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SEDIMENTS GRAIN SIZE SENSITIVENESS OF THE THAKURAN RIVER BASIN OF THE SUNDERBANS

Gautam Kumar Das
Department of Chemical Engineering, Jadavpur University, Kolkata– 700032, India
Email: sunderbans@hotmail.com

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Abstract: Geomorphologically defined areas like mid-channel bars or flood-tidal delta, river mouth bar or ebb-tidal delta, point bar, swash platform, wash-over flat and river banks (levee) have been identified in the Thakuran River of the estuarine Sunderbans. These areas are delineated based on studies of the granulometric properties. A coarsening of graphic mean size (M_Z), betterment of sorting ($ó_1$), and negative to positive skewness (SK_1) have been noticed from the seaward to landward direction. Variations of these textural parameters are related to decreasing energy levels along the same direction. A bipartite granulometric model of sedimentation having sand-to-mud from the seaward to the landward direction of the tidal creek has been discerned. This is in contrast to a tripartite granulometric model typical of estuaries.

Keywords: Texture; grain size; cumulative curves; sorting; skewness; kurtosis; mean size; Thakuran River; Sunderbans.

1. INTRODUCTION

Sunderbans (21° to 22°-30´N and 88° to 88°-29´E) stands at the lower part of the active deltaic portion of the Ganges-Brahmaputra - the world's largest delta (Fig. 1). A complex network of geomorphic environment characterizes Sunderbans, India. Both mudflats and sandy beaches occur at the sea face depending on their locations on high and low energy zones respectively. Tidal rivers / inlets are generally muddy systems barring some sandy flats that occur in the mid channel bars and sandy swash bars at the mouths of rivers / inlets. The creeks are in the absolutely muddy systems. Mangrove swamps occur on the intertidal mudflats of estuaries, creeks and inlets. Narrow marshes occur on the upper intertidal to the supratidal zones in a sporadic manner.

The Thakuran River (Lat. 21^{0}35´to 22^{0}10´N and Long. 88^{0}35´E) is one of the many tidal creeks on the low, flat alluvial plains of the Ganges-Brahmaputra delta facing the Bay of Bengal in the south (Fig. 1). The Thakuran is totally a tide-influenced creek in which the process of sediment movement is accomplished by bidirectional tidal flows and wind-induced waves. The luxuriant mangroves forests here belong to a tide-dominated setting. The macrotidal mangrove-fringed creeks and estuaries are typically funnel-shaped and the wide opening of the Thakuran River at the sea face is no exception to this law. Width of this water course, on the other hand, decreases exponentially with increasing distance from the sea face [1].

The sediments are siliciclastic with sand-silt-clay as the chief constituents. Texturally, a bipartite model of sedimentation is present which is marked by sand-to-mud facies from the seaward to the landward direction. Cleaning of mud by high wave action, reworking of material by greater tidal amplitude and influx of sand by long shore currents have increased the proportion of sand in the seaward stretch of the river bed. The flood current is able to push the sand inland up to a distance of 35 to 40 km. beyond this point further landward, mud constitutes the chief deposits. As the creeks are not fed by any freshwater from upland, the typical situation of a tripartite grain size model of estuaries does not hold good at Sunderbans.

2. METHODOLOGY

In all 121 sediments samples were collected from different geomorphic zones as well as from different sedimentary structures of both physical and biogenic origin. As per requirement some samples were collected from upper few centimeters. These samples actually represent the physical conditions of depositions for a short period of time prior to sampling and these were compared with sediments after the beds were reworked by benthic animals. Grain size analyses of the sandy samples were carried out using sieves of 0.5 phi size interval. The samples were sieved in an electrically operated Ro-Tap Shaker for about 20 minutes. The muddy samples were analysed by the classical pipetting method [2]. Prior analysis of the muddy samples by pipetting method, the samples were passed through 0.062 mm (4 phi) sieve to separate the muddy fraction from the sandy fractions. Cumulative curves were drawn by plotting size-frequency values on arithmetic probability paper.

Grain-size statistics were computed based on the formulae of [3]. The graphic mean size is an arithmetic average of a series of diameter values. The median diameter is the 50th percentile diameter of a cumulative frequency curve drawn on arithmetic probability paper. Textural parameters were plotted on graph papers to determine their patterns. Correlation co-efficients and data from the best-fit curves were calculated following standard statistical methods. The relevant statistical size parameters like graphic mean size (M_Z), the inclusive graphic standard deviation ($ó_1$), graphic skewness (SK_1) and kurtosis (K_G) of individual grain size distribution have been utilized for hydrodynamic interpretations following [4, 5 & 6].

The pattern of cumulative curves of the sediment samples was compared to the tidal channel curves of Visher [5] for interpreting the modes of sediment transport in each sub-population of the distributions. Interpretations on the sources of sediments were done applying the principle of McLaren [7]. Environmental sensitiveness of the size parameters was tested following plots of Moila and Weiser [8] and Friedman [9].

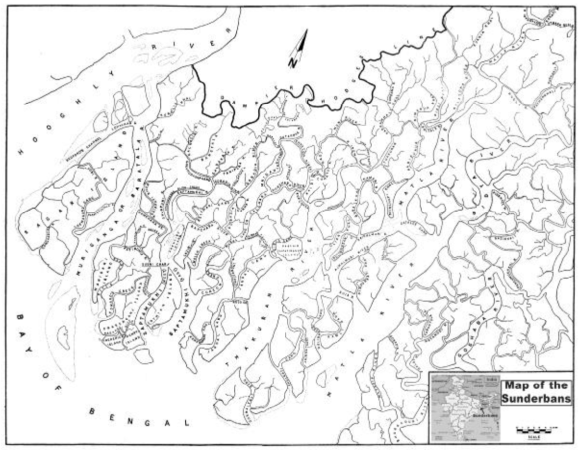

Fig.1 Map of the Sunderbans showing the location of the Thakuran River

3. PREVIOUS WORKS

Several workers have discussed the relationship between grain size characteristics and depositional pattern in a tide dominated estuarine and coastal environment [10 & 11]. Differences in grain size within a given depositional environment have also been discussed by a number of workers. McLaren [7], Stubblefield and Swift [12] studied the grain size of beach sediments, whereas, DeMaeyer et al. [13], DeMaeyer and Wartel [14] worked on grain size characteristics of near shore and offshore sand ridges.

Interpretation of the grain size frequency curve is based upon the pattern of curves and splitting of each curve into segments separated by the marked breaks or inflections. It is generally supposed that each segment relates to a given mode of transport [5 & 15]. In fact, the cumulative curves are assumed to be composed of two or more overlapping Gaussian (normal) distributions [4 & 15] or of different truncated normal distributions [4 & 5]. Sagoe and Visher [16] and Middleton [17] have examined the relationship between the grain size distribution and hydraulics in which the inflection points of the cumulative curves represent a specific change of hydraulic conditions.

