Coastal erosion triggered by a shipwreck along the coast of Goa, India

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Temporal satellite imageries (1999, 2001, 2003, 2006, 2008 and 2011), wave model (DHI) results and field measurements have been used to evaluate whether the grounded ship *MV River Princess* played a role in triggering erosion along the famous Candolim–Sinquerim beaches of Goa. Coastal sand dunes bore the maximum impact. The cause of the erosion is unique. The orientation of the ship with respect to the coastline, its length, the distance of the ship from the coastline and, more importantly, the direction of the waves prevailing over the region suggest that the wreck acted like an offshore breakwater and triggered erosion along this coast. A tombolo was also formed on the lee side of the vessel, a process that eventually led to the formation of an accretion zone on the lee side. The zone of deposition is evidenced by the presence of a sand bar which gets partially exposed during low tide. As the littoral current along this coast is southward, the sand bar blocked the southward littoral drift. As a consequence, the sand depletion that followed subsequently induced erosion of the sea front. The extent of net erosion has been estimated at around 0.10934 sq. km (109,340 sq. m) during the past 12 years. A stretch of 1.5 km of the coast has receded by a maximum of 85 m. In economic terms, the loss of prime property is estimated at minimum 28 crore rupees. The direct impact of the wreck in eroding the coast is more explicit during the SW monsoon. The powerful intensity of winds and higher significant wave height (H_s = 2.59 m) during the SW monsoon deteriorate the shore front that is now devoid of sand dunes and, as a consequence, has gradually become fragile due to severe erosion.

Keywords: Coastal erosion, cyclone, remote sensing images, shipwreck.

GOA is one of the most famous tourist coasts of the world. In general, the sea front of Goa is characterized by wide, linear and scenic beaches backed by sand dunes and intersected by headlands that extend into the sea[1–4]. Coastal zones of Goa are important as they are the main source of revenue for the state. Goa is heavily disturbed in the recent times due to the sudden boom of real estate sector, mushrooming of industries, inconsistent tourist flows, with a consequent impact on coastal ecosystems. Changes in the land-use/land-cover, geomorphology, ecology and sensitivity of coasts were studied earlier[1–4]. Chandramohan *et al.*[5] studied in detail the rip currents zones, wave and littoral sediment characteristics of Goa coast. In addition to the anthropogenic activities, natural hazards and unexpected accidents disturb the coastal zone. Sudden increase of port activities has increased the threat around ports. There have been several studies related to coastal erosion along the Indian coast. Shoreline changes and erosion rate were estimated for regions around Paradip[6], Mangalore[7], Mumbai[8], parts of Tamil Nadu[9–12] and Kerala coast[13].

A super tanker *MV River Princess* drifted ashore and grounded along Goa coast off Candolim in the early morning of 6 June 2000, due to a cyclone (Figure 1). The wreck remained in place for 12 years. The bow of the ship pointed southwest, 208° from north, and the position of the mid ship was 15°30′32.64″N, 73°45′43.83″E. The depth of water was 5 m. The ship measured 258 m in length and 35 m in width. The bow and aft of the ship were 390 and 187 m respectively, from the shoreline.

The coastal stretch from Candolim to Sinquerim lying to the south of the ship has been under the grip of erosion since 2001 and severe erosion occurred here during the southwest monsoon periods of 2006, 2007 and 2008 (Figure 2). It has also been reported that the grounded ship gave rise to trace metal pollution in this region[14]. Rusted metal pieces from the hull of the ship were found in the waters. The bathymetry of the beach has become irregular due to transient shoals and morphological changes[14] and it poses hazards to the tourists who venture into the sea for swimming.

This study addresses a unique case where severe erosion was triggered by a grounded ship. The cause, extent and rate of erosion just over a decade, as reported here, present a unique scenario. The objective of the present study is to analyse the extent of coastal geomorphological changes induced by the grounded ship *MV River Princess* on the Candolim–Sinquerim coastline. The dynamics behind erosion is discussed based on the southwest and northeast monsoon wave patterns and alignment of the ship with respect to the shoreline.

