velocities.
F_m	Massive clay (Fig. 3e, f)	5-12 (Average 7)	Gray colored massive clay to mud, mostly structureless.	Settling of suspended loads in prolonged calm water condition during flood periods.
F_l	Laminated clay (Fig. 3e, f)	7– 25 (Average 10)	Gray colored, finely laminated clay to mud; fine sand to silt streaks are common, sometimes alternating clay and sand layers occur; occasional secondary deformation structure (e.g., convolute bedding) present.	Intermittent deposition of suspended load during slack water period.

Textual Analysis

Grain size Parameters

The statistical parameters such as graphic mean, standard deviation, skewness, and kurtosis provide valuable insights into sedimentation conditions and environments (FOLK & WARD 1957; FRIEDMAN 1961, 1967, 1979; MASON & FOLK 1958; PASSEGA 1957, 1964; PASSEGA & BYRAMJEE 1969; SING *et al.* 2007). These parameters are calculated and tabulated in Table 2. However, the frequency curves of the Teesta River sediments show that most samples are unimodal in nature with peaks at 3.0 φ, 3.2 φ, 3.5 φ, and 3.7 φ (Fig. 4), suggest the uniform depositional setting of the Teesta River sand. Only two samples which were collected from the downstream location of the Teesta Barrage are showing bimodal nature with peaks at 1.1 φ and 2.8 φ (sample St-10), and 1.2 φ and 2.9 φ (sample St-11) (Fig. 4a) which indicate that the fluctuating hydrodynamic condition.

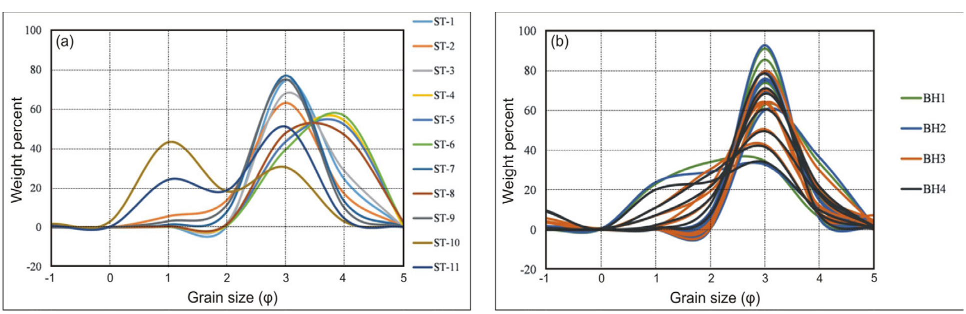

Fig. 4. Frequency curves of the Recent sediments from the Teesta River: (a) for samples collected from the Teesta River's banks and bars, and (b) for the borehole samples.

Table 2. Calculated statistical parameters of the Recent sedimentary deposits of the Teesta River, Bangladesh. Statistical formulas are after Folk & Ward (1957).

Location	Sample No	Graphic Mean (φ)	Standard Deviation (φ)	Graphic Skewness	Graphic Kurtosis	M (μm)	C (μm)
Surface samples	St-1	2.70 Fine Sand	0.47 Well Sorted	0.22 Fine Skewed	1.03 Mesokurtic	159.32	253.29
	St-2	2.46 Fine Sand	0.68 Moderately Well Sorted	-0.13 Coarse Skewed	1.45 Leptokurtic	179.24	859.65
	St-3	2.74 Fine Sand	0.52 Moderately Well Sorted	0.21 Fine Skewed	0.97 Mesokurtic	156.04	263.78
	St-4	3.05 Very Fine Sand	0.58 Moderately Well Sorted	-0.10 Near Symmetrical	0.80 Platykurtic	117.44	249.67
	St-5	3.05 Very Fine Sand	0.59 Moderately Well Sorted	-0.07 Near Symmetrical	0.81 Platykurtic	118.26	256.78
	St-6	3.09 Very Fine Sand	0.57 Moderately Well Sorted	-0.14 Coarse Skewed	0.82 Platykurtic	112.66	253.88
	St-7	2.53 Fine Sand	0.42 Well Sorted	0.05 Near Symmetrical	1.05 Mesokurtic	174.34	374.58
	St-8	3.01 Very Fine Sand	0.60 Moderately Well Sorted	0.01 Near Symmetrical	0.80 Platykurtic	124.14	262.05
	St-9	2.46 Fine Sand	0.47 Well Sorted	-0.12 Coarse Skewed	1.21 Leptokurtic	180.49	720.94
	St-10	1.30 Medium Sand	1.00 Moderately Well Sorted	0.30 Fine Skewed	0.66 Very Platykurtic	479.63	1228.07
	St-11	1.82 Medium Sand	0.94 Moderately Well Sorted	-0.40 Very Coarse Skewed	0.71 Platykurtic	230.05	1020.93
BH1	S1	2.85 Fine Sand	0.57 Moderately Well Sorted	0.23 Fine Skewed	0.89 Platykurtic	146.60	248.96
	S2	2.66 Fine Sand	0.54 Moderately Well Sorted	0.20 Fine Skewed	1.13 Leptokurtic	163.80	414.94
	S3	2.56 Fine Sand	0.36 Well Sorted	0.12 Fine Skewed	0.96 Mesokurtic	171.94	261.28
	S4	1.73 Medium Sand	0.94 Moderately Well Sorted	-0.06 Near Symmetrical	0.84 Platykurtic	289.17	959.26
	S5	2.62 Fine Sand	0.48 Well Sorted	0.21 Fine Skewed	1.19 Leptokurtic	167.24	2828.43