4. SHAPE OF THE CUMULATIVE CURVES

Sediments samples 121 in numbers were collected for the purpose of grain size analysis from different geomorphological areas like point bar, mid channel bar, swash bar, river banks and areas of other morpho-ecological interests. Usually soils are a combination of sand, silt, and clay whose relative proportions determine the soil's texture. It was possible to group the grain size – frequency curves into three categories depending on the shapes of cumulative curves, grain size range and number of inflections present in each curve. Interpretations of the curves were done applying Visher's method [5] of grain size analyses. Three different types of curves as obtained by synthesizing the size-frequency data are depicted in Fig. 2.

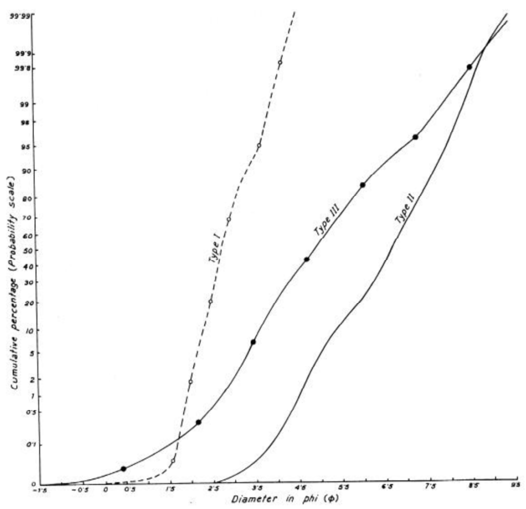

Fig. 2 Three representative grain size distribution curves of the Thakuran River samples

The representative curves reveal the following characteristics :

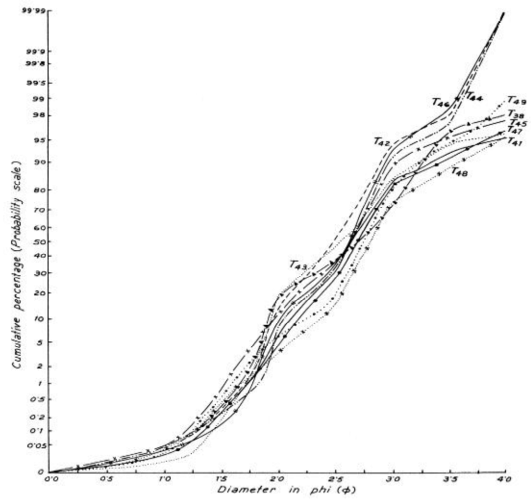

Fig. 3 Cumulative curves (Type I) of Paschim Sripatinagar mid-channel bar sand

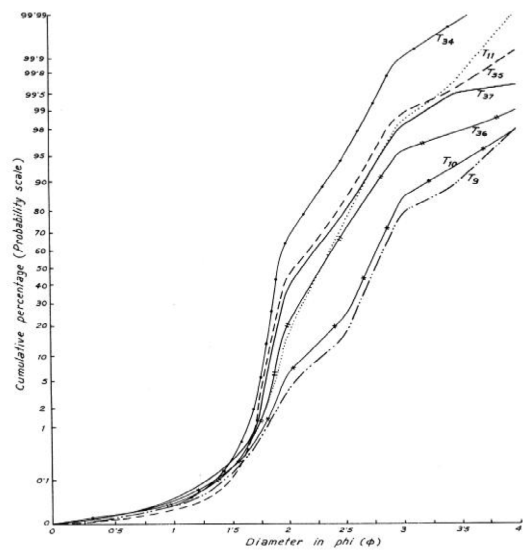

Fig. 4 Cumulative curves (Type I) of Paschim Sripatinagar mid-channel bar sand

Type I: *Cumulative curves having size range within 0.0 to 4.0 phi i.e. within sand sizes.*

This type of cumulative curve represents samples collected from mid–channel bar, swash bar and point bar surface. The curve is almost straight i.e. lognormal when plotted on a log-probability paper with a modal value around 2.5 phi. All the curves constructed from these samples show breaks at i) 2 phi towards the coarser end having materials less than 10% and at ii) 3 phi towards the finer end having materials less than 20% (Figs. 3, 4 & 5). This type represents sediments mainly transported as intermittent suspension load [17]. The modal value is at 2.5 phi. The sediments are well-sorted and the distributions are mostly non-skewed (Table 1). Individual curve of this type shows excellent superimposition one over the other indicating similar patterns (Figs. 3, 4 & 5).

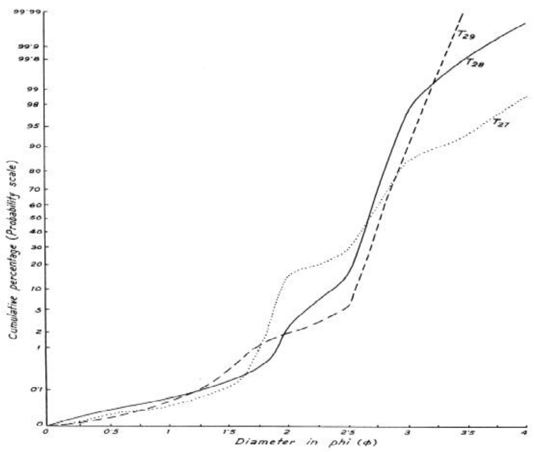

Fig. 5 Cumulative curves (Type I) of Bulchery point bar sand

Type II: *Cumulative curves having size range within 2.5 to 9.5 phi i.e. ranging from fine sand to clay sizes.*

The cumulative curve of this type represents samples collected from the upper portions of riverbank and mid-channel bars with muddy surface. The curve is slightly sinuous in pattern and deviates a bit from log normality when plotted on log probability paper (Fig. 2). Grain size ranges from fine sand to clay (2.5 to 9.5 phi). A few distribution curves, involve a wider range from 2.5 phi to 11 phi (Fig. 6). A significant tailing off occurs towards the relatively coarser size imparting a generally negatively skewed character. Inflections occur at 5 phi and 7 phi. Materials coarser than 5 phi constitute less than 20% whereas finer than 7 phi is less than 10%. The modal value is at 5.5 phi. The sediments are mostly moderately sorted. The curves represent sediments mainly transported as intermittent suspension load with a more pronounced tailing off towards the coarser fraction (Table 2). Cumulative curves constructed from the samples show a unique similarity in pattern and superimpose one another when plotted on the log-probability paper (Figs. 6, 7, 8 & 9).

