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RESEARCH ARTICLE

Coastal erosion in response to wave dynamics operative in Sagar Island, Sundarban delta, India

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Abstract Coastal erosion at Sagar Island of Sunderban delta, India, has been critically studied. The area is in the subtropical humid region. There are mainly three seasons viz: winter, summer and the monsoon. Different wave dynamic parameters were measured from theodolite observations with leveling staff and measuring gauges during lunar days at two sections of the western and eastern parts of the coastal zone during post-and pre-monsoons. A comparative study was made on the erosion/depositional pattern between the two sections in relation to different hydrodynamic parameters prevailing in these two sections. Plane table mapping was carried out to demarcate the different geomorphic units. The marine coastal landforms show dune ridges with intervening flats bordered by gently sloping beach on one side and a flat beach on the other side. The western part of the beach is mainly sandy; whereas the eastern part is silty and clayey with mud bank remnants. Actual field measurements indicate that the coastal dune belt has retreated to the order by about 20 m since 1985. The eastern part of the beach has lowered by about 2 m since 1985 and the western part was raised almost to the same tune. It is observed that accretion in the western and central parts of the beach took place; whereas severe erosion in the eastern part made the beach very narrow with remnants of mud banks and tree roots. Frequent embankment failures, submergence and flooding, beach erosion and siltation at jetties and navigational channels, cyclones and storm surges made this area increasingly vulnerable.

Keywords Bay of Bengal, coastal erosion, Sagar Island, Sundarban delta, wave dynamics

1 Introduction

Coastal erosion is a common phenomenon reported from all the coastal states in India and indeed, from all over the world. The rate of shoreline changes is one of the common measurements used by coastal scientists, engineers and land planners to indicate the dynamics and the hazards of the coast (Niyogi, 1970; King, 1972; Narayanaswamy and Varadachari, 1978; Anwar et al., 1979; Baba, 1979; Moni, 1980; Komar, 1983; Mallik et al., 1987; Savage and Foster, 1989; Mallik and Rao, 1990). The coastal vulnerability database for Mangalore coast, western India was developed by Hegde and Reju (2007) in order to implement the best erosion protection structure.

The coastline of West Bengal along the Bay of Bengal is about 350 km long and is dominated by the Ganga delta, which covers around 60 % of this coastline (Fig. 1). A large portion of the Ganga delta has been abandoned and is now occupied by a dense swamp area designated as Sundarban delta after the tectonically induced river capture of Hooghly resulted from basement faulting in combination with erratic major floods in the region (Elliot, 1978). A number of active faults are identified in Quaternary sediments of the delta region (Morgan and McIntire, 1959). The deltaic coastline is highly digitized, which has been rather stable for the last few hundred years, though the delta plain shows considerable progradation during the Holocene (Singh and Swamy, 2006). Several distributaries are beheaded losing link channels to the Ganga and straightened their lower courses in search of a shorter route to the sea. The use of satellite imagery (Paul and Bandyopadhyay, 1987; Bandyopadhyay, 2000; Ghosh et al., 2001) indicates that the island has been subjected to erosion by various processes. The island as a whole has been eroding since 1881, with a major change during 1914 (Gopinath and Seralathan, 2005). Now, the wide funnel-shaped mouth is being attacked by sea waves and destructive tidal currents, which have produced erosive transgression over the sub-aerial part of the sub-delta. However, the Hooghly, through the distributary Bhagirathi River, is linked with Ganga waters. Sagar Island, a part of Sundarban delta, is located at the mouth of the Hooghly estuary, Bay of Bengal. The composite deltaic plain of

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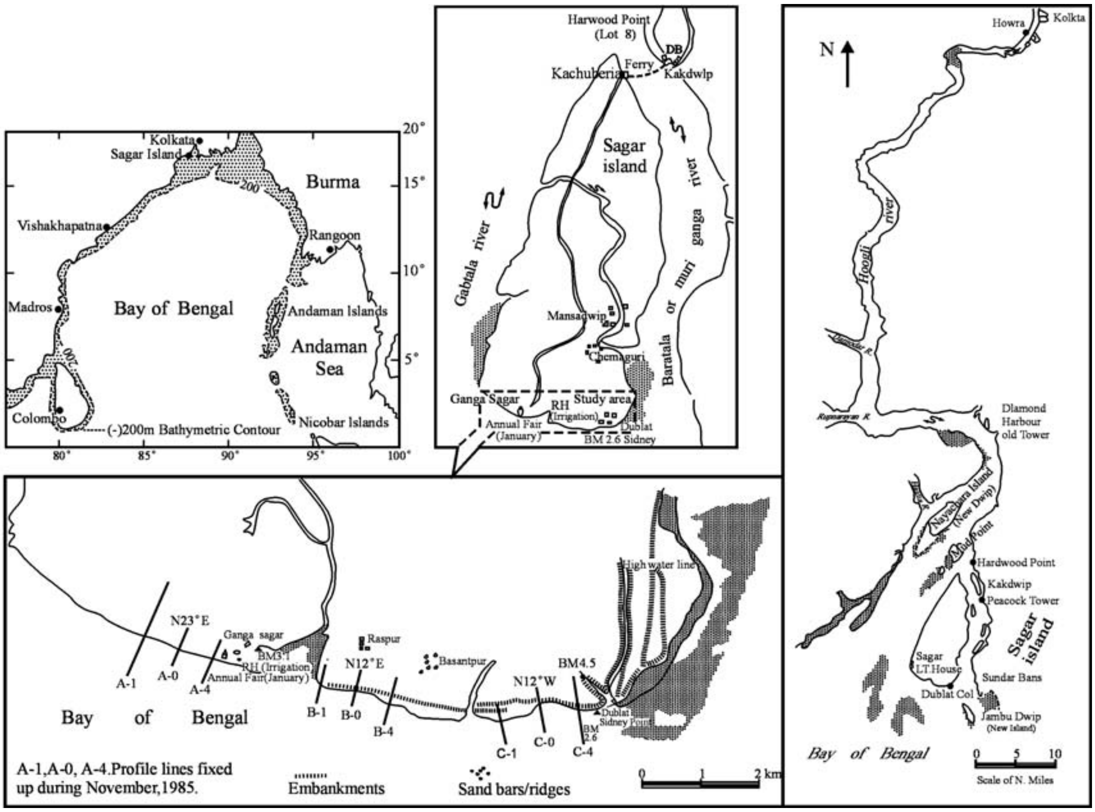

Fig. 1 Location Map

Sundarban, which originated by the braiding of distributary channels of the Ganga-Brahmaputra river system, covers parts of India and Bangladesh.