Location	Sample No	Graphic Mean (φ)	Standard Deviation (φ)	Graphic Skewness	Graphic Kurtosis	M (μm)	C (μm)
	S6	2.59 Fine Sand	0.50 Well Sorted	0.17 Fine Skewed	1.22 Leptokurtic	168.40	316.44
	S7	2.54 Fine Sand	0.31 Very Well Sorted	0.04 Near Symmetrical	0.9 Platykurtic	171.94	250.00
BH2	S1	2.97 Fine Sand	0.33 Very Well Sorted	0.33 Strongly Fine Skewed	1.23 Leptokurtic	133.97	248.27
	S2	2.67 Fine Sand	0.55 Moderately Well Sorted	0.20 Fine Skewed	1.17 Leptokurtic	164.94	493.12
	S3	2.57 Fine Sand	0.42 Well Sorted	-0.14 Coarse Skewed	1.66 Very Leptokurtic	164.94	486.33
	S4	2.72 Fine Sand	0.17 Very Well Sorted	0.17 Fine Skewed	1.91 Very Leptokurtic	153.89	244.86
	S5	1.90 Medium Sand	0.95 Moderately Well Sorted	0.03 Near Symmetrical	0.79 Platykurtic	267.94	986.23
	S6	2.72 Fine Sand	0.46 Well Sorted	0.14 Fine Skewed	1.76 Very Leptokurtic	153.89	4594.79
	S7	2.67 Fine Sand	0.43 Well Sorted	-0.04 Near Symmetrical	1.39 Leptokurtic	153.89	460.09
BH3	S1	2.37 Fine Sand	0.62 Moderately Well Sorted	-0.13 Coarse Skewed	1.16 Leptokurtic	183.01	697.37
	S2	2.68 Fine Sand	0.35 Very Well Sorted	0.34 Strongly Fine Skewed	1.09 Mesokurtic	164.94	246.56
	S3	2.87 Fine Sand	0.44 Well Sorted	0.22 Fine Skewed	1.31 Leptokurtic	143.59	466.52
	S4	2.72 Fine Sand	0.51 Moderately Well Sorted	0.27 Fine Skewed	1.30 Leptokurtic	159.32	435.28
	S5	2.17 Fine Sand	1.03 Poorly Sorted	-0.28 Coarse Skewed	1.28 Leptokurtic	196.15	4594.79
	S6	1.98 Medium Sand	0.98 Moderately Well Sorted	-0.15 Coarse Skewed	1.16 Leptokurtic	233.26	5098.24
	S7	2.40 Fine Sand	0.91 Moderately Well Sorted	0.00 Near Symmetrical	2.34 Very Leptokurtic	189.46	4438.28

Location	Sample No	Graphic Mean (φ)	Standard Deviation (φ)	Graphic Skewness	Graphic Kurtosis	M (µm)	C (µm)
BH4	S1	2.50 Fine Sand	0.43 Well Sorted	-0.03 Near Symmetrical	1.12 Leptokurtic	176.78	435.28
	S2	2.67 Fine Sand	0.50 Moderately Well Sorted	0.00 Near Symmetrical	1.56 Very Leptokurtic	159.32	574.35
	S3	2.57 Fine Sand	0.65 Moderately Well Sorted	-0.11 Coarse Skewed	1.18 Leptokurtic	164.94	737.13
	S4	2.68 Fine Sand	0.51 Moderately Well Sorted	-0.08 Near Symmetrical	1.23 Leptokurtic	153.89	517.63
	S5	2.25 Fine Sand	0.89 Moderately Well Sorted	-0.17 Coarse Skewed	0.93 Mesokurtic	189.46	1802.50
	S6	1.82 Medium Sand	1.05 Poorly Sorted	-0.28 Coarse Skewed	1.00 Mesokurtic	241.48	8876.56
	S7	1.70 Medium Sand	1.09 Poorly Sorted	-0.06 Near Symmetrical	0.77 Platykurtic	297.30	10196.49
Average		2.49	0.61	0.02	1.14	-	-