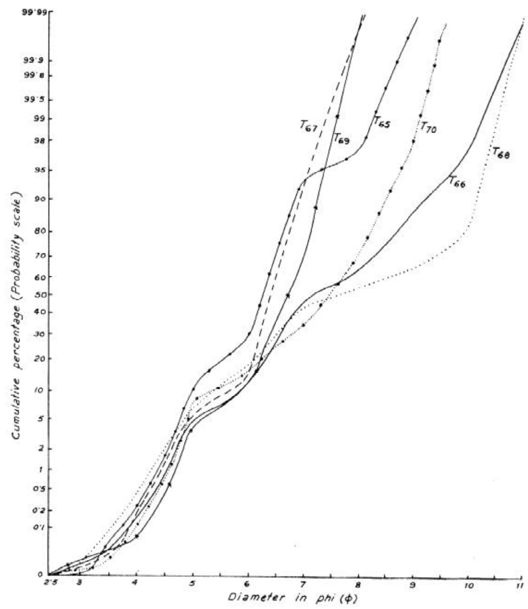

Fig. 6 Cumulative curves (Type II) of muddy bank samples between Bhubankhali and Jata.

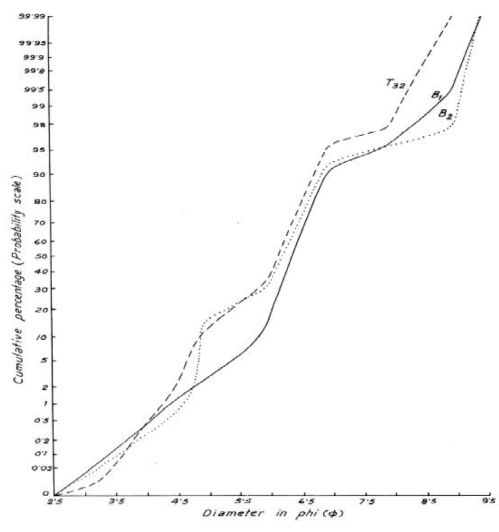

Fig. 7 Cumulative curves (Type II) of the mid-channel bar mud samples of Bhubaneswari (B_1 & B_2) and Damkal (T_{32})

Type III: *Cumulative curves having size range -1.0 to 9.0 phi i.e. ranging from very coarse sand to clay sizes.*

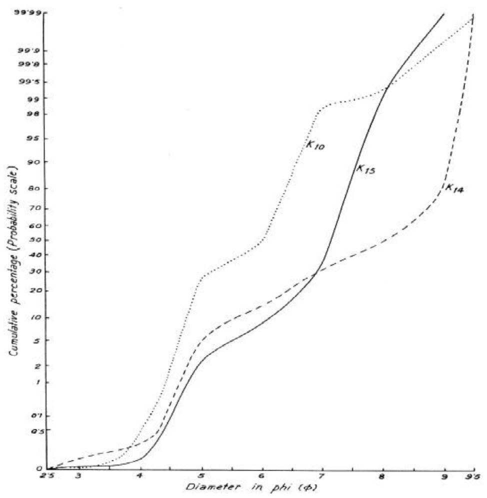

Fig. 8 Cumulative curves (Type II) of muddy bank samples around Paschim Sripatinagar.

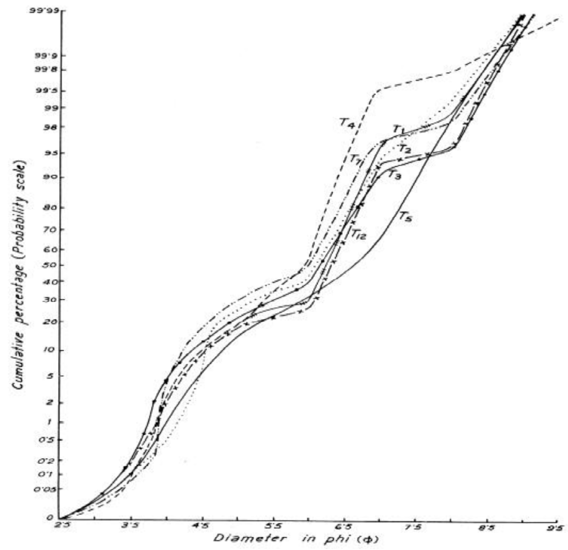

Fig. 9 Cumulative curves (Type II) of muddy samples of Paschim Sripatinagar mid channel bar

Table 1 Statistical size parameters and sand-silt-clay percentage of the sediment samples of Thakuran basin of the Sunderbans

1 Sample Locations (Distance in km from landward to seaward direction)	2 Sample no.	3 Graphic mean size (Mz)	4 Inclusive graphic standard deviation (σ_1)	5 Inclusive graphic skewness (SK_1)	6 Graphic Kurtosis (K_G)	7 Sand %	8 Silt %	9 Clay %
Bhubankhali (10 km)	T_{70}	7.23	1.15	–0.27	0.92	3.20	96.80	–
Chuprijhara (14-16 km)	T_{67}	6.40	0.52	-0.17	1.76	1.10	98.90	–
	T_{68}	7.70	1.86	0.12	0.66	0.89	63.70	35.41
	T_{69}	6.65	0.62	-0.29	1.37	0.43	99.57	–
Purba Jatar Deul (19-20 km)	T_{65}	6.05	0.72	-0.33	1.34	0.88	99.12	–
Bhuneswari dwip (25 km)	B_1	6.0	0.99	–0.05	1.47	5.04	91.02	3.94
	B_2	6.43	0.66	–0.07	2.19	4.42	94.94	0.64
	B_3	6.31	0.71	–0.09	1.39	4.33	90.76	4.91
	B_4	6.39	0.69	–0.13	1.98	5.34	91.39	3.27
Damkal Dwip (30 – 32 km)	T_{32}	6.05	0.67	-0.29	1.06	4.38	93.59	2.03
	B_5	6.10	0.65	-0.21	0.97	5.37	92.01	2.62
	B_6	6.07	0.69	-0.23	1.02	5.81	91.39	2.80
	B_7	6.09	0.63	-0.31	0.99	6.01	92.47	1.52