The present study is restricted to Sagar Island of India, which is our main concern in respect to its erosion activity. The Indian part of Ganga-Brahmaputra composite deltaic coast shows a continuous trend of shoreline retreat (Bandyopadhyay and Bandyopadhyay, 1996). The north-south length of the island is about 30 km with a maximum width of about 12 km. The ground elevation of the Sagar Island in the study area varies from 2.10 to 2.75 m above mean sea level. The coastal plain is essentially a flat terrain. The western deltaic distributaries of the Ganges River system are present in the area. These distributaries are Hooghly (Gabtala) river and Muriganga river flowing through the west and east of Sagar Island respectively. In recent years, the Sagar Island has been shrinking due to the active erosion of the two said rivers. Fluvial, marine, tidal and aeolian processes are the chief agents actively shaping this coastal zone.

1.1 Objectives

The objective of this study is to carry out: i) the geomorphological and geological mapping of the coastal zone of Sagar Island; ii) repeat beach profiling during post-monsoon and pre-monsoon periods with a view to bringing out the accretion and the denudation sites; iii) measurement of post-monsoon and pre-monsoon wave parameters during 10 lunar days along two fixed profile lines set up in November, 1985; iv) observe day to day change of beach profiles during successive lunar days; and v) coastal sediment transport pattern from different geomorphic units, and thus provide a comprehensive picture on the coastal sediment transport pattern in relation to coastal dynamics.

1.2 General climate and hydrography

The area is in the subtropical humid region. The general climatic condition and the hydrography at the mouth of the Ganga-Brahmaputra Rivers are shown in Table 1.

2 Methodology and data collection

Plane table mapping on 1 cm = 50 m scale was carried out covering an area of about 2.5 km^2 of the coastal zone of Sagar Island (Fig. 2). In general, the Sagar is a high energy, macro-tidal coast with a tidal range larger than 4 m (Pethic, 1984; Paul, 2002). The macro-tidal environment of West Bengal shores often provides extensive areas of mud flats. However, as measured during the survey period of 2003–2004, the tidal range varies from 3.008 m (post-monsoon) to 3.814 m (pre-monsoon) exhibiting meso-tidal

Table 1 Climate and hydrography at the mouth of the Ganga-Brahmaputra Rivers

season types	months	average wind velocity/($km\cdot h^{-1}$)	wind direction	%
summer (pre-monsoon)	February-May	11.5	SSW-SW	20
rainy (monsoon)	June-September	11.1	SSW-SW	65
winter (post-monsoon)	October-January	6.6	NNE-NE	14
temperature	Summer: 32–38°C	Winter: 10–18°C		
rainfall	varies seasonally, 750–1950 mm; 80% during June–September			
relative humidity	80%–85% (April–September); 70%–75% (October–March)			
wind velocity	16.7–50 km/h (April–June); 10.7–11.8 km/h (December–February)			
wave frequency (for waves greater than 2.4 m)	10%–20%			
largest wave height (with frequency of 3% or more)	3.7–4.9 m			
wave height during cyclone	7 m or more			
tides	semidiurnal; flood times: 5.00 h, ebb time: 7.50 h; maximum flood velocity: 3.6 m/s; maximum ebb velocity 3.4 m/s			
tidal amplitude	spring: 4.8–5.2 m; Neap: 2.1–2.8 m			
tidal length	290 km along Hooghly estuary			
average sediment discharge through Hooghly estuary	900×10^6–1200×10^6 t/a			
average water discharge through Hooghly estuary	970 km^3/a			
tropical cyclonic storms	2–3 in a year; initiates large-scale littoral drift, coastal erosion and underwater accumulation of material			

range (tidal range 4–2 m). The response to coastal dynamics on the erosion and depositional sites in the Hooghly estuarine, southern sea front of Sagar Island, 24 Parganas (S) district, West Bengal, during post and pre-monsoon periods of 2003 and 2004 was critically studied. Two transects, A-0 and C-0, across the beach were selected at the western and eastern parts of the coast respectively.

A wave-breaker zone adjacent to these transects was identified. Basic data like wave crest heights with corresponding wave period, trend of wave crests, bearing of swash marks, beach face angle, tidal range and inter-tidal widths were measured during ten lunar days [New moon (NM), NM + 1, NM + 2, NM + 3, NM + 8, NM + 9, NM + 10, NM + 11, FM-1, FM (Full moon)], five measurements were taken alternately in each transect during post and pre-monsoon periods. Beach profiles were measured from theodolite observations taking relative ground height (reduced ground level i.e. RGL) with respect to the reference height at an interval of 30 m and where there is a break of slope, relative height was taken at closer interval. Three measuring gauges in each sector were fixed pushing deep into the beach sediments up to their ‘0’ m mark at a considerable distance of about 10 m in between two gauges before the high tide starts, to measure these basic data. During measurements, advancing wave breaker zone cover these gauges. When the high tide starts, the wave height and period were continuously recorded with the help of a theodolite at the moment when the waves touch the gauges.

In each case, measurements of wave crest heights with corresponding periods, bearings of wave crest and swash mark, were taken 40 minutes before and continued till 40 minutes after the highest tide time. Wave heights were directly measured with the help of theodolite and measuring gauges. Four sets of data from the three measuring gauges were recorded for a period of 10 minutes for wave crest height and in successive 10-minute intervals for wave period in each set of data along with corresponding wave crest trend. Twice the wave crest height is the wave height. Average wave heights, significant wave heights (average of maximum 1/3 of the wave heights) were calculated. From the significant wave height, wind speed was estimated following Beaufort scale (Cojan and Renard, 2002).