The mean size values of the Teesta River sands range from 3.09 φ to 1.30 φ (average 2.50 φ), indicating very fine to medium sands that follows generally decreasing trend from upstream to downstream (Fig. 5a). The borehole sand samples are also dominantly fine grained, only five samples fall within the group of medium grain sand (Table 2). Whereas, the standard deviation values of the river sands vary from 0.17 φ to 1.09 φ (Table 2) which specify that sorting of the sediments are very well- to poorly-sorted. However, most of the samples, collected from both river banks and boreholes, are dominantly well- to moderately well-sorted. The sorting of the sands becomes better in downstream compared to the upstream (Fig. 5b).

The skewness of the studied samples is highly variable from coarse-skewed through near symmetrical to fine-skewed, and values varies from -0.40 to 0.33 (Table 2). About 34% of the samples are fine skewed and another 34% are fall in the near-symmetric field. On the other hand, the kurtosis values fluctuate between 0.66 and 2.34, and show mostly leptokurtic in nature with minor mesokurtic and platykurtic sediments (Table 2). The predominance of fine fractions along with well to moderately well sorting and mostly leptokurtic to mesokurtic natures of the Teesta River sands suggests that the sands have reached a state of maturity.

Bivariate plots of statistical parameters

The bivariate plots of different textural parameters are used frequently to discriminate the sedimentation conditions (Folk & Ward 1957; Sahu 1964; Stewart 1958). The ratios between mean grain size and standard deviation of the Teesta River sediments are clustered at the half-way in the downward hook of the right-hand limb of the inverted "V" shaped trend in mean grain size versus standard deviation bivariate plot after FOLK & WARD (1957) (Fig. 6a) which suggest that these sands dominated by moderately well-sorted to well sorted and unimodal distribution nature (Fig. 7a).

In the mean grain size vs. kurtosis diagram, the sediments under study are scattered in the central right part of the graph (Fig. 6b) and shows mostly mesokurtic to leptokurtic distribution (Fig. 7b). These results indicate that the Teesta River sediments are primarily composed of nearly pure sand modes with a limited mixing of finer modes that effect the sorting of sediments which are mostly moderately well to well sorted (Fig. 7a). In addition, these results are agreed with that mean size versus skewness plots (Fig. 6c) where the studied samples are scattered closely along the right-hand trend and exhibit predominantly near symmetrical to positive skewness (Fig. 7c).

On skewness versus kurtosis diagram (Figs. 6d and 7d), the data are dispersed almost in the center of the two attributes indicates unimodal sediments with the little affinity of another mode. A few samples show extreme values which may indicate bimodal nature. The bimodal nature is probably the result of mixing of particles brought in by different processes or transporting agents, for example, water carried sediments could be redistributed by chute channels.

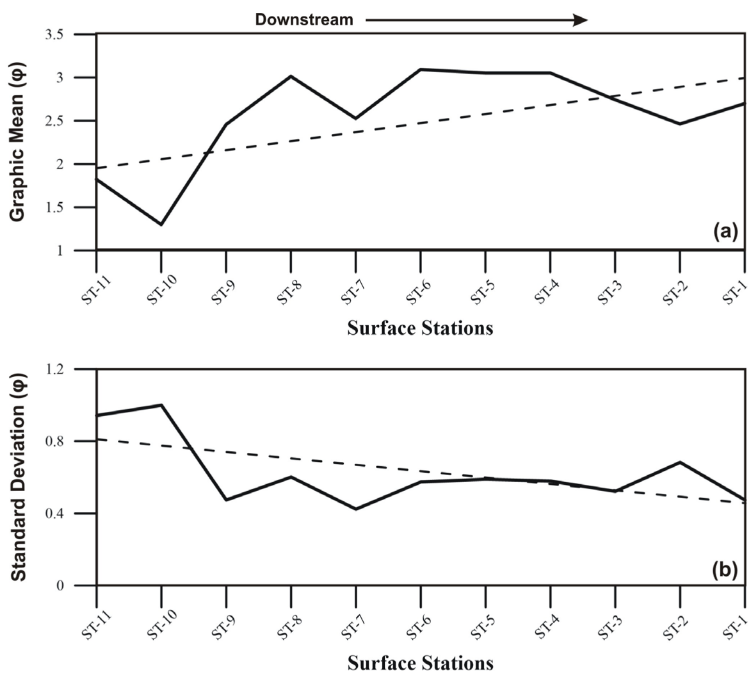

Fig. 5. Spatial distributions of (a) grain size and (b) sorting of the Teesta River sand deposits.

