Analysis of short-term shoreline oscillations along Midnapur-Balasore Coast, Bay of Bengal, India: a study based on geospatial technology

Adarsa Jana^{1,2} · Sabyasachi Maiti² · Arkoprovo Biswas^{2,3}

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Abstract Shoreline is one of the quickly fluctuating linear landscapes of the coastal zone which is active in nature. In the present study, the analysis of remote sensing data sets covering Midnapur-Balasore coast, with an average time span of 6 months, has shown that they can be used to evaluate the short-term shoreline oscillations. In the present study, multi temporal satellite images of Landsat have been used to demarcate the short-term position of the shoreline changes. The techniques such as littoral cells, shore line change rate and beach recovery and devastation concept has been applied in this study. Finally the use of remote sensing data has proven as a good technique to estimate and quantify short-term shoreline oscillations along Midnapur-Balasore coast.

Keywords Shoreline oscillations · Remote sensing · Midnapur-Balasore coast · Littoral cell · Landsat ETM+ · Shoreline change rate

Introduction

Shoreline is one of the most important dynamic coastal features where the land, air and sea meet. It undergoes frequent changes, short term and long term, caused by hydrodynamic changes (e.g., river cycles, sea level rise), geomorphological changes (e.g., barrier island formation, spit development) and other factors (e.g., sudden and rapid seismic and storm events) (Scott 2005). The change in shoreline is mainly associated with waves, tides, winds, periodic storms, sea level change, the geomorphic processes of erosion and accretion and human activities. Monitoring changes in shoreline helps to identify the nature and processes that caused these changes in any specific area, to assess the human impact and to plan management strategies. Erosion and sediment accretion are on-going natural processes along all coasts. Human activities (e.g., dredging, beach mining, river modification, and installation of protective structures such as breakwaters, removal of backshore vegetation, reclamation of near shore areas) can profoundly alter shoreline processes, position and morphology, in particular by affecting the sediment supply (Berger and Iams 1996). The study of the rate of change in shoreline position is important for a wide range of coastal studies, such as development of setback planning, hazard zoning, erosion-accretion studies, regional sediment budgets and conceptual or predictive modeling of coastal morphodynamics (Sherman and Bauer 1993; Al Bakri 1996; Zuzek et al. 2003). The conventional techniques for determining the rate of change of shoreline position include: field measurement of present mean high water level, shoreline tracing from aerial photographs and topographic sheets; comparison with the historical data using one of the several methods, (viz., end point rate (EPR) (Fenster et al. 1993), average of rates (AOR), linear

✉ Adarsa Jana
adarsa.rsitkgp@gmail.com

Sabyasachi Maiti
maiti@gg.iitkgp.ernet.in

Arkoprovo Biswas
arkoprovo@gmail.com

¹ NRDMS Centre, Office of the District Magistrate, Administrative Building, Tamluk, Purba Medinipur, West-Bengal 721636, India

² Department of Geology and Geophysics, Indian Institute of Technology Kharagpur, Kharagpur, West-Bengal 721302, India

³ 33/B, Kalianibas Main Road, P.O. Nonachandanpukur, Kolkata, West-Bengal 700122, India

regression (LR), and jackknife (JK) (Dolan et al. 1991). Linear regression (LR) method of determining shoreline position change rate is found to be important among all such techniques, as it minimizes potential random error and short-term variability (cyclical changes) through the use of a statistical approach (Douglas and Crowell 2000). Recent advancements in remote sensing and geographical information system (GIS) techniques have led to improvements in coastal geomorphological studies, such as: semi-automatic determination of shorelines (Ryu et al. 2002; Yamano et al. 2006); identification of relative changes among coastal units (Jantunen and Raitala 1984; Siddiqui and Maajid 2004, Jana et al. 2012, 2014, 2016); extraction of topographic and bathymetric information (Lafon et al. 2002) and their integrated GIS analysis (White and El Asmar 1999). The remote sensing data could be used effectively to monitor the changes along the coastal zone including shoreline and inlet dynamics with reasonable accuracy. It helps the conventional survey by its repetitive and less cost-effectiveness. The objectives of the present study involved: (a) Identification of the littoral cells and transects by assessing the coastal processes and coastal geomorphology of the study area. (b) Identification of seasonal shoreline position for understanding the coastal morphodynamic. (c) Assessment of beach recovery and devastation and finally (d) Identification and integration of results for mapping the areas prone to erosion and accretion.