The following working formulae are used to estimate the different wave parameters (Biarman, 1989; Cojan and Renard, 2002; Paul, 2002; Purkait, 2007):

$$\text{Velocity of longshore current } (V_L) \text{ in m/s} = 2gT\tan\beta\sin\alpha\cos\alpha, \quad (1)$$

where g = acceleration due to gravity = 9.81 m/s^2; T = wave period in second; β = beach face angle (degree); α = wave approach angle (degree) which is the difference between the bearings of swash mark and the wave crest.

$$\text{Wave form velocity } (C) = \sqrt{g(d+H)}\text{m/s}, \quad (2)$$

where d = still water depth (m); H = wave height (m).

$$\text{Wave length } (L) = T\sqrt{gd} \text{ in metre}, \quad (3)$$

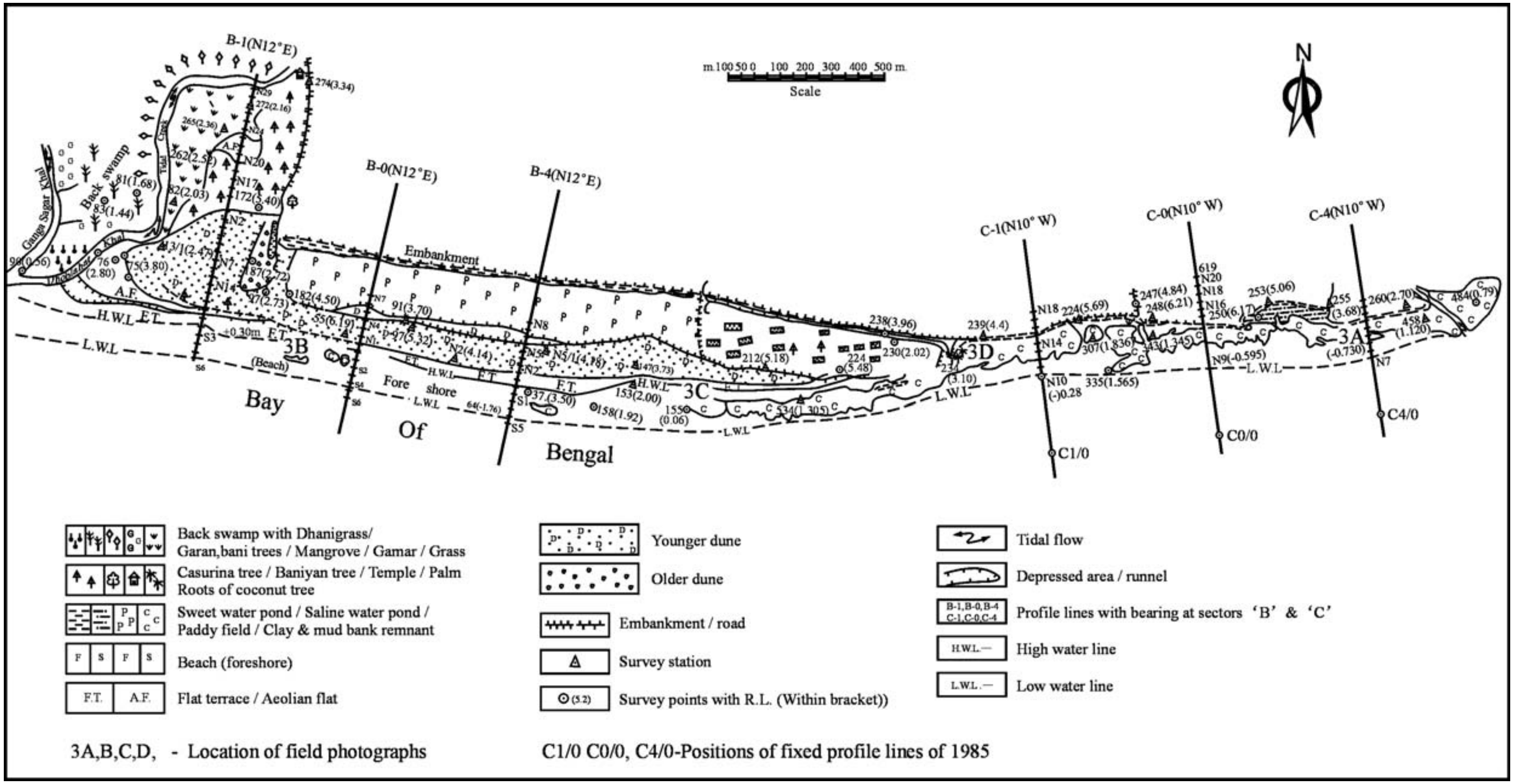

Fig. 2 Geomorphological map of the coastal area of Sagar Island at Central part (Topoban area, sector – B) and eastern part (Dublat area, sector – C), Bay of Bengal, District-24 Parganas (South), West Bengal

$$\text{Wave steepness} = H/L. \quad (4)$$

The total energy (E) per unit area of a wave is given by

$$E = 1/8(\rho g H^2), \quad (5)$$

where ρ is the density of the water (in kg/m^3), g is 9.81 m/s^2, and H is the wave height (m), the energy (E) is then in Joules per square meter (J/m^2).

$$\text{Rate of sediment transport } (R_S)$$

$$= 0.77EC\ \sin\alpha(\text{m/s}), \quad (6)$$

$$\text{Surf scaling factor } (\varepsilon) = (H2\pi)/(gT\tan^2\beta), \quad (7)$$

if $\varepsilon > 2.5$, the breakers are of collapsing type, and, if $\varepsilon < 2.5$, surging type. Collapsing breakers are similar to plunging breakers, except that instead of the crest curling over, the front face collapses. Such breakers occur on beaches with moderately steep slopes and under moderate wind conditions (i.e., wave of intermediate steepness). Surging breakers are found on the steepest beaches. Surging breakers are typically formed from long, low waves, and the frontal faces and crests remain relatively unbroken as the waves slide up the beach (i.e., low, sinusoidal wave of long period).

Wave approach angle = Angle between wave crest bearing and the swash line bearing.

Significant wave height ($H_{1/3}$) = Average of the maximum one third of the wave heights.