1 Sample Locations (Distance in km from landward to seaward direction)	2 Sample no.	3 Graphic mean size (Mz)	4 Inclusive graphic standard deviation (σ_1)	5 Inclusive graphic skewness (SK_1)	6 Graphic Kurtosis (K_G)	7 Sand %	8 Silt %	9 Clay %
Maipith (42 km)	T_{15}	5.97	0.94	-0.48	1.28	3.61	87.88	8.51
	T_{16}	5.92	0.87	-0.62	0.80	4.46	85.40	10.14
	T_1	5.95	0.73	-0.39	0.96	11.74	87.88	0.38
	T_2	5.90	0.84	-0.30	0.66	22.61	72.88	4.51
Maipith (42 km)	T_3	5.96	0.96	-0.15	0.93	13.14	85.42	1.44
	T_4	5.77	0.63	-0.43	0.74	12.94	86.92	0.14
	T_5	6.30	1.08	-0.30	0.69	18.49	77.73	3.78
	T_6	4.86	1.45	0.22	0.93	42.62	57.12	0.26
	T_7	5.80	0.79	-0.34	0.63	28.64	68.60	2.76
	*T_{17} (90 cm)	4.85	0.74	0.86	0.66	39.43	51.32	9.24
Paschim Sripatinagar north (42 – 44 km)	T_{33}	6.45	0.47	0.01	1.77	0.69	97.29	2.02
	T_{34}	2.02	0.22	0.50	1.31	99.98	0.02	-
	T_{35}	2.17	0.30	0.76	0.87	99.91	0.09	-
	T_{36}	2.32	0.36	0.13	0.86	98.32	1.68	-
	T_{37}	2.22	0.33	0.31	0.84	99.56	0.14	-
	T_8	3.55	0.84	0.09	2.52	85.01	14.29	0.70
	T_9	2.85	0.43	0.03	1.74	97.98	2.02	-
	*T_{10} (90 cm)	2.68	0.40	0.09	1.64	97.96	2.04	-
	T_{11}	2.32	0.31	0.11	0.97	100.0	-	-
	T_{12}	6.01	0.90	-0.25	1.72	7.0	90.36	2.64
	T_{13}	2.27	0.32	0.17	0.74	99.81	0.19	-
	T_{14}	2.78	0.37	0.21	1.93	95.61	4.39	-
	T_{38}	2.60	0.52	-0.06	0.72	97.80	2.20	-
	*T_{39} (30 cm)	2.56	0.57	0.80	1.35	93.69	6.31	-
	*T_{40} (60 cm)	2.65	0.55	0.17	1.60	92.03	7.97	-
	*T_{41} (90 cm)	2.63	0.52	0.13	1.20	93.07	6.93	-
	T_{42}	2.45	0.35	-0.10	0.90	100.0	-	-
	*T_{43} (30 cm)	2.68	0.49	0.15	0.25	95.05	4.95	-
	*T_{44} (60 cm)	2.60	0.36	-0.12	1.38	100.0	-	-
	*T_{45} (90 cm)	2.65	0.38	-0.11	1.22	97.36	2.64	-
	T_{46}	2.56	0.34	-0.07	1.04	100.0	-	-
	*T_{47} (30 cm)	2.78	0.47	0.18	1.99	95.64	4.36	-
	*T_{48} (60 cm)	2.96	0.51	0.31	1.34	85.76	14.24	-
	*T_{49} (90 cm)	2.88	0.50	0.27	1.94	94.43	1.57	-
	*T_{50} (120 cm)	2.88	0.53	0.32	2.10	91.22	8.78	-

1 Sample Locations (Distance in km from landward to seaward direction)	2 Sample no.	3 Graphic mean size (Mz)	4 Inclusive graphic standard deviation (σ_1)	5 Inclusive graphic skewness (SK_1)	6 Graphic Kurtosis (K_G)	7 Sand %	8 Silt %	9 Clay %
Paschim Sripatinagar north (44 – 46 km)	K_4	6.05	0.84	0.10	1.37	0.80	98.80	0.40
	K_5	6.76	1.40	-0.37	2.08	6.89	90.32	2.79
	K_6	6.31	0.87	0.45	2.16	1.32	94.48	4.20
	K_7	6.50	0.59	-0.18	1.93	3.44	95.44	1.12
	K_8	5.41	0.78	0.35	3.17	0.16	96.12	3.72
	$^*K_{10}$ (120 cm)	5.46	1.19	-0.69	0.97	18.12	78.12	3.76
	$^*K_{14}$ (120 cm)	7.76	1.35	-0.38	0.78	2.36	97.53	0.11
	$^*K_{15}$ (120 cm)	7.01	0.61	-0.41	1.53	1.36	94.88	3.76
	K_{16}	5.96	0.89	-0.69	0.91	4.39	94.78	0.43
	K_{17}	5.97	0.99	-0.41	1.68	3.75	92.30	4.05
	K_{18}	5.89	0.76	-0.33	0.78	1.24	97.13	1.73
	K_{19}	5.86	1.40	0.46	0.91	0.94	94.47	4.79
	K_{20}	5.76	0.64	-0.48	0.84	6.43	93.01	0.56
	K_{21}	5.81	0.43	0.64	0.43	18.16	81.43	0.41
	K_{22}	5.99	0.81	-0.36	0.67	3.18	88.94	7.88
Achintyanagar (48 km)	P_1	6.30	0.52	-0.26	2.51	4.17	87.96	7.87
	P_2	5.58	0.76	-0.72	0.49	20.16	79.48	0.36
	P_3	6.40	0.99	-0.81	1.58	7.43	92.04	0.54
	P_4	6.32	0.56	-0.56	2.34	0.85	94.36	4.79
Upendranagar (49 km)	L_1	6.31	1.34	-0.69	0.70	6.44	93.20	0.36
	L_2	5.58	1.69	-0.66	0.64	24.24	72.12	3.64
	L_3	4.45	1.80	0.32	0.60	49.84	49.40	0.76
	L_4	2.58	0.32	-0.34	1.50	96.61	3.39	-
	L_5	4.66	1.64	0.32	0.68	49.48	50.16	-
	L_6	2.61	0.21	-0.22	-1.22	100.0	-	-
	$^*L_8$ (90 cm)	4.53	0.46	0.73	2.60	77.56	21.00	1.44
Rakhalpur (50 km)	T_{61}	2.72	0.35	-0.08	2.13	98.30	1.70	-
	$^*T_{62}$ (30 cm)	2.85	0.39	0.25	1.81	97.77	2.23	-
	$^*T_{63}$ (60 cm)	2.98	0.44	0.39	0.96	97.02	2.98	-
	$^*T_{64}$ (90 cm)	2.97	0.47	0.32	1.55	96.92	3.08	-
Sridharnagar (52 -54 km)	T_{55}	2.80	0.25	0.15	1.64	98.84	1.16	-
	$^*T_{56}$ (30 cm)	2.75	0.31	0.06	1.71	98.67	1.33	-
	$^*T_{57}$ (60 cm)	2.73	0.31	0.18	1.41	98.59	1.41	-
	$^*T_{58}$ (90 cm)	2.76	0.31	0.11	1.77	97.92	2.08	-
	T_{59}	3.05	0.46	0.31	1.15	95.99	4.01	-
	T_{60}	2.63	0.32	0.00	1.40	98.94	1.06	-