Nearshore oceanographic parameters are given in Figure 1. Significant wave height (H_s) and wave direction have been simulated using MIKE21 spectral wave (SW) model by applying blended winds obtained from the Centre de Recherche et d'Exploitation Satellitaire (CERSAT), IFREMER, Plouzané, France. The blended wind data have been prepared in order to enhance the quality and spatial and temporal resolution of remotely sensed surface winds. These wind vectors are blended with model-generated winds using optimum interpolation (OI) based on kriging method. Details of the model set-up and validation of the model are given by Vethamony *et al.*[15]. Monthly variations of H_s and wave directions and

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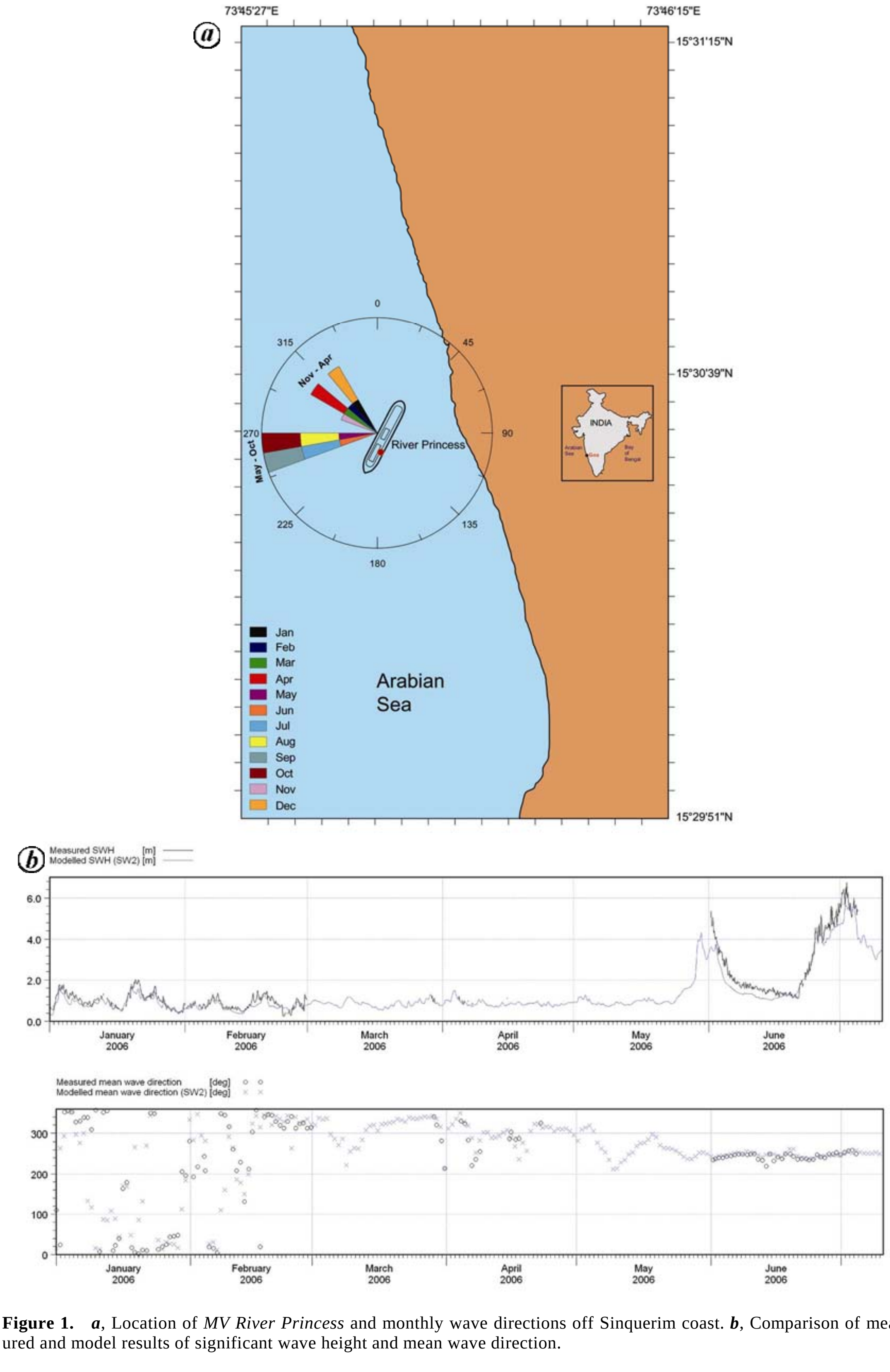

Figure 1. *a*, Location of *MV River Princess* and monthly wave directions off Sinquerim coast. *b*, Comparison of measured and model results of significant wave height and mean wave direction.