3 Analytical results

Results of computation of the wave dynamic parameters for post-monsoon and pre-monsoon periods are shown in Tables 2 and 3, respectively. The western part of the beach at sector ‘A’ is more or less stable; whereas extensive erosion is observed at the eastern part of the beach (south of Dublat) at sector ‘C’. The salient features are described under the following heads:

3.1 Beach landforms, width and slope

Broadly, three geomorphic units have been delineated: i) Beach proper (foreshore), ii) Backshore with coastal aeolian dunes, and iii) Back swamp.

The coastal plain is essentially a flat terrain. The marine coastal landforms show dune ridges along with intervening flats bordered by gently sloping beach on one side and a flat beach on the other side (Fig. 2). The western part of the beach (at sector ‘A’, near Kopil Muni’s temple) is dominantly composed of fine sand with patchy occurrence of small scale ripple marks; whereas the eastern part of the beach (at sector ‘C’, Dublat-Boatkhali area) is dominated by the occurrence of remnants of mud bank with roots of coconut trees and mud balls (Field photos of Figs. 3(a)–(d)). During post-monsoon period, the width of the beach in the western part varies from 138 to 362 m, average being 264.8 m whereas in the eastern part it varies from 51 to 142 m, average being 104 m. During pre-monsoon period, the width of the beach in the western part varies from 199 to 409 m, average being 319.28 m and in the eastern part it varies from 52 to 180 m, average being 133.6 m. In sector ‘B’ (Topoban area) in between sectors ‘A’ and ‘C’, the beach is also of fine sand. Ridges, flat terraces and runnels are developed almost parallel to the beach both at ‘A’ and ‘B’ sectors, indicating presence of long shore currents. The beach gradually becomes narrower from sectors ‘A’ to ‘B’ to ‘C’ with increasing coastal erosion and velocity of long shore current being 0.174 m/s in the western part and 0.704 m/s in the eastern part during post monsoon and 0.135 to 0.295 m/s from the western to eastern parts during pre-monsoon. This indicates that the velocity of long shore current becomes more positive from west to east that may be attributed to more coastal erosion from west to east of the beach.

During post-monsoon, the slope (beach face angle) of the beach in the western part varies from 0.471° to 0.731°, average being 0.651° whereas in the eastern part it varies from 1.848° to 2.216°, average being 1.976°. During pre-monsoon period, the slope of the beach in the western part varies from 0.520° to 0.662°, average being 0.615° whereas in the eastern part it varies from 1.435° to 1.681°, average being 1.636°.

The coastal dunes border the beach. The dunes are of foredune type and low in height (~1 m). The isolated occurrences of such dunes, at places, probably indicate wide fluctuation of wind speed as observed in Fig. 2 at places of the backshore area around the profile line B-1 and also at sector ‘A’ in the backshore area. Due to active erosion, dunes have not been developed in the eastern part (Figs. 3(a) and (b)) whereas in the central part (sector ‘B’) coastal dunes are located all along the high water line indicating coastal erosion and transgression of shoreline landward. Some older dunes occur further inland. These are longitudinal type with relatively more height (~3 m) and length (~10 m). Casurina plantations have been made to stabilize the dune. However, recently developed coastal foredune are getting stabilized by the natural growth of a variety of creepers ‘Isomoea pescaprae’, locally called ‘Halkalmi’.

The back swamp area is muddy in nature, partly washed out occasionally by seawater. Tidal creeks of more than 500 m lengths, 10–15 m widths, about 2 m depths with gentle slope (less than 5°) are developed within this back swamp area. Mangroves, Dhanigrass (local name), Sundari trees (from which the name Sundarbans have been derived), Garan, Casurina trees etc have been planted to mitigate coastal erosion. Artificial concrete dams with wire cage/mud embankments with bamboo poles (Figs. 3(b) and (c)) have been constructed to prevent erosion.

Fig. 3 Field photographs showing beach erosion at Sagar Island: 3(a) Beach erosion; 3(b) Mud embankment with bamboo poles to prevent beach erosion; 3(c) Beach erosion showing remnants of tree roots; 3(d) Remnant of mud bank exposed on the beach

3.2 Water level and tidal range

During high tide period, water level reaches to the base of the coastal dunes in sector 'B' (central part of the beach) resulting in the erosion of the beach. In the eastern part of the beach (sector-C), coastal dunes do not form due to extensive erosion and the shoreline transgresses landward causing devastating bank erosion and collapse of the embankment. In the western part, however, coastal dunes develop and become gradually stabilized, developing flat terraces. During post-monsoon, the tidal range (difference between the RL of high water line and low water line) varies from 1.135 to 4.185 m, average being 3.008 m in the western part and 1.930 to 4.585 m, average being 3.586 m in the eastern part. During pre-monsoon, the tidal range varies from 1.805 to 4.495 m, average being 3427m in the western part whereas it varies from 1.525 to 5.595 m, average being 3.814 m in the eastern part.

3.3 Hydrodynamics

A comparison of the hydrodynamic parameters between western and eastern part of the coastal zone during post-monsoon period is as follows (Table 2).

Water depth varies from 0.143 to 0.417 m, average being 0.283 m in the western part and 0.417 to 0.571 m, average being 0.516 m in the eastern part; wave period varies from 5.804 to 10.218 seconds, average being 8.393 seconds in the western part and 6.274 to 13.792 seconds, average being 9.825 seconds in the eastern part; velocity of long shore current varies from 0.028 to 0.339 m/s, average being 0.174 m/s in the western part and 0.063 to 0.673 m/s, average being 0.704 m in the eastern part; wave length varies from 10.818 to 16.003 m, average being 13.377 m in the western part and 13.004 to 29.978 m, average being 22.06 m in the eastern part; wave height varies from 0.298 to 0.629 m, average being 0.464 m in the western part and 0.436 to 0.882 m, average being 0.726 m in the eastern part; significant wave height varies from 0.443 to 0.831 m, average being 0.665 m in the western part and 0.615 to 1.154 m, average being 0.953 m in the eastern part; surf scaling factor varies from 148.468 to 544.954, average being 310.685 in the western part and 25.731 to 59.999, average being 40.6 in the eastern part; breakers are of collapsing type both in the western and eastern parts; rate of sediment transport varies from 0.008 to 0.063 m/s, average being 0.042 m/s in the western part and 0.039 to 0.418 m/s, average being 0.304 m/s in the eastern part; wave energy varies from 191.31 to 492.98 J/m^2, average being 286.471 J/m^2 in the western part and 236.55 to 969.455 J/m^2, average being 687.377 J/m^2 in the eastern part.