Study area

The study area chosen in the present work is a 134.42 km long coastal stretch on the east coast of India, covering parts of Balasore and Midnapur littoral tracts occurring in Odisha and West Bengal States respectively, adjoining Bay of Bengal (Fig. 1). The western end of the study area is bounded by Panchpara Inlet in Balasore (Odisha), while Rasulpur River in Midnapur (West Bengal) forms the eastern boundary. Geographically, the study area is bounded by latitudes $21^{\circ}30'0''\text{N}$ – $21^{\circ}48'0''\text{N}$ and longitudes $87^{\circ}12'0''\text{E}$ – $87^{\circ}54'0''\text{E}$ and fall under Subranarekha Delta Plain and Kanthi Coastal Plain. It is covered by five Survey of India (SOI) Toposheets of 1973 at 1:50,000 scale, viz., Nos. 73O/2, 73O/6, 73O/10, 73O/13 and 73O/14. Two major rivers located in the study area are Subarnarekha and Rasulpur River in Balasore and Midnapur district respectively which are the chief sources of both water and sediment supply in the present study area. It is a low-lying meso-tidal tropical coast of Bay of Bengal, northeast India (Bhattacharya et al. 2003). The Midnapur-Balasore coastal tract is characteristically almost flat with wave dominated sandy beach along with chains of sand dunes and mud flats (Dey et al. 2005).

Geologically, this is the coastal stretch of Indo-Gangetic plain; covered by recent to sub-recent alluvium of very thick Tertiary sediments (Paul 2002). The geomorphic divisions like beach, active dunes, mud flats, chenier plains etc. of present study area has been developed within last 6000 years (Paul 2002; Dey et al. 2005). The study area has overall uniform geomorphology with landward boundary comprising of older dune complex. This is followed by series of cheniers, beach ridges and intermediate mudflats. It also has a seaward boundary made up of recent remobilized sand and clay at various places (Chakrabarti 1991).

Materials and methods

Data sources and selection

The study was carried out using multi-temporal satellite images of Landsat ETM+ (enhanced thematic mapper plus) over the period of 2000–2009 (path 139 and row 45) of both post- monsoon and pre-monsoon season. The orthorectified Landsat data was downloaded from USGS data archive (www.eros.usgs.gov). The images were processed using the ERDAS Imagine 9.1 software. Landsat ETM+ has been used, as it is ideally suited for the coastal studies. The tidal conditions during data acquisition were considered for minimizing tidal influences. During low tide condition, maximum land is exposed; consequently different shoreline-proxies, such as, low water line, land–water boundary, and high water line, are distinctly visible. On the other hand, during tidal condition of ‘rising’, the minimum portion of the beach is unsaturated, and high-water shoreline proxy can be easily demarcated. In the present study, low-tide rising condition of data-acquisition was consider, for specific demarcation of high-water line for both post-monsoon and pre-monsoon seasons. The details regarding satellites data and their acquisition dates, times and tidal conditions are listed in Table 1.

Considerations of littoral cells and transects

Analysis of shoreline change is often based exclusively upon the littoral cell concept and modelling of hydrodynamic processes (Barter et al. 2003). Primarily the development strategies of the Shoreline Management Plans (SMPs) were based upon littoral cell boundaries, which have been defined at zones of sediment convergence and divergence (Anon 1993). In the present study the 134.42 km long coastal stretch including down drift portion of the inlet under investigation has been broadly subdivided into seven “littoral cells” (LC1–LC7) to understand the short-term shoreline dynamics. The seven littoral cells with their spatial extent are: (1) The first cell,

Fig. 1 Location map of the study area (after Jana et al. 2016)

Table 1 Details of the satellite data used for short-term shoreline oscillations study with acquisition date and time, tidal conditions and seasons

Satellite/sensor	Time (GMT +5:30)	Date of acquisition	Tide condition		Season
			Tidal height (m)	Condition	
Landsat ETM+	10:00:06	29 March, 2000	2.29	Rising	Post-monsoon
Landsat ETM+	09:57:56	10 December, 2000	4.26	Slack	Pre-monsoon
Landsat ETM+	09:57:38	03 May, 2001	2.8	Slack	Post-monsoon
Landsat ETM+	09:55:52	26 October, 2001	2.83	Slack	Pre-monsoon
Landsat ETM+	09:56:16	22 May, 2002	2.75	Slack	Post-monsoon
Landsat ETM+	09:55:21	29 October, 2002	2.48	Rising	Pre-monsoon
Landsat ETM+	09:56:11	17 November, 2003	2.32	Rising	Pre-monsoon
Landsat ETM+	09:56:40	05 February, 2004	3.99	Slack	Post-monsoon
Landsat ETM+	09:56:33	19 November, 2004	2.06	Rising	Pre-monsoon
Landsat ETM+	09:57:14	23 February, 2005	4.21	Slack	Post-monsoon
Landsat ETM+	09:57:14	24 December, 2005	1.92	Rising	Pre-monsoon
Landsat ETM+	09:57:40	26 February, 2006	3.89	Slack	Post-monsoon
Landsat ETM+	09:57:47	27 December, 2006	1.66	Rising	Pre-monsoon
Landsat ETM+	09:58:06	17 March, 2007	4.06	Slack	Post-monsoon
Landsat ETM+	09:57:56	15 January, 2008	1.77	Rising	Pre-monsoon
Landsat ETM+	09:57:43	19 March, 2008	3.86	Slack	Post-monsoon
Landsat ETM+	09:57:17	17 January, 2009	1.93	Rising	Pre-monsoon
Landsat ETM+	09:57:31	18 February, 2009	2.13	Rising	Post-monsoon