wave periods are given in Table 1. These values are fetched from the point (15°30′32.64″N, 73°45′43.83″E) which is around 5 m water depth within the model domain. A comparison of measured and model results of significant wave height and mean wave direction is shown in Figure 1 *b*. Northwesterly waves are present in the region during winter, and pre-monsoon seasons (January–May), and westerly–southwesterly winds during the southwest monsoon. The wave direction varies between 250° and 315°. The mean wave direction during southwest monsoon (May–October) varies between 250° and 270° and during winter and spring inter-monsoon (November–April), the wave direction is around 315°. The prevailing wave directions during November–April and May–October are presented in Figure 1 *a*. The intensity of waves is represented by H_s given in Table 1. Maximum H_s of 2.59 m is attained during July when the southwest monsoon winds reach a maximum. The wave period is high during the SW monsoon months (June–August) and minimum during February.

The ship is grounded in the near-shore region where the littoral currents are active. Analysis of the wave direction data and ship parameters shows that (i) alignment of the ship with respect to the coast, (ii) length of the ship and (iii) distance of the ship from the coast suggest that the ship acted like an offshore breakwater. As the waves approach from west/northwest direction, they encounter the ship on its course. As a result, the waves get attenuated, forming a sheltered region in the shoreward side (lee side) of the ship, where the wave energy and near-shore currents become very weak. This causes a tombolo formation on the lee side which in turn induces settling of sediment and accretion in the region between the ship and the shoreline. This is seen as a bypass shoal, connecting the ship with the shoreline. A sand bar is clearly visible between the ship and the shoreline (Figure 3) when it gets partially exposed during low tides, creating a pathway between the shore and the ship. Also, since the ship is aligned at an angle with the coastline, the northern tip of the ship is closer to the shore and there is a possibility of more sand deposition in the northern half of the lee side. Coastal structures which interfere with the littoral transport are the most common cause of coastal erosion in the adjacent regions. In this case, the waves were always approaching either from the west or west–southwest or from northwest direction and the area between the ship and the shoreline, that is the lee side has become a sheltered zone as the ship prevented the waves which otherwise facilitated a southward littoral drift in this region. As a result, huge quantities of sand were trapped at the lee side which prevented the southward littoral drift and thereby removed the sand out of the sediment budget, thus causing erosion in the adjacent shoreline in the southern regions. The accretion in the lee side has occurred over a distance of ~ 300 m along the coastline. Field observations as well as satellite imageries have also confirmed accretion in the form of a bar of sand at this location.

Our studies explore the role of the grounded ship in triggering the erosion. It is inferred that the main cause of erosion of the southern coastline (towards Sinquerim) was the reduction in southward littoral drift due to both the ship and sand bar formation on the lee side of the ship. It is well known that sediment transport or littoral drift along the near-shore region is the main process that