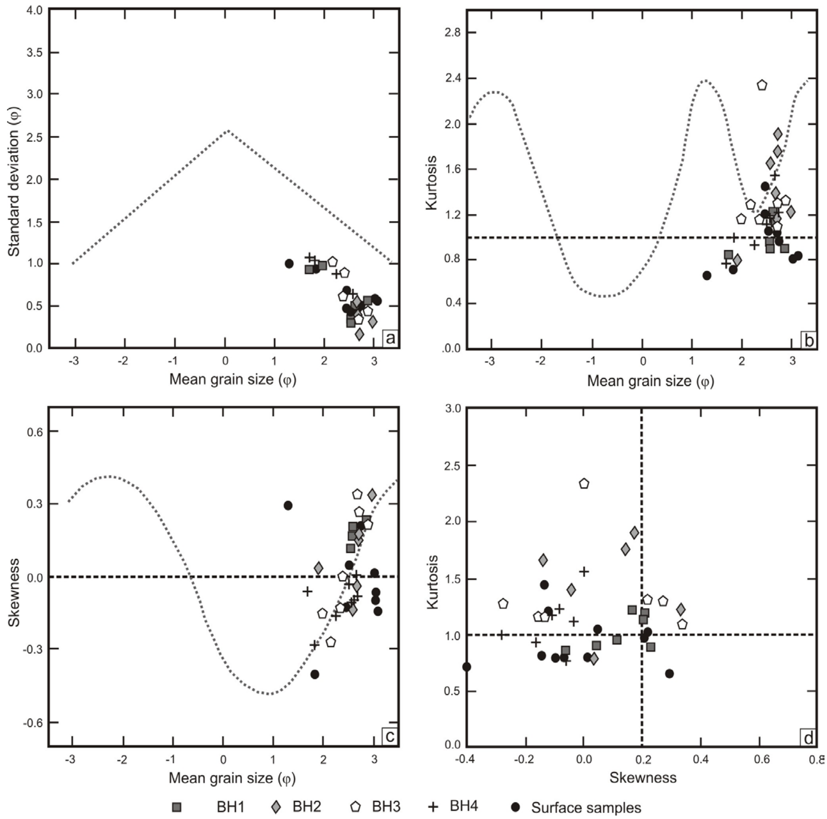

Fig. 6. Bivariate plots for the Teesta River sediments (after FOLK & WARD 1957). (a) Mean grain size vs. standard deviation, (b) Mean grain size vs. kurtosis, (c) Mean grain size vs. skewness, and (d) Skewness vs. kurtosis.

Discussion

Sedimentary facies association: Interpretation of depositional settings

The Teesta River comprises the geomorphic features related to a braided river, such as major channel, secondary channels, numerous chute channels, different types of bars and floodplain (Fig. 2). The facies related to these geomorphological elements are well exposed at cut bank areas during dry season. The facies association of the area shows several fining upward sequences with lag gravels, sandy trough cross-beds (S_t) to occasional massive sands (S_m) filling channels, that overlain generally by tabular cross-bedded sands (S_p) which formed due to migrating bars across channels (Fig. 8). These sequences are sporadically overlain by vertically accreted, ripple- laminated to laminated fine to very fine sands (S_r) and muds (F_l and F_m) (Fig. 8). Mud layers were deposited during slack-water stages, i.e., during flood phases, when the suspended fine silt to clay particles is deposited over the floodplain and inundated bars. However, laminated sands (lithofacies S_h) are generally deposited during flash floods due to heavy rainfall in upstream areas, which causes the flow velocity abruptly increases and sands deposit under upper flow-regime plane bed conditions (MIALL 2006). This lithofacies is overlaid generally by lithofacies S_p or S_r indicating waning flow velocities at the end of a flood event (Fig. 8b, e).

The sediments transported by the Teesta River are deposited as different types of bars in channels due to decreasing flow velocity during dry season, therefore, the channel flow is divided and multiple channels are developed in a braided form. The rapid fluctuation of flow velocities lead to both shifting of channels over its easily eroded banks as well as development of bars.