A comparison of the hydrodynamic parameters between western and eastern parts of the coastal zone during pre-monsoon period is as follows (Table 3).

Table 2 Post-monsoon data of wave parameter measurements at Sagar coastal zone

Sl. No.	parameters	Lunar days						Lunar days					
		new moon (NM)	NM + 2	NM + 8	NM + 10	FM-1	average	NM + 1	NM + 3	NM + 9	NM + 11	full moon (FM)	average
1	date	20.2.04	22.2.04	28.2.04	2.3.04	6.3.04		21.2.04	23.2.04	29.2.04	3.3.04	7.3.04	
2	inter-tidal width/m	362	328	194	138	302	264.8	132	142	51	64	131	104
3	R.L difference between HWL & LWL	3.765	4.185	2.19	1.135	3.765	3.008	4.585	4.580	1.930	2.475	4.36	3.586
4	beach face angle (β) (degree)	0.596	0.731	0.647	0.471	0.714	0.651	1.991	1.848	2.169	2.216	1.907	1.976
5	Swash line bearing (degree)	295–115	105–285	106–286	108–288	108–288		91–271	86–266	95–275	92–272	89–269	
6	distance of gauges on profile line from fixed point /m	95, 115, 152	278, 285, 293	341, 349, 358	365, 371, 379	304, 312, 320		372, 364, 354	74, 79.6, 87.6	334, 327, 319	342, 335, 329	359, 355, 348.8	
7	mean water depth/m	0.143	0.250	0.354	0.250	0.417	0.283	0.496	0.550	0.571	0.417	0.546	0.516
8	mean wave height (H) in m	0.392	0.578	0.629	0.422	0.298	0.464	0.882	0.762	0.842	0.706	0.436	0.726
9	significant wave height ($H_{1/3}$) in m	0.731	0.787	0.831	0.533	0.443	0.665	1.154	0.978	1.017	1.002	0.615	0.953
10	mean wave period /s	9.817	9.694	5.804	10.218	6.432	8.393	13.792	12.856	6.274	6.432	9.771	9.825
11	mean wave approach angle (α) in degree	9.25	3.75	1.25	1	12.75	5.6	8.25	5.75	13.25	8	3.75	7.8
12	velocity of longshore current/ ($m \cdot s^{-1}$)	0.318	0.158	0.028	0.029	0.339	0.174	1.331	0.063	1.039	0.673	0.417	0.704
13	wave form velocity (C) in m/sec	2.290	2.849	3.106	2.567	2.648	2.692	3.676	3.588	3.723	3.318	3.103	3.482
14	wave length (L) in m	11.852	15.211	10.818	16.003	13.003	13.377	29.978	29.862	14.846	13.004	22.610	22.060
15	wave Steepness/ ($H \cdot L^{-1}$)	0.033	0.038	0.058	0.026	0.023	0.036	0.030	0.026	0.057	0.054	0.037	0.037
16	max. & min. wave height /m	0.90, 0.10	1.00, 0.10	0.90, 0.40	0.70, 0.30	0.70, 0.10	0.84, 0.2	1.8, 0.30	1.0, 0.50	1.30, 0.50	1.30, 0.30	0.80, 0.10	1.3, 0.34
17	surf scaling factor /$\in$	236.471	234.451	544.954	389.08	148.468	310.685	33.912	36.480	59.999	46.879	25.731	40.600
18	breakers type	collapsing	collapsing	collapsing	collapsing	collapsing		collapsing	collapsing	collapsing	collapsing	collapsing	
19	rate of sediment transport/ ($m \cdot s^{-1}$)	0.058	0.063	0.027	0.008	0.053	0.042	0.418	0.213	0.617	0.235	0.039	0.304
20	wave energy (E) in / ($J \cdot m \cdot s^{-2}$)	191.31	415.55	492.98	221.83	110.687	286.471	969.455	724.386	885.149	621.347	236.55	687.377
21	transect	A-0						transect	C-0				