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Chulkati II (54 km)	T_{25}	6.35	0.46	-0.18	1.73	1.58	98.42	-
Dhanchi North (57 km)	T_{51}	2.62	0.29	-0.12	1.57	98.99	1.01	-
	$^*T_{52}$ (30 cm)	2.72	0.47	0.46	1.89	97.94	2.06	-
	$^*T_{53}$ (60 cm)	2.82	0.42	0.27	1.69	97.53	2.47	-
	$^*T_{54}$ (90 cm)	2.77	0.40	0.11	2.04	97.22	2.78	-
Dhanchi (58 km)	D_4	2.92	0.40	0.24	1.37	98.28	1.72	-
	$^*D_5$ (30 cm)	2.23	0.53	0.43	0.92	98.16	1.84	-
	$^*D_6$ (60 cm)	6.27	0.47	-0.29	1.99	0.91	99.09	-
Dhanchi (60 km)	T_{22}	2.80	0.36	0.17	1.98	98.52	1.48	-
	$^*T_{23}$ (60 cm)	2.77	0.34	0.18	2.05	97.37	2.63	-
	$^*T_{24}$ (90 cm)	2.85	0.41	0.15	1.93	98.27	1.73	-
	D_1	6.53	0.48	0.06	1.45	-	100.0	-
	D_2	6.55	0.60	-0.16	1.57	1.24	98.76	-
	D_3	6.73	0.81	-0.02	1.13	0.40	99.28	0.32
Dhanchi (65 km)	T_{18}	2.83	0.35	0.14	2.04	97.88	2.12	-
	$^*T_{19}$ (30 cm)	2.92	0.42	0.21	1.69	97.53	2.47	-
	$^*T_{20}$ (60 cm)	2.98	0.39	0.19	2.05	96.84	3.16	-
	$^*T_{21}$ (90 cm)	3.02	0.45	0.16	1.27	96.38	3.62	-
Chulkati III (69 km)	T_{26}	5.87	0.78	-0.39	0.63	18.26	81.74	-
Dhanchi South (73 km)	D_7	7.80	1.44	0.17	0.99	-	80.02	19.98
	D_8	6.42	0.55	-0.24	1.93	-	100.0	-
	D_9	6.47	1.43	0.12	0.91	-	95.89	4.11
	D_{10}	6.28	0.61	-0.35	1.88	2.91	96.96	0.13
	D_{11}	2.97	0.54	0.23	1.17	96.84	3.16	-
	D_{12}	2.82	0.36	0.14	2.04	98.60	1.40	-
	D_{13}	2.80	0.40	0.17	1.87	98.67	1.33	-
	D_{14}	2.75	0.69	0.14	1.09	96.94	3.06	-
	D_{15}	2.67	0.43	-0.02	1.74	98.31	1.69	-

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Dhanchi South (73 km)	$^{*}D_{16}$ (30 cm)	2.81	0.41	0.05	1.69	98.55	1.45	-
	$^{*}D_{17}$ (60 cm)	2.62	0.36	-0.06	1.65	98.49	1.51	-
	$^{*}D_{18}$ (90 cm)	2.92	0.63	0.11	1.05	95.80	4.20	-
Bulchery Island	T_{27}	2.53	0.49	-0.15	1.99	98.01	1.99	-
(74 km)	T_{28}	2.67	0.21	-0.06	1.64	99.47	0.53	-
Bulchery South	T_{29}	2.77	0.18	0.15	0.98	100.0	-	-
(80 km)	T_{30}	5.85	0.75	-0.44	0.60	6.45	92.50	1.05
	T_{31}	5.82	0.81	-0.29	0.63	22.63	75.34	2.03

Asterisks for depth samples: depth of collection within parenthesis.

Table 2 Characteristics of the three categories of grain size distribution curves showing inflections and sub-population pat

	Type I	Type II	Type III
Grain size range	Sandy (0 to 4 phi)	Fine sandy to clayey (2.5 to 9.5 phi)	Sandy to clayey (-1.5 to 9.5 phi)
Inflection	2 phi to 3 phi	5 phi to 7 phi	2 phi to 6 phi
Amount of coarser sub-population	10%	20%	1%
Amount of finer sub-population	20%	10%	50%
Modal value	2.5 phi	6.5 phi	5 phi
Sorting (σ_1)	Well sorted	Moderately sorted	Moderately to poorly sorted
Skewness (SK_1)	Non-skewed (-0.1 to +0.1)	Mostly slightly negatively skewed (-0.16 to 0.69)	Positively skewed (+0.22 to +0.45)
Principal mode of transport	Intermittent suspension load	Intermittent suspended load with minor admixture of suspended load	Intermittent suspended load with a huge admixture of suspended load

Table 3 Correlation between types of grain size distribution and geomorphological areas of sampling

Grain size distribution type	Upper portions of mid-channel bar, swash bar and point bar	Lower portions of mid-channel bar and point bar	Bank Lower / Upper	
Type I	X	-	-	-
Type II	-	-	-	X
Type III	-	X	X	-

The cumulative curve of type III represents samples collected from lower portions of riverbanks and point bar margins. The curve forms a slightly zigzag pattern and reflects a non – lognormal distribution when plotted on log-probability paper (Fig. 2). Grain size ranges from -1.0 to 9.5 phi. A more significant tailing off occurs towards the finer end of the curves giving them a positively skewed nature. The inflections are noted at 2 phi and 6 phi. The inflections are noted at 2 phi and 6 phi. Materials coarser than 2 phi constitute less than 1%, whereas, below 6 phi constitute greater than 50%. The modal value is at 5 phi (Table 1). Sorting is moderate to poor but poorer than type I and type II sediments. The tailing off towards the fine is a reflection of the admixture of finer suspended load to the intermittent suspension sand load population. All curves show a nice similarity of pattern and almost superimpose when plotted together (Figs. 10 & 11).

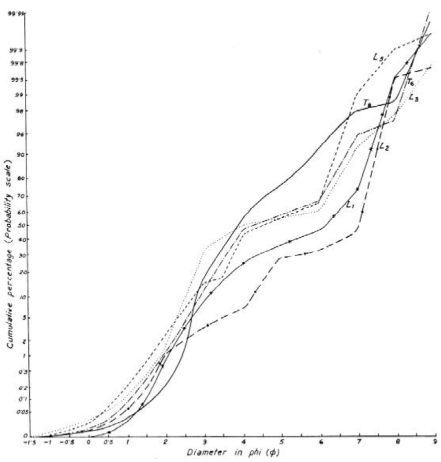

Fig. 10 Cumulative curves (Type III) of sandy to muddy point bar samples at and around Upendranagar

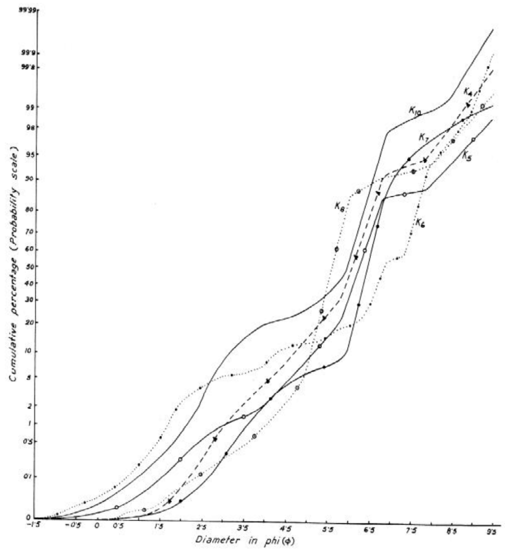

Fig. 11 Cumulative curves (Type III) of sandy to muddy river bank samples at and around Paschim Sripatinagar

5. INTER-RELATIONSHIP BETWEEN GRAIN SIZE AND MORPHOLOGICAL UNITS

The foregoing analysis makes it evident that different units have distinctiveness in terms of their grain size characteristics, which, in turn, reflect variation in hydrodynamic conditions.