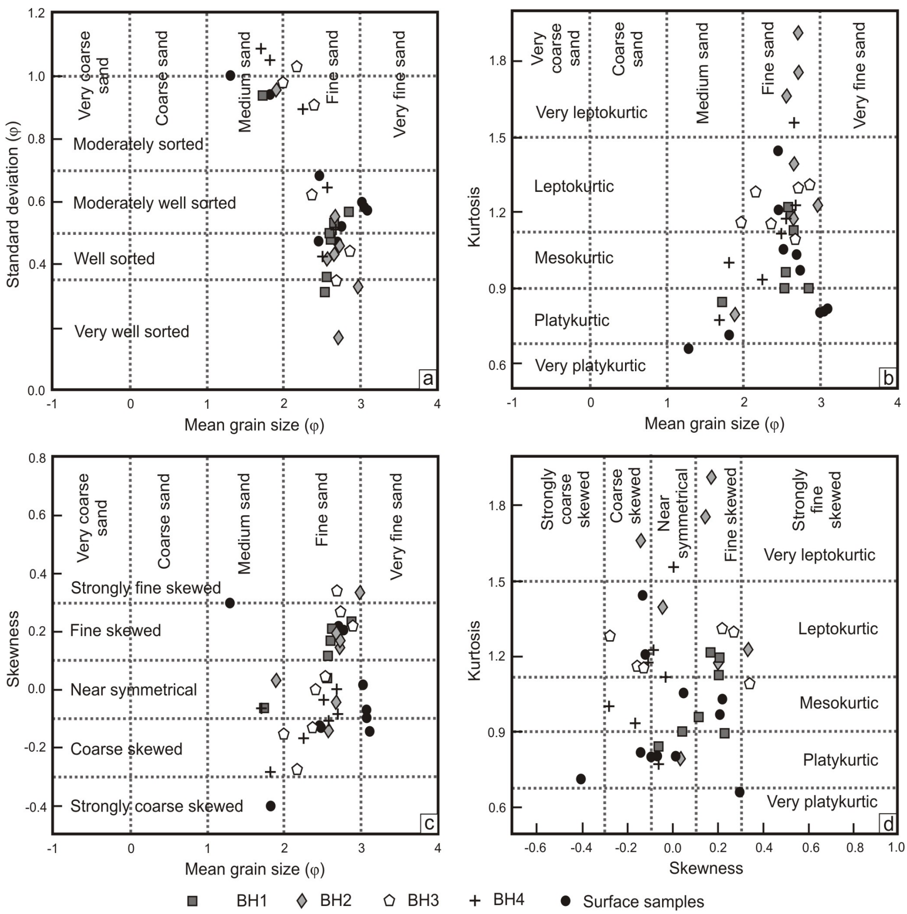

Fig. 7. Scatter plots of the textural parameters for the Teesta River sediments. (a) Mean grain size vs. standard deviation, (b) Mean grain size vs. kurtosis, (c) Mean grain size vs. skewness, and (d) Skewness vs. kurtosis.

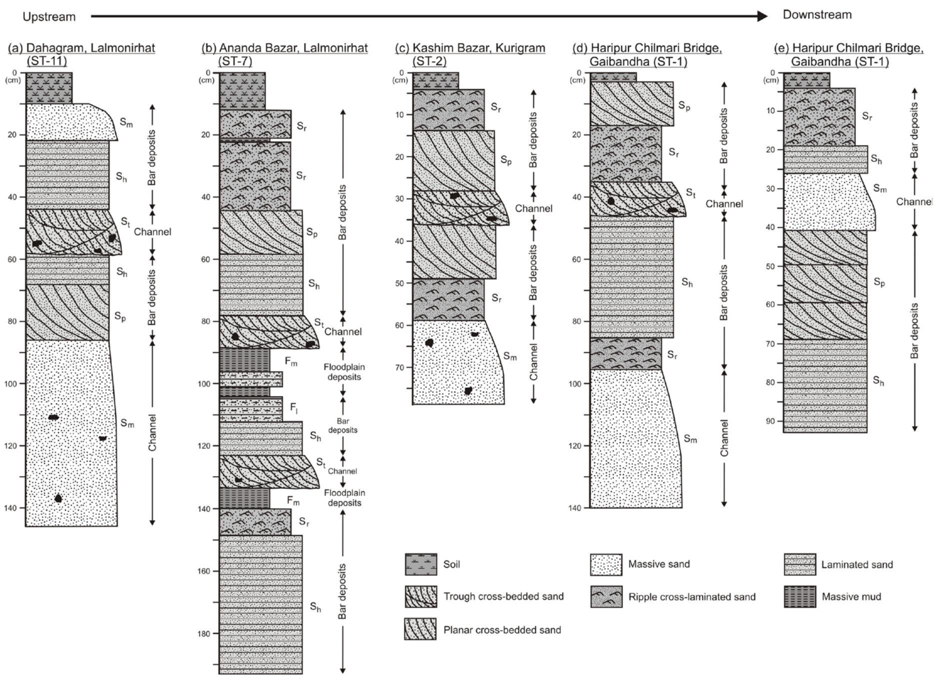

Fig. 8. Detailed sedimentological logs of Recent sediment deposits of the Teesta River, showing characteristic lithology, texture, sedimentary structures, and lithofacies. The right-marginal column shows the possible genetic interpretation of facies associations. Table 1 for the explanation of lithofacies and Fig. 1 for sedimentological logging locations.