LC1, of 37.9 km length, starts from the southwestern end of the study area, bounded by Panchpara Inlet and extends up to Subarnarekha River; (2) LC2 of 24.6 km length, starts from the downdrift stretch of Subarnarekha River and extends up to Talsari Inlet, adjacent to the seawall; (3) LC3, 6.4 km long, covers Digha Development region comprising of seawall; (4) LC4 of 3.12 km length, occurs between the seawall and Digha Inlet; (5) LC5, 9.6 km long,

starts from Digha Inlet and extends up to Jaldah Inlet, (6) LC6 of 19.4 km length, lies between Jaldah Inlet and Pichhabani Inlet; and finally (7) the last cell, LC7, 33.4 km long extends from Pichhabani Inlet to Rasulpur River, at the northeastern end of the study area (Figs. 2, 3). Each littoral cell has been subdivided into a number of transects (e.g., tr1.1–tr7.80), perpendicular to the shoreline of the reference shoreline of 2000 at 300 m intervals. In addition,

Fig. 2 Post-Monsoon shoreline positions (2000–2009) prepared from landsat ETM+ satellite images. The two insets exhibit magnified portions of shorelines

transects perpendicular to the tips of the spits have also been considered. A total of 380 transects have been analyzed in the study area (Figs. 2, 3).

Shoreline detection and digitization

Landsat ETM+ satellite images over the period of 2000–2009 were used to obtain shoreline in this study. Shoreline detections by automatic (Ryu et al. 2002; Loos and Niemann 2002; Yamano et al. 2006; and Maiti and Bhattacharya 2009) and manual digitization techniques are complicated due to presence of water saturated zones in the vicinity of the land water boundary. Initially in the present study, the shorelines have been identified and delineated using the processed NIR bands of multi-date satellite

images through on screen digitization in ERDAS Imagine 9.1 software with reasonable zoom level. The processing of the NIR bands included ‘gray level thresholding’ and ‘segmentation by edge enhancement technique’ (Lee and Jurkevich 1990). The selected pixels, representing shorelines as described above, have been converted into vector layers. Uncertainties in some portions of the delineated shorelines were observed. To remove these uncertainties, in order to map continuous shoreline positions, other proxies, viz., ‘dune toe’ or ‘vegetation line’ (Zuzek et al. 2003) were carried out manually in stages. For example, if ‘dune toe’ failed to give satisfactory continuity of the shoreline position at a particular portion of uncertainty, then ‘vegetation line’ proxy was used. Thus, finally the continuous shoreline positions of pre-monsoon and post-

Fig. 3 Pre-Monsoon shoreline positions (2000–2009) prepared from landsat ETM+ satellite images. The two insets exhibit magnified portions of shorelines

monsoon season (Figs. 2, 3) (2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008 and 2009) were drawn.

Shoreline change rate calculation

The rate of shoreline change is one of the most common measurements used by coastal scientists, engineers, and land planners to indicate the dynamics and hazards of the coast (Dolan et al. 1991). It is an important parameter in the prediction of the future trend of shoreline shift. To measure the amount of shoreline shift along each transect, 2000 shoreline position (obtained from Landsat ETM+) has been chosen as a baseline or zero (0) position. With

reference to that baseline, seaward shifting of the shoreline along transect is considered as a positive value, while landward shifting is considered as a negative value. All measurements along the same transect both post-monsoon and pre-monsoon season are plotted in a cross-plot, with 'year' plotted along the X-axis and the corresponding shoreline shift with respect to 2000 shoreline position plotted along Y-axis. In the cross-plots, positive trends indicate accretion, whereas negative trends as erosion. Figure 4 represents a typical cross-plot with a negative trend for transect (tr1.67) of LC1. The plot also represents the linear regression equation as a measure of shoreline change rate and Regression coefficient (R^2) as a measure of

Fig. 4 Cross-plot of time versus amount of shoreline shift with respect to 2000 shoreline position, pre and post-monsoon season along transect (tr 1.67) within littoral cell LC1

Fig. 5 Plot of post-monsoon and pre-monsoon shoreline change rate distribution in littoral cells (LCs)

uncertainty. Thus, for the entire stretch of the coastline under investigation the transect-wise shoreline change rate information has been calculated and plotted for both post-monsoon and pre-monsoon seasons (Fig. 5).