Table 3 Pre-monsoon data of wave parameter measurements at Sagar coastal zone

Sl. No.	parameters	Lunar days						Lunar days					
		new moon (NM)	NM + 2	NM + 8	NM + 10	FM-1	average	NM + 1	NM + 3	NM + 9	NM + 11	full moon (FM)	average
1	date	20.4.04	22.4.04	28.4.04	30.4.04	4.5.04		21.4.04	23.4.04	29.4.04	1.5.04	5.5.04	
2	inter-tidal width/m	409	360	199	240.40	388	319.28	150	158	52	128	180	133.6
3	R.L difference between HWL & LWL	4.495	4.065	1.805	2.285	4.485	3.427	4.36	4.385	1.525	3.205	5.595	3.814
4	beach face angle (β) (degree)	0.630	0.647	0.520	0.545	0.662	0.615	1.666	1.590	1.681	1.435	1.781	1.636
5	Swash line bearing (degree)	104–284	109.5–289.5	100–280	95–275	105–285		93.5–273.5	99–279	95–275	86–266	92–272	
6	distance of gauges on profile line from fixed point /m	226, 233, 242	257, 259.6 282.6	335, 344, 357	331.4, 340.8, 348.8	263, 269, 277		363, 358, 351	351, 341, 336	302, 297, 290	327, 321, 314	358, 350, 342	
7	mean water depth/m	0.575	0.675	0.475	0.688	0.988	0.68	0.808	0.558	0.983	0.708	1.142	0.840
8	mean wave height (H) in m	0.436	0.531	0.479	0.547	0.606	0.520	0.556	0.621	0.851	0.787	0.891	0.741
9	significant wave height ($H_{1/3}$) in m	0.664	0.737	0.611	0.731	1.095	0.768	0.777	0.856	1.108	1.146	1.208	1.019
10	mean wave period /s	9.385	8.585	8.375	7.866	7.841	8.410	9.667	8.403	10.143	6.888	9.959	9.012
11	mean wave approach angle (α) in degree	7.5	1.5	7.25	2.25	3.75	4.45	3.75	5.25	4.5	1.5	2.250	3.45
12	velocity of longshore current/ $(m \cdot s^{-1})$	0.262	0.050	0.187	0.058	0.116	0.135	0.360	0.417	0.457	0.002	0.238	0.295
13	wave form velocity (C) in m/sec	3.149	3.44	3.059	3.480	3.954	3.416	3.658	3.401	4.241	3.830	4.466	3.919
14	wave length (L) in m	22.290	22.092	18.079	20.428	24.405	21.459	27.222	19.666	31.503	18.157	33.329	25.975
15	wave Steepness/ $(H \cdot L^{-1})$	0.020	0.024	0.026	0.027	0.025	0.024	0.020	0.032	0.027	0.043	0.027	0.030
16	max. & min. wave height /m	1.00, 0.10	1.10, 0.10	0.90, 0.20	1.10, 0.20	1.20, 0.10		1.00, 0.10	1.20, 0.10	1.60, 0.20	1.40, 0.20	1.60, 0.20	
17	surf scaling factor /$\in$	246.384	312.314	457.902	494.908	370.608	376.423	43.545	61.463	62.476	122.026	59.116	69.725
18	breakers type	collapsing	collapsing	collapsing	collapsing	collapsing		collapsing	collapsing	collapsing	collapsing	collapsing	
19	rate of sediment transport/ $(m \cdot s^{-1})$	0.080	0.026	0.090	0.010	0.009	0.043	0.075	0.122	0.056	0.014	0.033	0.060
20	wave energy (E) in / $(J \cdot m \cdot s^{-2})$	237.782	353.482	286.941	374.230	459.49	342.385	386.938	482.524	906.154	775.960	994.996	709.314
21	transect	A-0						transect	C-0				

Water depth varies from 0.475 to 0.988 m, average being 0.680 m in the western part and 0.558 to 1.142 m, average being 0.84 m in the eastern part; wave height varies from 0.436 to 0.606 m, average being 0.52 m in the western part and 0.556 to 0.891 m, average being 0.741 m in the eastern part; wave length varies from 18.079 to 24.405 m, average being 21.459 m in the western part and 18.157 to 33.329 m, average being 25.975 m in the eastern part; significant wave height varies from 0.611 to 1.095 m, average being 0.768 m in the western part and 0.777 to 1.208 m, average being 1.019 m in the eastern part; wave period varies from 7.841 to 9.385 second, average being 8.410 second in the western part and 6.888 to 10.143 second, average being 9.012 second in the eastern part; velocity of long shore current varies from 0.050 to 0.262 m/s, average being 0.135 m/s in the western part and 0.002 to 0.457 m/s, average being 0.295 m/s in the eastern part; surf scaling factor varies from 246.384 to 494.908, average being 376.423 in the western part and 43.545 to 122.026, average being 69.725 in the eastern part; breaker at both parts is of collapsing type; rate of sediment transport varies from 0.009 to 0.090 m/s, average being 0.043 m/s in the western part and 0.014 to 0.122 m/s, average being 0.06 m/s in the eastern part; wave energy varies from 237.782 to 459.49 J/m^2, average being 342.385 J/m^2 in the western part and 386.938 to 994.996 J/m^2, average being 709.314 J/m^2 in the eastern part.

3.4 Bed sediments

Sediments are very fine sand and silt with a bimodal distribution pattern having the prominent mode at 2.5 phi with secondary mode at 4.0 phi. The secondary mode becomes more prominent gradually from east to west of the beach with increasing weight frequency percentage along sector 'A' (Fig. 4). In general, high percentage of sand in the foreshore is recorded on the western part of the beach while the eastern part is characterized by high silt and clay. Due to vulnerable erosion in the eastern part, remnants of mud banks with clay chunks/balls are scattered all along the beach.

4 Discussion

4.1 General character of the coastal zone

In general, the coastal zone of Sagar Island is characterized by beach proper (foreshore) with unconsolidated loose fine sandy deposits along the western part. Patchy unconsolidated sand underlain by muddy bank remnants occupies the eastern part. Beach slope is less than 5°. In front of it is the breaker zone which is about 200 m wide. The beach foreshore is bordered by low elevated coastal dunes, which are completely absent in the eastern part. Casurina plantations with mangrove forests stabilized this swampy backshore area.

The coastal plain is essentially a flat terrain. The marine coastal landforms show dune ridges along with intervening flats bordered by gently sloping beach on one side and the flat beach on the other side with back swampy area.

The area is in the subtropical humid region. There are mainly three seasons viz: i) winter (October-January), the minimum temperature becomes ~9°C; ii) summer (February-May), the maximum temperature becomes as high as ~47°C; and iii) monsoon (June-September), the average rainfall varies seasonally, 750–1950 mm; 80% during monsoon. The relative humidity is 70% – 85%.

Actual field measurements indicate that the coastal dune belt retreated by about 20 m since 1985. The eastern part of the Sagar beach has lowered by about 2 m from 1985 and the western part was raised almost to the same tune. It is observed that accretion in the western and central part of Sagar Island beach took place; whereas severe erosion in the eastern part made this area very narrow with remnants of mud banks and tree roots (Chakroborty, 1987).

4.2 Closure depth of equilibrium beach profile during pre-monsoon and post-monsoon

From the comparative study of the beach profiles, the day-to-day changes of beach profiles on macro scale were observed (Figs. 5(a) and (b)). It is noted that the erosion takes place in the central part of the beach indicating that this part acts as a pumping station from where sediments are sometimes transported further inland forming coastal aeolian dunes and sometimes transported further to the offshore area forming offshore sand bars or ridges. In the western part of the beach, closure depth of equilibrium beach profile during post-monsoon goes down to −0.5 m level (Fig. 5(a)); whereas during pre-monsoon it was '0' m level (Fig. 5(b)). This indicates an erosion of 0.5 m during the monsoon period. The mechanism of such sediment transport pattern might provide clues to the formation of coastal aeolian dunes or juvenile offshore sand bars/ridges.