Transportation and sedimentation processes

Like other braided rivers, the Teesta River transports huge quantity of bedload sediments (Fig. 9a). These bedload sediments are mainly fine to medium grained and show the diverse sorting from poorly to very well sorted (Fig. 7a). A decreasing trend of grain size and a reverse pattern of sorting towards downstream of the river (Fig. 5) suggesting gradual declination of energy conditions, though energy levels show minor fluctuations throughout the depositional period of the Teesta River sands. Likewise, samples of the Teesta River (Fig. 7c) reveal the unidirectional channel transportation or the deposition of sediments in low to medium level of energy environment (e.g., SELVARAJ *et. al*. 2003; HAKRO *et al*. 2021). However, the negative skewness of the Teesta River sediments might be the result of the chute cutoff during flood events which eroded, transported and redistributed the previously deposited bar sands within chute channels or newly formed bars.

The CM diagram (after PASSEGA 1964, 1957) is one of the best methods for interpreting the transportation and sedimentation modes. The first percentile values refer to the grain size that is representative of the maximum competence of the transporting medium (PASSEGA 1957, 1964; PASSEGA & BYRAMJEE 1969). In CM diagram, PASSEGA & BYRAMJEE (1969) distinguished three basic limits, e.g., C_r ($C_{rolling}$), C_u ($C_{uniform\ suspension}$) and C_s ($C_{graded\ suspension}$) (Fig. 9b). The C_r forms the lower size limit of grains transported through rolling (with a contribution of suspension; the C_s characterizes the maximum diameter of grains transported in 'graded suspension', i.e., mainly through saltation; and C_u is the limit for the maximum size of grains transported in homogenous suspension, i.e., in the upper part of the water column. The CM diagram for the Teesta River sediments points out that these sediments are transported by a wide range of processes from graded suspension to saltation and rolling (Fig. 9b). Moreover, these modes of transportation and sedimentation are coincided with the grain size cumulative curves (Fig. 10) as suggested by VISHER (1969). In this diagram, cumulative curves are plotted in three to four straight-line segments that represent different gain size clusters that are transported simultaneously but by different transport modes such a suspension, saltation and traction transport. The Table 3 and cumulative plots (Fig. 10) of the Teesta River surface sands suggest that saltation (41.77-93.90%, average 75.01%) is the dominant transport process before deposition, while suspension process (3.05–58.23%, average 19.72%) is also significant in downstream areas (Table 3). However, traction processes, i.e., rolling, sliding, impact and creeping are occurred mainly in the upstream part of the river where nearly 47.11% of sediments are transported by these processes (Table 3).

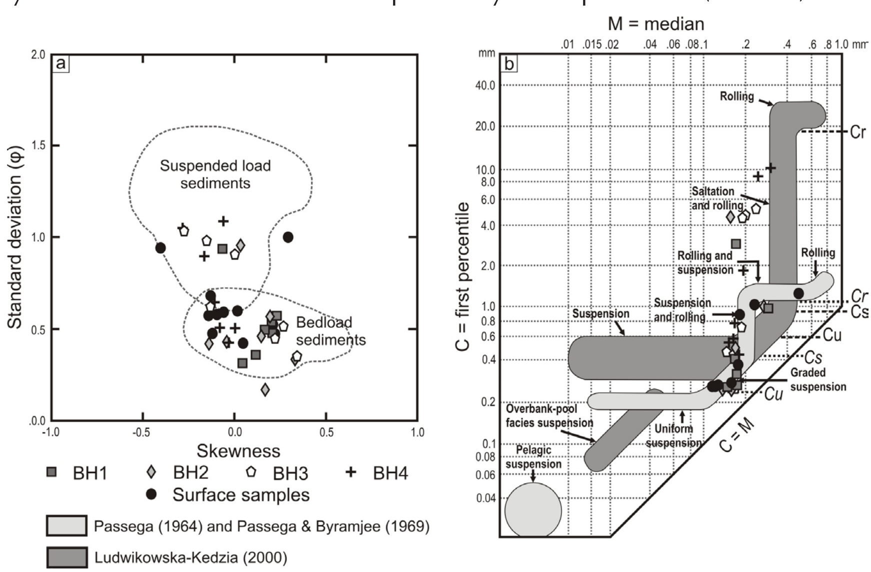

Fig. 9. (a) Bivariate plot of skewness vs. standard deviation (after SINGH *et al.* 2007) to discriminate the modes of sediment transport of the Teesta River sediments. (b) C-M diagram showing transport mechanism of the Teesta River sediments (fields are after PASSEGA & BYRAMJEE 1969 and LUDWIKOWSKA-KĘDZIA 2000).