Beach recovery and devastation

Shoreline change is an important characteristic in coastal area which depends on the beach recovery and devastation. Beach recovery indicates the sediment deposition and beach devastation indicate shifting coastline towards inland

causing the lowering of beach elevation and the loss of beach sediments. Based on earlier studies, it has been generally observed that during monsoon season (June to September) beach is severely eroded by frequent impact of storm, incidental high tides, and high river discharges. So, post-monsoon season (October to January) usually shows overall erosion in beach region compare to pre-monsoon season (February to May) within the same year. After post-monsoon usually calm condition of sea prevails during the winter season. This promotes gradual deposition of sediment and seaward shifting of shoreline up to the pre-

monsoon season, just before the arrival of monsoon. In the present study, the beach devastation is considered as the distance between pre-monsoon and the following post-monsoon shoreline positions within the same year. On the other hand, the difference in the shoreline positions between post-monsoon and the following pre-monsoon has been considered as beach recovery. Spatial disposition of shoreline changes within devastation and recovery period have been separately estimated along all transects for the period ranging from 2000 to 2008 (Fig. 6).

Results and discussions

The first cell, LC1, on the extreme southwestern end of the study area, shows 35.71 % (post-monsoon) and 33.02 % (pre-monsoon) erosion of transects and (64.29 % (post-monsoon) and 66.98 % (pre-monsoon) accretion of transects (Table 2). Further, the existing spit near the eastern boundary of this cell has been gradually eroding. In this littoral cell the total amount of beach recovery is 320 m and maximum and minimum amount of beach recovery is 228.73 m and -208.005 m respectively (Table 3). On the other hand, the total amount of beach devastation is 448 m, and maximum and minimum amount of beach devastation is 443.17 m and -270.07 m respectively (Table 3). The highest amount has been observed at Subarnarekha river mouth in both graphs.

The next cell, LC2, exhibits both erosion 29.51 % (post-monsoon) and 40.54 % (pre-monsoon) of transects and accretion 70.49 % (post-monsoon) and 59.46 % (pre-monsoon) of transects. This may be due to plantation of casuarinas trees on the high sand dunes, which is the source of heavy amount of sediment, and also due to low gradient of beach slope (1:6). In this cell, the total amount of beach recovery is 115 m, maximum 204.006 m, minimum -73.19 m and the total amount of beach devastation is 161 m, maximum 278.73 m and minimum -163.59 m. In this littoral cell, the highest amount has been observed in the eastern part of Subarnarekha river mouth.

The littoral cell, LC3, LC4 and LC5 shows gradual accretion for the next 16.5 km up to Shankarpur coastal stretch. Among these three cells, the highest amount of accretion is found in cell LC4, between seawall and Digha inlet. Recovery amount in LC3 is more than that in the LC2 and devastation is less than that in LC2. In this littoral cell, initially, recovery increases, and then decreases. Hence, in this littoral cell deposition is more. But in case of LC5, the recovery has been increasing every year, except during the period, post-monsoon 2007 to pre-monsoon 2008. In the devastation graph of this cell, erosion is found to be decreasing. The total amount of recovery is 190 m and devastation is 228 m.

The next cell, LC6, exhibits more accretion than erosion with 91.53 % (post-monsoon) and 90.63 % (pre-monsoon) accretion of transects and 8.47 % (post-monsoon) and 9.38 % (pre-monsoon) erosion of transects. This huge amount of accretion caused probably due to artificial protections, created by the dumping of sand bags and gabions. This cell also shows spit development near eastern boundary. In LC6, recovery has been gradually decreasing. In one transect (tr6.16) only, one high value has been observed in 2008, otherwise this cell shows decrease every year. In devastation graph, the highest value is observed in this same transect (tr6.16). The total amount of recovery is 150 m and devastation is 180 m.

The last cell, LC7, also shows both erosion 16.67 % (post-monsoon) and 29.41 % (pre-monsoon) of transects and accretion 83.33 % (post-monsoon) and 70.59 % (pre-monsoon) of transects, while two spits existing in the middle of the cell are eroded.