4.3 Hydrodynamic condition of shore erosion

The critical analysis of the wave dynamic aspects provides a comprehensive picture on the shore erosion. The eastern part of the beach is more vulnerable to erosion than the western part. This can be attributed to the different hydrodynamic conditions prevailing in these two regions. These parameters are inter-related and collectively influence the coastal geomorphology, erosion and depositional pattern. When we consider the different hydrodynamic parameters separately from western to eastern part of the shore during two periods (i.e., post and pre-monsoon) of study, it is observed that water depth, significant wave height, wave period, velocity of long shore current, wave

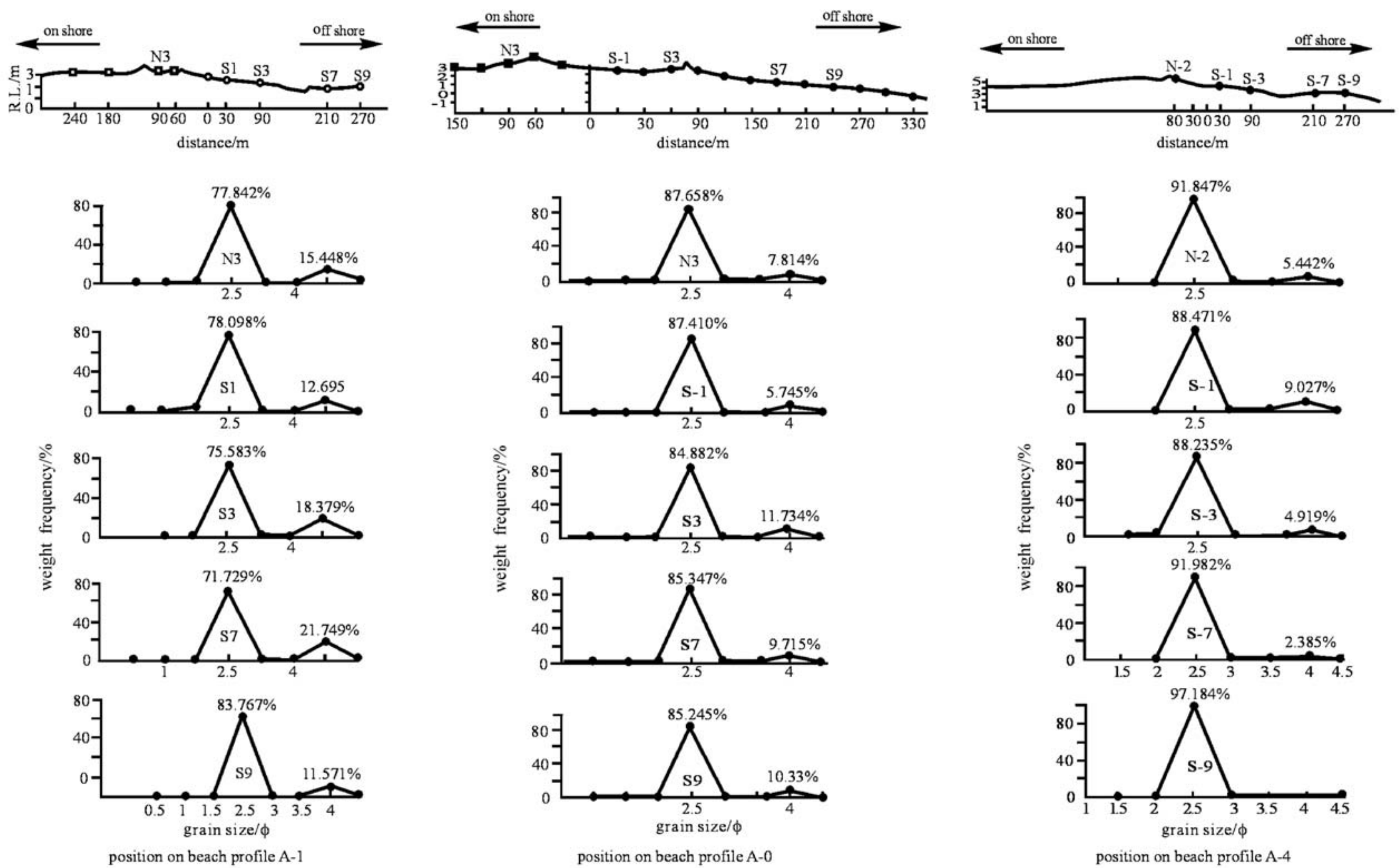

Fig. 4 Grain size distribution patterns at different positions on the beach profiles along transects A-1, A-0, and A-4, showing the development of secondary mode with gradual increase of weight frequency % from east (A-4) to central (A-0) to west (A-1). Increasing of weight frequency of secondary modes indicates the presence of strong long shore current from east to west of the beach at this sector

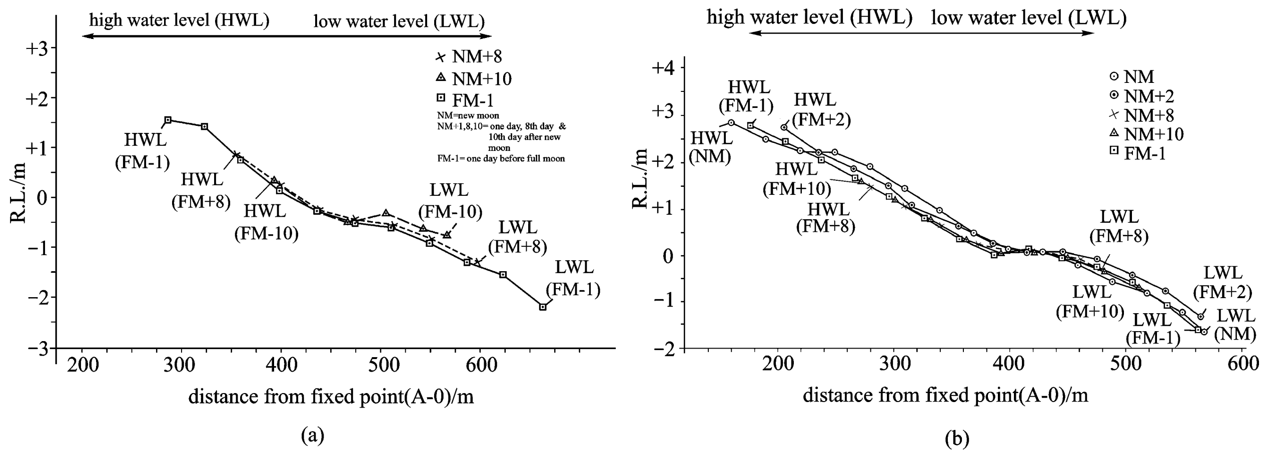

Fig. 5 Day to day change of beach profiles along transect A-0 during lunar days. (a) Post-monsoon period; (b) Pre-monsoon period