It is evident from the correlation table between grain size distribution and geomorphologic areas of sampling (Table 3) that grains deposited from intermittent suspension point to prevalence of higher energy conditions in the upper portions of the point bar and mid channel bar (Type 1). Grains deposited from intermittent suspension along with a bulk of finer suspended load reflect a traction cum fall out deposition in a very low energy condition in the upper portions of the river bank

(Type II). Type III having poorest sorting and suspension settling of both fine sand and mud indicates an intermediate hydrodynamic condition in the lower flanks of point bars and mid-channel bars.

6. CLASSIFICATION OF SEDIMENT TYPES

Folk [18] proposed a triangular diagram to classify sedimentary rocks but its application for the classification of estuarine or tidal sediments was not tested. Shepard [19] proposed a triangular diagram to classify different sediment types and to distinguish different sedimentary facies in estuarine environments [6, 20 & 21]. The sand-silt-clay percent of each sample of the present study area has also been plotted in the Shepard's triangular diagram in order to classify the different sediment types.

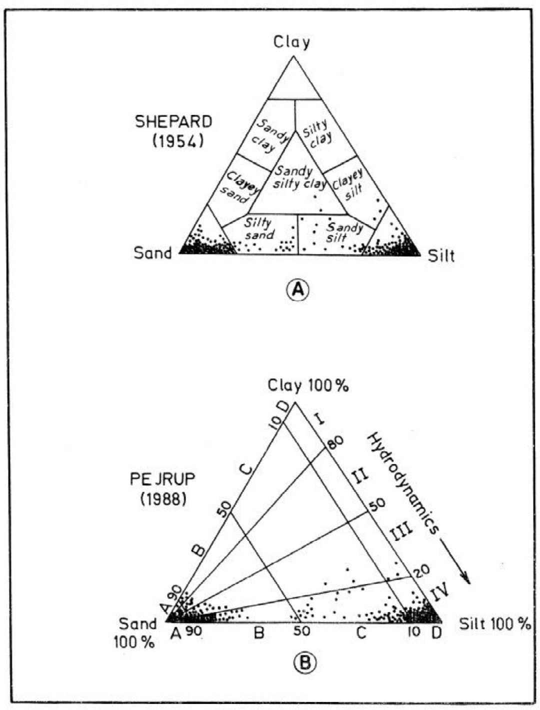

Fig. 12 A. Plot of sand-silt-clay percentage of samples in the triangular diagram of Shepard (1954). B. Plottings of the same samples in the hydrodynamic fences of Pejrup (1988).

The cluster of plots primarily lies within sand and silt field (Fig. 12A). The cluster in the sand field mostly denotes samples collected from the river close to the sea face particularly from the mid-channel bar and swash platform. The concentration of plots in the silt field denotes samples collected from the river more towards landward direction particularly, from the bank and also from point bars and mudflats adjoining the tidal creeks. The silty sand and sandy silt samples result from differential mixing of sand and silt fractions and signify the transitional middle stretch of the river.

6.1 Sediment Trend Matrix of Grain-Size Relations

A sediment trend matrix of grain size relation for the three types of grain-size distributions is given in Table 4. McLaren [7] showed that such a matrix helps in identifying the possible source of a given deposit in a system-related environment. The sediment samples collected from the different geomorphic zones of the estuarine river networks of the Sunderbans resemble a gradation from one another as the materials belong to closely related sub-environments. McLaren [7] suggested that if a source-sediment is subjected to transportation its original grain size distribution will be modified in one of the following ways:

1. For a total deposit of a sediment in transport; the deposit is finer, moderate to well-sorted and more negatively skewed than the source sediment.
2. The lag sediment is coarser, better sorted and non-skewed to positively skewed than the source sediment.
3. The selective deposit from sediment in transport can be either finer or coarser with better sorting and more positive skewness than that of the source sediments.

Applying the reasoning of McLaren [7] to the estuarine river sediments of the Sunderbans it appears that sediment of Type II can be considered as a source for sediment of Type I and again the sediment of Type I can be possible source of Type III (Table 4). Removal or truncation of silt fraction from Type II sediments changes the sediments to Type I so that sediments lie within sand sizes with better sorting and non-skewed nature. A stronger water current in the source area is responsible to produce such a change. Again, admixture of clay and sand in a relatively sheltered area brings the Type II sediments to Type III with moderate to poorer sorting and positive skewness.

6.2 Sediment – Hydrodynamic Relation

The hydrodynamic conditions for the depositional environment of the Sunderbans have been worked out by plotting sand, silt and clay percent of all the samples in the triangular diagram of Pejrup [6]. According to Pejrup, the hydrodynamic conditions for the depositional environment of an estuary or tidal creek may be described by the percentage of clay in the mud fraction. Sections I to IV within the triangle mark the increasingly violent hydrodynamic conditions (Fig. 12B). The sediments are classified further on the basis of their sand content into four sections from A to D. Thus the triangle has sixteen (16) divisions each labeled by a letter and a number as A I to A IV; B I to BIV; C I to C IV and D I to D IV. The division A I represents sediments having 100 to 90% sand deposited under high hydrodynamic conditions. All other divisions from A II to A IV having a specified range of sand content characterize deposition under decreasing hydrodynamic conditions.

Mid-channel bar, point bar and swash bar sandy samples generally fall in section IV (as A IV, B IV, C IV and D IV) and indicate strong hydrodynamic conditions of deposition. Again, sediment samples from the river bank and contiguous swamp have a slightly higher content of clay (D III) and represent a quieter hydrodynamic condition of deposition. Some samples, however, plot in between sections III and IV. Variations in the sand content of sediments are caused by the changes in differentiation trend from primary (Type II) to secondary (Type I) and then to tertiary (Type III) depending on the distances of transport and segregations involved therein (Table 3).

As a matter of fact grain size of the Sunderbans estuarine river sediments (e.g. Thakuran River) nicely reflects the nature of source sediments and their hydrodynamic conditions of deposition. Generally, erosion prevails towards the seaward reach of the river with high wave energy and deposition dominates in the landward reaches of relatively quieter environment. Thus, finer muddy sediments are deposited on the river banks, flanks of the mid-channel bars and point bars with low depositional energy. The coastal ridges off the Belgian coast also show similar segregation of finer from coarser fractions [14].