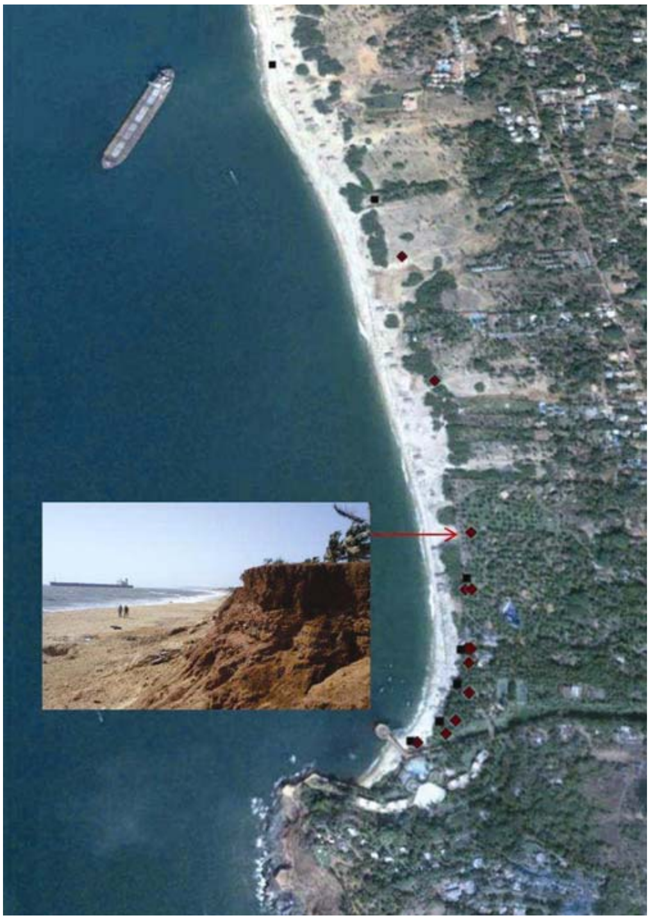

Figure 2. GPS points collected on 12 May 2008 (black squares) and 12 October 2011 (red diamonds) plotted on a *Google Earth* image of 5 February 2003 (courtesy: *Google Earth*). (Inset) Complete elimination of a sand dune, about 4 m height, due to erosion on the Sinquerim coast (12 May 2008). The grounded super tanker *MV River Princess* is seen in the background.

Table 1. Monthly variations of significant wave height (H_s) and mean wave direction off Sinquerim coast, Goa

Month	H_s (m)	Mean wave direction (deg)	Wave period (S)
January	0.61	321	4.13
February	0.52	312	3.84
March	0.71	302	4.27
April	0.77	303	4.07
May	1.15	269	5.07
June	1.71	254	6.48
July	2.59	259	7.13
August	1.78	264	6.07
September	1.27	259	5.59
October	0.75	263	4.96
November	0.57	292	4.67
December	0.58	322	4.17

contributes towards the nourishment of beach sediments. The littoral drift is defined as the movement of sediment in the near-shore zone by the action of waves and along-shore currents[16]. The littoral processes facilitate the required sediment supply along the shoreline and help in sustaining a stable beach profile. Littoral transport studies carried out along the west coast of India suggest that littoral drift in the region is towards south[17,18]. Information on wind and wave directions also supports the presence of a southward littoral transport[15]. The presence of *MV River Princess* and the sand bar formation on its lee side adversely affected the southern coast as it blocked the littoral drift towards south. Consequently, due to the weak littoral currents the sediment supply to the beach lying to southern side of the ship reduced, resulting in sand depletion along Sinquerim coast. In the course of time, as there was no sand supply to the beach, the beach began to show symptoms of erosion. This sand starvation is therefore manifested in the form of erosion. Erosion occurring at Sinquerim is an example of lee side accretion and subsequent erosion that is normally associated with regions of offshore breakwaters[19].