length, rate of sediment transport and wave energy all tend to be more positive in sense from the western to the eastern part of the shore in terms of the influence on the coastal erosion pattern during both pre-monsoon and post-monsoon periods.

4.4 Sediment transport pattern

From the field observation and sedimentological studies at the western part of the beach, it is observed that there is a long shore current in this area that help develop small tidal creeks/runnels within the beach. Development of secondary mode with increased weight frequency percentage from east to west is also indicative of the influence of strong long shore current from east to west of the shore. The increased wave energy in the eastern part as compared to the western part causes bank erosion. As a result, part of the beach materials first deposited by the onshore current resulting in an initial increase of beach slope and then transported by long shore current parallel to the beach shoreline from east to west of the beach. Due to the high-energy onshore current, remnants of mud banks, clay balls and roots of coconut trees are exposed in this part. The loose sandy materials are subjected to transport by the long shore current causing relative stabilization of the western part of the shore. This stability is also enhanced by the successive development of the coastal dunes, which are almost absent in the eastern part. These coastal dunes along with the embankment in the eastern part are partly or totally destroyed and the high water level reaches the base of the embankment. This indicates transgression of shoreline landward in the eastern part capturing the paddy fields of the backshore area.

4.5 Socio-economic aspect and coastal hazards

The coastal plains play an important role in socio-economic development based on land use such as agriculture, horticulture, breeding, tourism as well as industry. The majority of the coastal population of the Sagar Island belongs to fisherman and farmer communities. Fishing is the main source of income of the inhabitants. They live in isolated and scattered villages where the threat from hurricanes, coastal storms, sea-level rise, erosion, tsunamis etc is ever present. In Sagar Island, nearly 75%–80% of the natural vegetation is replaced by man-planted species like Jhabua, Coconut, Babla, Mango, Bamboo, Eucalyptus, Banana, Shisu, Palm, Casurina, Acacia etc. These are present in the settlement areas, on the roadsides, creek banks and canal banks. Without an adequate management program, the embankment failure often captures their paddy lands and hutments and forces them to change their habitation and hutments causing land degradation.

Dune scarps are formed during the full moon period when the wave energy tends to reach the maximum and the high water level reaches the dune base causing an irreversible erosion pattern. Accurate land use planning such as nourishment of mangrove forest and the management of the exploitation of natural resources seem to be efficient measures to preserve the coastal environment.

The western deltaic distributaries of the Ganges River system are present in the area. These distributaries are Hooghly (Gabtala) River and Muriganga River flowing through the west and east of Sagar Island. In recent years the Sagar Island has been shrinking due to active erosion of the two said rivers.

It is also worth noting that there is a lack of shell fragments in the beach sediments. It can possibly be attributed to the presence of dead zones where there is deficiency of oxygen for which the common living organisms like lamellibranches, gastropods, and echinoids etc have not survived. Such dead zones are alarming for the depletion of marine organisms in the studied area. There is decline in fisheries resources in the Sundarbans over the past 15 years, including a significant decline in the region's major catch: hilsa fish. From the analysis of the data of the forest department (Sen, 2004), it is also observed that there are pockets in the Bay of Bengal that show a considerable decline in oxygen level and nutrients essential for any form of life. The pockets spotted include the Matla-Saptamukhi junction and the eastern part of Sagar Island.

Around 680 million tons of untreated sewage goes into the sea and it includes hazardous industrial waste and fertilizers. Frequent embankment failures, submergence and flooding, beach erosion and siltation at jetties and navigational channels, cyclones and storm surges are all making this area increasingly vulnerable. The effect of shoreline retreat has a vulnerable impact on the coastal geomorphology and its inhabitants.

5 Conclusions

The Sagar Island exhibits a high-energy, macro-tidal coast. The marine coastal landforms show dune ridges along with intervening flats bordered by gently sloping beach on one side and a flat beach on the other side. The western part of the beach is dominantly of fine sand; whereas the eastern part is silty and clayey. From the comparative study of the day to day beach profiles during lunar days, it is observed that erosion takes place in the central part of the beach indicating that this part acts as a pumping station from where sediments are sometimes transported inland forming coastal aeolian dunes and sometimes transported to the offshore area forming sand bars or ridges. The mechanism of such a sediment transport pattern might provide clues to the formation of coastal aeolian dunes or juvenile offshore sand bars.

All the hydrodynamic parameters like water depth, significant wave height, wave period, velocity of long shore current, wave length, rate of sediment transport and wave energy tend to be more positive in sense in the eastern part than the western part. Due to such different hydrodynamic conditions, extensive erosion has been observed more in the eastern part of the beach than the western part. The width of the beach varies from 104 m in the eastern part to a maximum of 320 m in the western part. There is about 20 m landward transgression of the shoreline in the eastern part since 1985 to 2004 causing extensive beach erosion in this part of the beach, whereas in the western part it is almost stable; rather, a deposition of sediments took place.

The lack of shell fragments in the beach possibly indicates the presence of some dead zones where there is deficiency of oxygen. Such dead zones are alarming for the depletion of marine organisms. Around 680 million tons of untreated sewage goes into the sea including hazardous industrial waste and fertilizers. Frequent embankment failures, submergence and flooding, beach erosion and siltation at jetties and navigational channels, cyclones and storm surges are all making this area increasingly vulnerable.

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