6.3 A Bipartite Model of Grain-Size Distribution

An overall bipartite (mud-to-sand) grain size distribution characterizes Thakuran River sediments of the Sunderbans (Fig. 13B) in contrast to the general tripartite (sand-to-mud-to-sand) distribution [22] typical for estuaries (Fig. 13A). Rivers of the Sunderbans has no estuary at their funnel opening to the sea as they do not have any fresh water source upland. They behave like large tidal creeks. Their upland sediments are dominantly muddy whereas the sediments near the funnel opening belong to the sand-grade. For an example, a clear transition from sand to mud occurs at a distance of 40-42 km upstream of the Thakuran River from its confluence with the Bay of Bengal. A sharp shift in the modal class of the sediments in this stretch of the river near Paschim Sripatinagar is, clearly seen from the histograms representing grain size distributions (Fig. 14). The median value of the muddy samples lies at 6.5 phi whereas it is at 2.5 phi for the sandy samples. Elimination of mud seaward is due to higher wave action, greater tidal amplitude and influx of clear sand from the mouth. Eventually on the basis of grain-size, the river can be divided into sand from the mouth. Eventually on the basis of grain-size, the river can be divided into two major sedimentary provinces: a predominantly sandy province occupying the seaward 40 km and a finer silty to clayey province on the upper (northern) 40 km. the transition zone is marked by the interfingering of the two sediment provinces (Fig. 13).

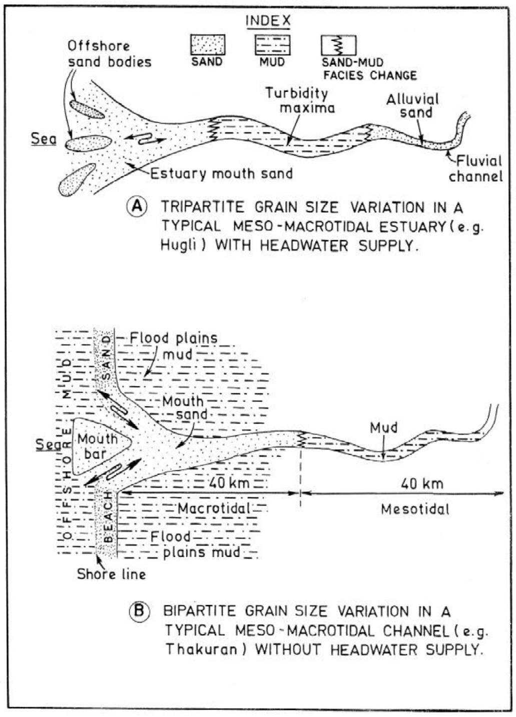

Fig. 13 An idealised diagram showing tripartite (A) and bipartite (B) grain size variations

The bipartite model of Thakuran without a true fluvial stretch of headwater supply is a distinct deviation from the condition of the common tripartite grain size variation in many macrotidal-mesotidal estuaries (e.g. The Hugli estuary). In such estuaries sand is brought in by flooding tides from nearby beaches and from near shores exposures for a distance of at least a few km upstream. At this point, along with salt-wedge formation, the saline tidal water encounters the fresh fluvial, sediment laden water and creates the very well documented zone of turbidity maximum with thick mud deposits (Fig. 14). Upstream of the muddy zone, river-derived sand is deposited. Lengths of these sandy and muddy reaches vary with the change in balance between tidal and fluvial processes. Published literatures on modern estuaries, in both mesotidal and macrotidal settings confirm such facies relationships [23, 24, 25, 26].

Table 4 Composition of statistical size parameters for the three grain size distribution types

Sediment source	Deposits		
	Size range	*Inclusive graphic standard deviation (σ_1)*	Inclusive graphic skewness (SK_1)
Type II	Sand-silt	Moderate	-ve
Type I	Sand	Well	Non-skewed
Type III	Sand-clay	Moderate to poor	+ve

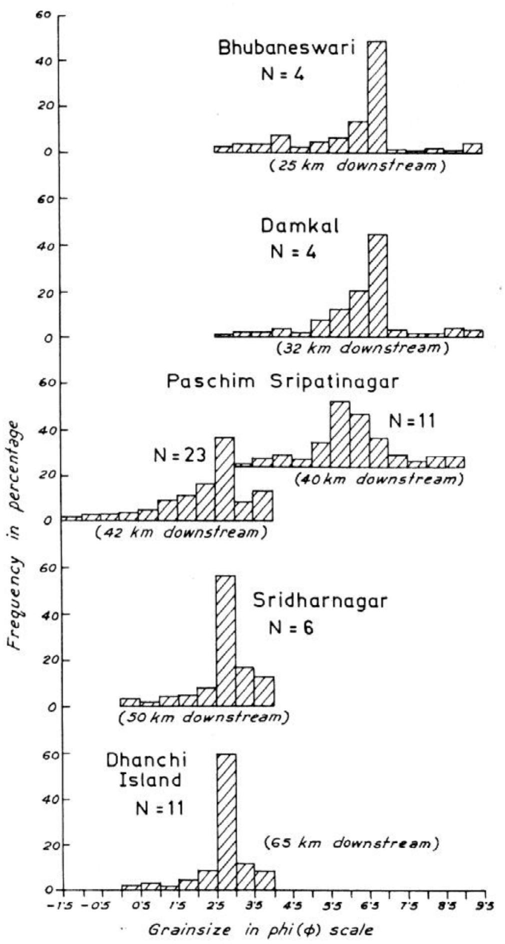

Fig. 14 Composite histogram of grain size distributions of the mid channel bar samples along river distance

The Thakuran River lacking any headwater supply does not possess the uppermost sand-filled portion. Here, in this river, the transition between the sand and mud facies occurs approximately a distance of 40 km upstream from the sea face. In this stretch of the river, the Paschim Sripatinagar mid-channel bar (4.5 km long in low tide) registers the mud (clayey silt) – sand transition. The northern half of the bar is generally muddy whereas, the southern half is dominantly sandy (Fig. 16).

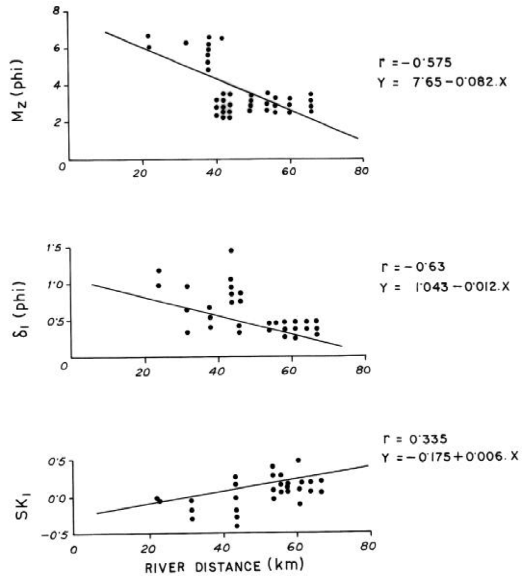

Fig. 15 Plot of Mean size (M_Z), Sorting (σ_1), Skewness (SK_1) of mid channel bar samples versus river distance

The lower reach of sand-filled estuaries (e.g. Hugli) or tidal creeks (e.g. Thakuran) terminating against muddy zones on both sides (tidal flats) can be easily mistaken for a shore-parallel barrier sand that terminates in muddy zone on both seaward and landward directions. A misinterpretation of this kind may result in a 90^0 error in mapping the local palaeo-shoreline. The correct interpretation of this sand having been deposited in a tidal estuary, perpendicular to the shoreline, may help to avoid such a serious error) [22].