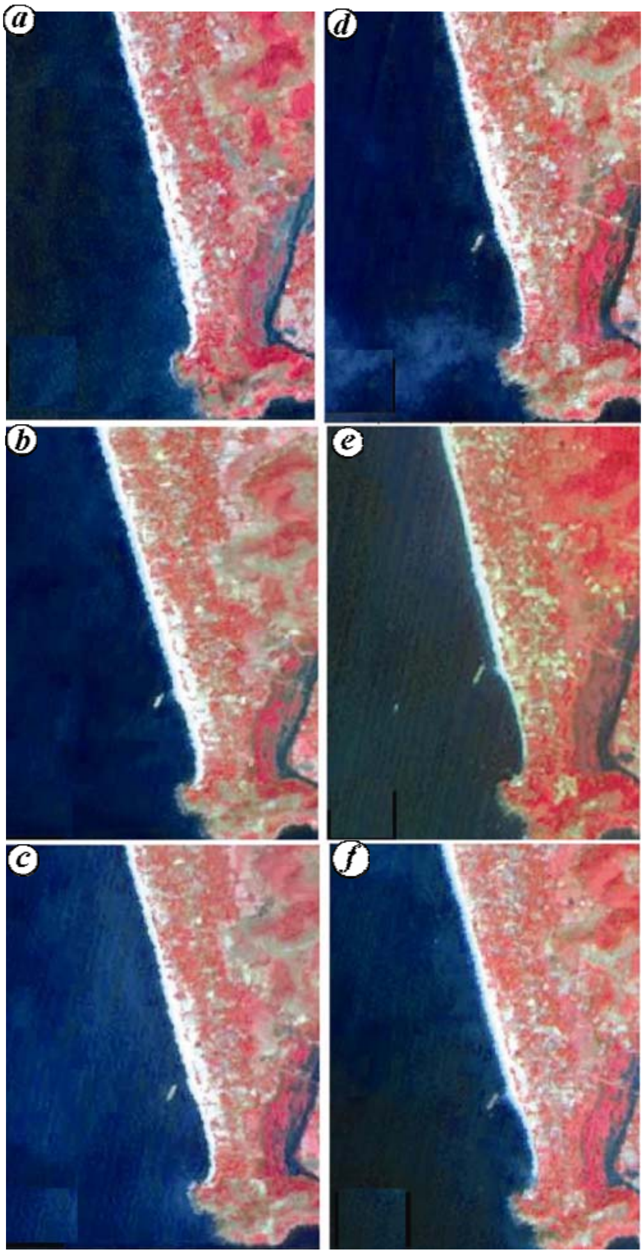

Figure 3. Multi-dated satellite imageries showing parts of Goa coast for the following years: (***a***) 1999, (***b***) 2001, (***c***) 2003, (***d***) 2006, (***e***) 2008, (***f***) 2011. Note the recession of the coast over the years.

Table 2. Date of pass and details of sensors of satellite imageries

Date of pass	Sensor	Resolution (m)
11 February 1999	ETM+	30.0
5 February 2001	LISS III	23.5
31 January 2003	LISS III	23.5
19 January 2006	LISS III	23.5
18 October 2008	LISS III	23.5
17 January 2011	LISS III	23.5

Multi-temporal satellite imageries for the years 1999, 2001, 2003, 2006, 2008 and 2011 were used after examining the similar tide conditions, cloud cover and bright sunlight. Details of the satellite imageries are given in Table 2.

Satellite imageries corresponding to 1999, 2001, 2003, 2006, 2008 and 2011 are shown in Figure 3. Preliminary analysis of the imageries indicates that in November 1999, before the grounding of the ship, the shoreline was almost a straight (Figure 3 *a*). The ship grounded in June 2000 and within six months, in January 2001, symptoms of erosion along the southern part of the coast and deposition on the lee side (between the ship and the shore line) were visible (Figure 3 *b*). This process continued and eventually altered the shoreline topography of the beach. The changes in the form of shoreline recession can be distinctly identified in the satellite imageries of 2001–2011 (Figure 3 *b*–*f*).

These imageries were geometrically corrected with a high accuracy of less than one pixel. RMS error of the geometric correction was less than one. Coastlines obtained from the imageries were digitized using GIS software. Quantitative analysis (Figure 4) of these imageries indicates that the landward shift of coastline from February 2001 to January 2006 was ~ 50 m. Further, the approximate landward shift in the shoreline from 1999 (before grounding) to 2011 is ~ 85 m, over a period of 12 years.

Digital shoreline assessment system (DSAS) was used to quantify the erosion and accretion along the beach. A baseline was created manually, seaward from the appended shorelines. Transects perpendicular to the baseline were laid at 40 m spacing with an uncertainty value of (±) 2. Statistical analysis (Table 3) for end-point rate (EPR) and net shoreline movement (NSM) was done, where EPR is the rate of change between the oldest and latest shoreline per year and NSM is the distance between the oldest and latest shorelines. The area of erosion is estimated at around 0.10934 sq. km (equivalent to 109,340 sq. m; Figure 5). DSAS result shows that the coastline has shifted up to a maximum of 85 m in transect no. 23, which falls in the middle of the coastal stretch (Figure 4). In terms of economy and considering the prevailing rates of coastal properties (2600 INR per sq. m), the total loss of land is estimated at around 28.4 crores rupees.

The coastal strip of Goa comprises fluvial, fluvio-marine, marine and aeolian landforms. Estuaries, estuarine islands, tidal flats, beaches, sand dunes, spits, bars and cliffs are the prominent geomorphic features[1,2]. Coastal sand dunes often extend beyond 300 m as observed in south Goa. It is evident from our field observations, and data from satellite imageries and wave climate analysis that a long stretch of beach (~ 1500 m) along the coast of Candolim–Sinquerim underwent severe erosion in the past 12 years. The erosive activity is evident from demolished sand dunes, uprooted shrubs and trees and damaged coastal structures, including a retaining wall along ~ 300 m stretch of the shoreline. The extent of coastal land lost to the sea has been estimated at around 109,340 sq. m. The main cause of the erosion is the grounded ship which triggered the formation of a sand bar on the lee side of the ship. Offshore hard structures invariably cause lee side erosion or accretion[18,19]. As the ship was grounded, it can be considered equivalent to an offshore, detached breakwater. It is positioned in the wave breaker zone, where the littoral and longshore currents are active. Due to the combined effect of both the ship and lee side accretion, the area between the ship and the shoreline became a sheltered zone that obstructed the southward littoral currents. Hence, the southward littoral drift was reduced, and there was negligible sand supply due to which the beach experienced sand deficiency. This sand starvation is manifested in the form of erosion.