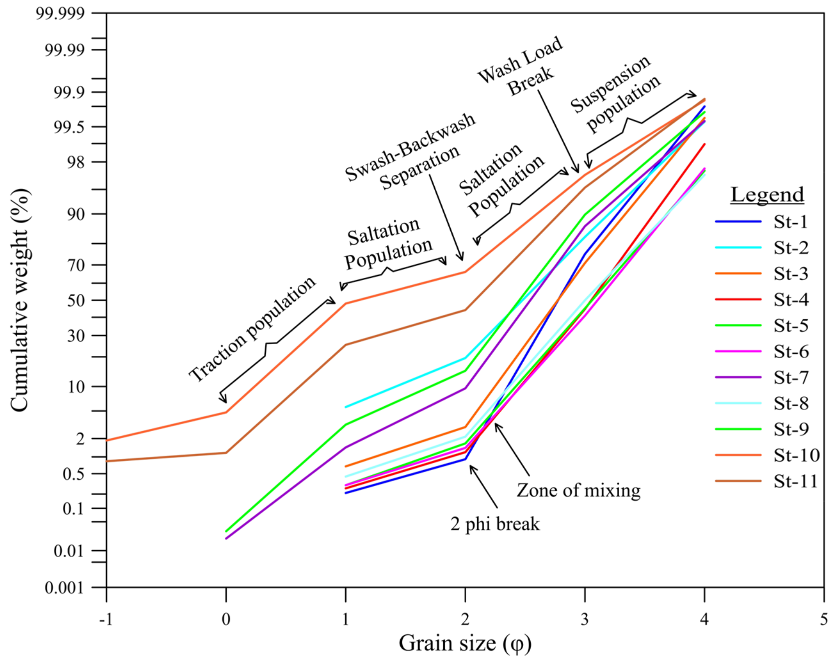

Fig. 10. Cumulative weight percent versus grain size (φ) diagram (after VISHER 1969) showing modes of sediment transport of the surface sediment samples of the Teesta River.

Table 3. Sediment load types and transportation processes of the Recent sedimentary deposits of the Teesta River, Bangladesh.

Location	Sample No	Bed load		Suspened load
		Traction (%)	Saltation(%)	Suspension (%)
Surface samples	St-1 to St-11	Maxi. 47.11 Min. 0.00 Average 6.96	Maxi. 86.82 Min. 41.77 Average 64.13	Maxi. 58.23 Min. 3.05 Average 28.91
BH-1	S1 to S7	Maxi. 23.75 Min. 0.00 Average 3.70	Maxi. 93.36 Min. 77.39 Average 84.21	Maxi. 34.90 Min. 6.64 Average 16.13
BH-2	S1 to S7	Maxi. 25.22 Min. 0.22 Average 4.11	Maxi. 93.90 Min. 62.16 Average 79.28	Maxi. 37.62 Min. 6.10 Average 16.61
BH-3	S1 to S7	Maxi. 12.25 Min. 0.20 Average 3.71	Maxi. 89.69 Min. 68.21 Average 80.01	Maxi. 31.12 Min. 8.53 Average 16.28
BH-4	S1 to S7	Maxi. 23.32 Min. 0.00 Average 6.95	Maxi. 91.95 Min. 65.37 Average 77.66	Maxi. 22.40 Min. 8.05 Average 15.39

Conclusion

Based on integrated textural and facies analyses, this study documented the sedimentological characteristics of the Teesta River sediments to delineate the energy conditions of the river, and sediment transportation and depositional mechanisms to comprehend the river dynamics. The following conclusions can be drawn:

1. Sediment deposits of the Teesta River are systematically categorized into seven distinct lithofacies: trough cross-stratified sands (S_t), planar cross-stratified sands (S_p), ripple cross-laminated sands (S_r), parallel laminated sands (S_h), massive sands (S_m), massive clay (F_m) and laminated clay (F_l). These lithofacies are grouped into fining-upward sequences in which lag gravels and S_t to occasional S_m filling channels are overlain by S_p, S_r and S_h lithofacies, suggest migrations of both channel and bars within channel. Occurrences of multi-storied fining-upward sequences in a single location suggest rapid shifting of channels and bars.
2. Texturally, the Teesta River sands are fine to medium grained, mostly moderately well to well sorted and typically fine to near symmetrically skewed which show unimodal nature. The energy conditions of unidirectional river flow gradually decrease downstream direction.
3. The sands of the Teesta River are dominantly bedload deposits with subordinate suspended loads. Therefore, these sediments have been transported and deposited by saltation to minor suspension processes. Nevertheless, traction process is restricted mainly in upper course of river.