6.4 Interrelationship of Grain-Size Parameters and River Distance

Attempt has been made to show the interrelationship of grain-size parameters and distance from the landward end of the river. Plots of graphic mean size (M_Z), inclusive graphic standard deviation ($ó_1$) and inclusive graphic skewness (SK_1) of the mid-channel bar and point bar sediments against river distance (Fig. 15 & Fig. 16) displayed the following characteristics:

i) Mean size (M_Z) of the samples of the mid-channel bar and point bar shows a distinct seaward coarsening from silt to sand inferring a negative linear correlation (r = -0.575 and -0.59 respectively).

ii) Sorting (σ_1) of the sediments shows betterment along the seaward direction. This is because of greater reworking of the sediments towards the sea face. Sorting – river distance relation shows a negative correlation (r= -0.63 and -0.57 respectively).

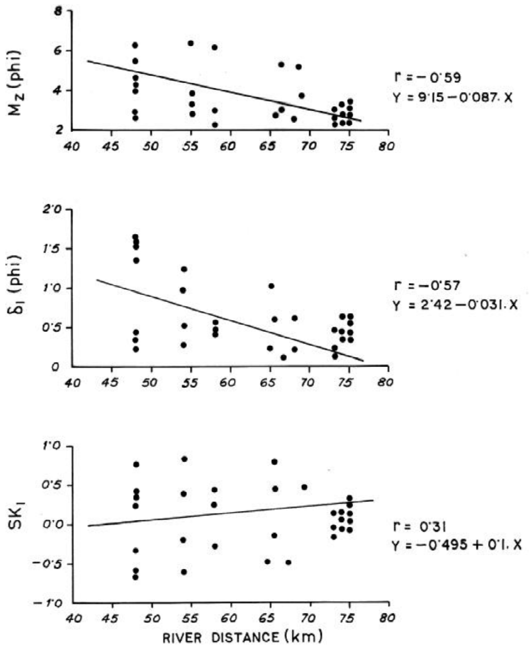

Fig. 16 Plot of Mean size (M_Z), Sorting (σ_1), Skewness (SK_1) of mid channel bar samples versus river distance

iii) Skewness (SK_1) versus river distance plot shows slightly negatively skewed to non-skewed nature barring a few exceptions. This change in skewness reflects a change in grain size distribution patterns from Type II to Type I (Table 2). This negative skewness of the landward sediments is because of the minor admixture of clay to the intermittent suspended load. The sediments near the sea face are almost non-skewed and reflect a lognormal distribution without any significant admixture of coarser or finer subpopulations.

7. ENVIRONMENT SENSITIVENESS OF SIZE PARAMETERS

Environment sensitiveness of the statistical grain size parameters was also tested following the classical work of Friedman [9] and Moila and Weiser [8]. The plots of graphic mean size (M_Z) versus inclusive graphic standard deviation ($ó_1$) for the total samples chiefly fall within the river environment and are distinctively different from the beach environment (Fig. 17A). Further, plots of the inclusive graphic standard deviation ($ó_1$) versus inclusive graphic skewness (SK_1) for the total samples also fall in the field for the river environment (Fig. 17B) as demarcated by Friedman [9] and Moiola and Weiser [8]. The fields for river and beach as demarcated by Moiola and Weiser [9] fit better for present plotting than that demarcated by Friedman [8].

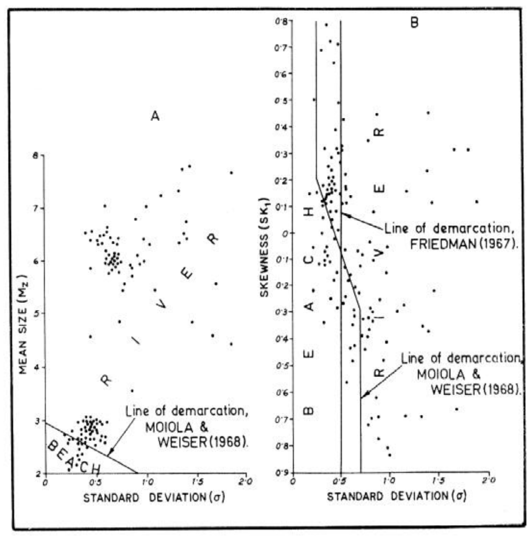

Fig. 17 Plot of Mean size (M_Z) versus Sorting (σ_1) and Sorting (σ_1) versus Skewness (SK_1) in the demarcated fields of river and beach environments

Test of environment sensitiveness of grain size parameters of river sediments of the Sunderbans helps understanding a very significant fact. It is clear in the case study of the Thakuran River that although the Thakuran River is a tide-dominated large tidal creek without any fresh water discharge from the landward side, its grain size parameters excellently corroborates that of a river system. A few plots of samples from the swash bar, however fall in the beach field (Fig. 17) and reflect similarities in hydrodynamic conditions in these two geomorphic domains.

Sediment texture of mangrove substrates of the Thakuran River basin appears to be very environment sensitive as because the textural parameters of sediments throw much light on the physical and hydrodynamic conditions of sediment transport, erosion and deposition in the mangrove areas.

8. CONCLUSION

There is rhythmicity in the nature of deposition, which perhaps indicates the depositional pulses for the ebb and flood flows through the rivers. The inflection points in the curves between successive ebb flood cycles are marked at 2.5 to 3.0 phi, 3.5 phi, 5 to 6 phi and 8 phi sizes respectively. Such rhythmicity in the nature of depositional behaviour of tidal sediments is supposed to be highly process– responsive. Sandy samples (ranging from 1.5 to 4 phi) collected from the point bars and mid channel bars of the rivers of Sunderbans, however, show a complete different pattern from that of sandy silty samples. The cumulative curves for these samples show a non-linear pattern and are nicely comparable to that of the other point bar samples. These samples show two major inflections one at 2.25 phi and the other at 3.0 to 3.5 phi. These inflections divide the curves into three sub populations as rolling, siltation and suspension respectively. The saltation population constitutes about 75% of the total material, the rest being deposited by either rolling or suspension. These samples are collected from unidirectional flow areas like runnels or depressed channels within point bars and mid channel bars. Silty sediments having range from 4 to 9 phi collected from similar areas also show exactly the same pattern where the three above mentioned subpopulations can be well recognised. In these curves, the inflections take place at 6 to 7 phi respectively. The central saltation population constitutes about 70%. These sediments do reflect their deposition from tractive movements of water in a unidirectional flow condition.

As a matter of fact grain size of the river sediments of Sunderbans reflects the nature of source sediments and their hydrodynamic condition of deposition. Generally erosion prevails towards the seaward reach of the rivers with high wave energy and deposition dominates in the landward reaches of relatively quieter environment. Thus finer muddy sediments are deposited on the riverbanks, flanks of the mid channel bars and point bars with low depositional energy.

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