However, during SW monsoon the factors responsible for erosion are different. Strong wind-driven currents and the dominantly westerly wave action affected the shoreline more intensively and caused severe damage. Most of the frontal sand dunes were completely destroyed. The shore normal of the beach near the ship is about 260°, which is almost the same as the direction of the southwest

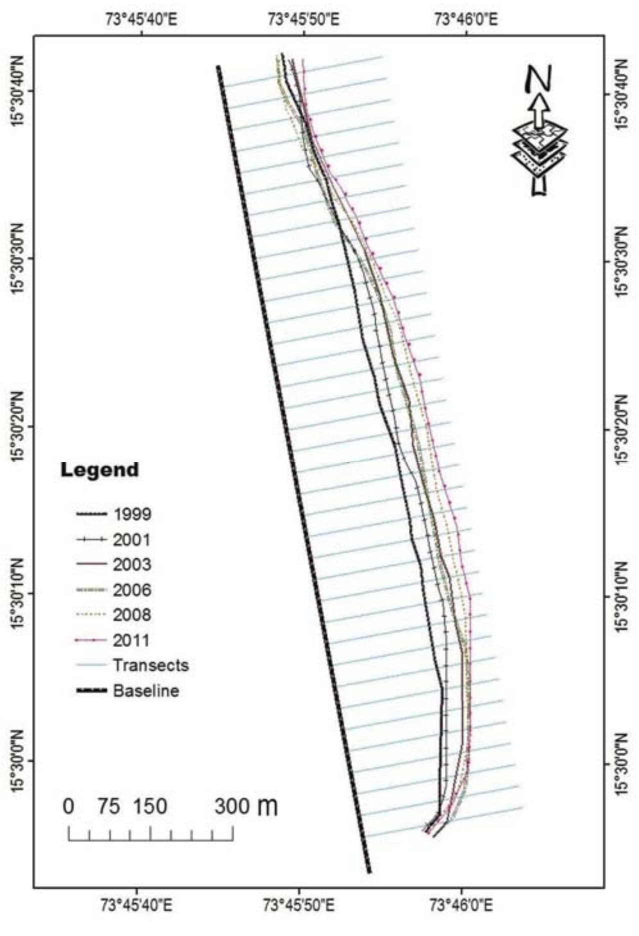

Figure 4. Shoreline traits and transects created using Arc GIS and DSAS software. The coast shifted 85 m inland over a short period of 12 years (1999–2011). Around 1.5 km stretch of this coast was severely eroded due to the effect of the grounded ship.

Table 3. Details of transects and results from DSAS software. Transect id 23 shows maximum coastal retreat

Transect Id	End point rate	Net shoreline movement
1	3.01	33.66
2	–1.99	22.23
3	–1.02	11.43
4	–0.81	9.06
5	–1.04	11.58
6	–1.23	13.74
7	–2.3	25.65
8	–3.02	33.7
9	–3.52	39.34
10	–4.27	47.68
11	–5.08	56.77
12	–6.07	67.83
13	–6.5	72.64
14	–6.77	75.61
15	–6.94	77.54
16	–7.22	80.73
17	–6.94	77.52
18	–6.45	72.14
19	–6.22	69.51
20	–6.33	70.79
21	–6.65	74.31
22	–7.07	78.96
23	–7.69	85.96
24	–6.91	77.27
25	–6.98	77.97
26	–7.29	81.45
27	–6.84	76.46
28	–6.25	69.88
29	–5.53	61.85
30	–4.67	52.23
31	–4.74	52.92
32	–4.8	53.61
33	–4.76	53.19
34	–4.47	50.01
35	–2.57	28.73
36	–0.88	9.87