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বাংলাদেশের তিস্তা নদী থেকে সংগৃহীত সাম্প্রতিক কালের স্তরীভূত পললের পাললিক বৈশিষ্ট্য ঃ পলল পরিবহন ও অবক্ষেপনের তাৎপর্য

মোঃ সোহানুর রহমান সোহান, রুমানা ইয়াছমিন, মোঃ জুল্লে জালালুর রহমান,
আবু সাদাত মোঃ সায়েম ও মোঃ সোহেল রানা

সারসংক্ষেপ

তিস্তা নদী হিমালয়ের উচ্চ এলাকা থেকে উদ্ভুত হয়ে ভারত ও বাংলাদেশ দিয়ে প্রবাহিত হয়ে বিপুল পরিমাণ পলি ব্রহ্মপুত্র-যমুনা নদীতে নিয়ে যায়। ভূ-প্রকৃতি অনুযায়ী, তিস্তা নদী একটি ব্রেইডেড প্রকৃতির নদী, যেখানে বিভিন্ন ধরনের চর ও প্লাবন ভূমি বিদ্যমান। এই গবেষনায় তিস্তা নদীর পাড় ও চরের উন্মুক্ত বালি এবং ভূগর্ভস্থ বোরহোলের নমুনা বিশ্লেষণ করে এই পললসমূহের প্রকৃতি নিরূপণের মাধ্যমে সেগুলোর পরিবহন ও অবক্ষেপণের ইতিহাস অনুধাবনের চেষ্টা করা হয়েছে। তিস্তা নদীর বালি সাতটি স্বতন্ত্র লিথোফেসিসে শ্রেণিবদ্ধ করা যায়: ট্রাফ ক্রস-স্ট্র্যাটিফায়েড বালি (S_t), প্ল্যানার ক্রস-স্ট্র্যাটিফায়েড বালি (S_p), ম্যাসিভ বালি (S_m), রিপল ক্র-ল্যামিনেটেড বালি (S_r), প্যারালাল ল্যামিনেটেড বালি (S_h), ম্যাসিভ কাদামাটি (F_m) এবং ল্যামিনেটেড কাদামাটি (F_1)। এই লিথোফেসিসগুলো একাধিক ফাইনিং-আপওয়ার্ড অনুক্রমে বিন্যস্ত, যা প্রবাহ বেগের পর্যায়ক্রমিক হ্রাস এবং নদীর গতিপথ ও চরের স্থানান্তর নির্দেশ করে। চ্যানেল ও চর থেকে সংগৃহীত বালির নমুনাগুলো সাধারণত ইউনিমোডাল প্রকৃতির, যা একমুখী প্রবাহ নির্দেশ করে, যদিও কিছু ক্ষেত্রে শ্যুট চ্যানেলের মাধ্যমে আংশিক পুনর্বিন্যাসের প্রমাণ পাওয়া গেছে। তিস্তা নদীর বালির বুননের বৈশিষ্ট্য অনুযায়ী এগুলো সূক্ষ্ম থেকে মাঝারি দানার, মাঝারি থেকে ভালভাবে বিন্যস্ত, প্রধানত ধনাত্মক তির্যকতা প্রদর্শন করে এবং লেপ্টোকার্টিক থেকে মেসোকার্টিক প্রকৃতির। এই বালিগুলো প্রধানত বেডলোড ডিপোজিট এবং গ্রেডেড সাসপেনশন থেকে শুরু করে সলটেশন পর্যন্ত পলি পরিবহন পদ্ধতিতে পরিবাহিত হয়েছে; বিশেষত নদীর উজানে ট্র্যাকশন প্রক্রিয়ার ভূমিকা ছিল উল্লেখযোগ্য। বিভিন্ন বাইভেরিয়েট ডায়াগ্রাম বিশ্লেষণে দেখা যায় যে, এই পলিগুলো মূলত নিম্ন থেকে মধ্যমাত্রার শক্তিশালী পরিবেশে জমা হয়েছে।