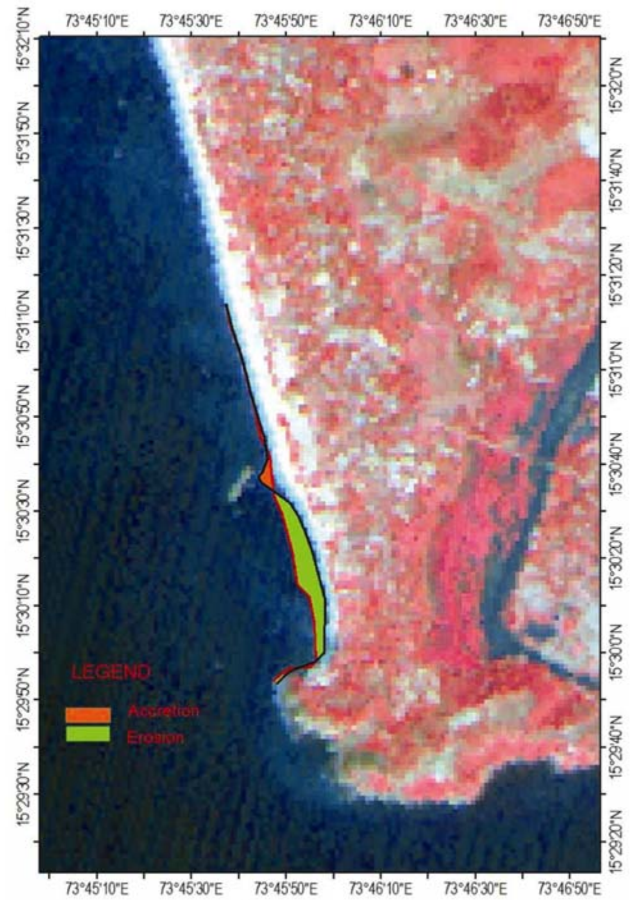

Figure 5. The extent of erosion (1999–2011), which is around 0.10934 sq. km calculated using remote sensing and GIS techniques.

waves. Since the southwest waves arrive almost perpendicular the shoreline, there will be little or no longshore transport during the SW monsoon. Although the northwest pre-monsoon waves may induce some transport, these waves have less energy than the southwest waves. Thus, during the SW monsoon, the predominant cause of erosion is not the disruption of longshore transport but storm erosion caused by the onshore–offshore transport due to the southwest waves. In comparison, during fair weather, the disruption of longshore transport is responsible for substantial erosion of the beach. Because of recurring attrition during the past 12 years, the shore front has become fragile and all the more prone to erosion.

As a beach erosion control measure, 42 geotubes filled with sand slurry were emplaced in June 2009 along 840 m of the beach face. The second set was fixed in October 2009 about 12–15 m seaward of the first row. Our observations reveal that five geotubes of the first set were damaged within a week, and many have sunk into the sand. The monsoon of 2010 took a heavy toll on the remaining structures. This measure failed at the site due to tidal, strong wave action and higher significant wave height (H_s = 2.59 m), particularly during monsoon. It was also found that the efficacy of this procedure was poor. Another study also confirmed that the wave regime led to bursting of geotubes and hence this technique could not arrest erosion[20].

For the sake of comparison, the effect of a stranded vessel on the northeastern coast of Sri Lanka is considered. As viewed in a *Google Earth* image (2009), the orientation of the 150 m long ship is NW–SE, and is located at 09°18′51″N lat. and 80°47′29″E long. The littoral current appears to flow from southwest towards northeast. Although initially the vessel was around 200 m from the shore (2009), the wreck is now linked to the beach (2011). Over a span of 2 years, around 200 m of the beach has accreted in the south, whereas in the north, an equal amount has eroded. Evidently, marooned ships do act as artificial wave breakers, disrupt littoral drift, block sediment transport and, if not salvaged on time, can cause extensive damage to beaches over a short period of time.

The saga of *MV River Princess* ended in April 2012. The wreck has been removed and is no longer seen above the sea level. Recent field checks do give initial clues that (i) the process of beach formation is active as a narrow strip of new beach is noticed (*Google* image of 2013); (ii) dune erosion was minimal during the monsoon of 2012 as evidenced by the return of ipomoea vegetation along the toes of eroded dunes at several places; (iii) the tombolo effect has dissipated and the shoreline now appears linear, and (iv) rock outcrops exposed on the eroded beach during 2006–2008 are now covered by sand. Artificial sand pumping or beach nourishment techniques may further help the damaged beach to regain its natural recovery rate. Regular beach profile measurements which are being conducted along this coast would reveal whether or not the beach will regain its past glory.

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