Conclusions

The use of remote sensing data to estimate short-term shoreline oscillations, i.e., coastal changes at a monsoonal scale reflecting seasonal (pre-monsoon and post-monsoon) changes is presented in this paper. To achieve this eighteen Landsat ETM+ satellite images with an average time span of 6 months over a period of 2000–2009 taken at the Midnapur-Balasore coast has been used. The area chosen for the present work is a 134.42 km long sandy beach on the east coast of India, covering parts of Balasore and Midnapur littoral tracts occurring in Odisha and West Bengal States respectively, adjoining Bay of Bengal. The western end of the study area is bounded by Panchpara Inlet in Balasore (Odisha), while Rasulpur River in Midnapur (West Bengal) forms the eastern boundary. Over last few years the area is facing shoreline erosion/accretion related problems, resulting in damages to the natural set up of the coastal region in the study area. The area under investigation has been broadly subdivided into seven “littoral cells” (LC1 to LC7) and each littoral cell has been subdivided into a number of transects (e.g., tr1.1–tr7.80), perpendicular to the shoreline to understand the seasonal shoreline dynamics. The analysis shows that in the first cell, LC1, the erosion is 35.7 and 33 % of transects and accretion is 64.3 and 67 % of transects, the next cell, LC2, also exhibits both erosion is 29.5 and 40.5 % of transects and accretion is 70.5 and 59.5 % of transects during post-monsoon and pre-monsoon season respectively. An accretional region have been found for the next 16.5 km up to Shankarpur coastal stretch comprising littoral cells, LC3, LC4 and LC5. The LC6, shows more accretion (91.5 and 90.6 % of transects) than erosion (8.5 and 9.4 % of

Fig. 6 Beach recovery (a) and devastation (b) graph of the study area from 2000 to 2008 comparison with post and pre-monsoon data

Table 2 Regional and littoral cell wise post and pre-monsoon statistical summary of shoreline change rate information

	LC1		LC2		LC3		LC4		LC5		LC6		LC7		Regional total	
	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre
Length of shoreline (km)	37.9		24.6		6.4		3.12		9.6		19.4		33.4		134.42	
Mean shoreline change rate (month/year)	120.3	152.27	-30.79	-50.18	-16.36	19.4	18.41	11.44	41.1	37.78	15.47	-28.49	-35.76	89.95	112.37	232.17
Minimum shoreline change rate (month/year)	-157.6	-187.5	-82	-81.08	-2.43	1.64	-13.71	-1.53	-5.42	-6.32	-52.85	-6.32	-5.55	-17.86	-319.5	-298.9
Maximum shoreline change rate (month/year)	39.17	88.63	63.23	91.29	7.75	9.02	18.8	20.99	69	44.92	86.21	47.36	391.46	201.9	675.62	504.07
Standard deviation of rates (month/year)	33.27	36.68	17.92	22.24	3	1.87	8.02	7.56	14.85	8.54	18.05	10.08	55.38	34.85	150.5	121.83
Total transects that record erosion	35	35	18	30	4	0	3	2	12	3	5	6	15	30	92	106
Total transects that record accretion	63	71	43	44	16	20	7	8	25	32	54	58	75	72	283	305
Total transects that record statistical uncertainty ($R^2 < 0.5$)	37	34	47	60	17	6	9	7	29	29	21	46	62	81	222	263
% of total transects that record erosion	35.71	33.02	29.51	40.54	20	0	30	20	32.43	8.57	8.47	9.38	16.67	29.41	25.21	140.92
% of total transects that record accretion	64.29	66.98	70.49	59.46	8	100	70	80	67.57	91.43	91.53	90.63	83.33	70.59	77.53	559.08
% of total transects that record statistical uncertainty ($R^2 < 0.5$)	37.76	32.08	77.05	81.08	85	30	90	70	78.38	82.86	35.59	71.88	68.89	79.41	60.82	447.3

Negative values indicate erosion and positive values indicate accretion

Table 3 List of maximum, minimum and total amount of beach recovery and devastation in different littoral cell of the study area

	LC1 (m)	LC2 (m)	LC3 (m)	LC4 (m)	LC5 (m)	LC6 (m)
Shoreline shift during recovery period						
Max	228.72	204.01	177.9	160.36	188.88	151.58
Min	−208.01	−73.19	−75.16	−144.44	−89.18	−427.81
Total	320	115	130	135	190	150
Shoreline shift during devastation period						
Min	443.17	278.74	62.54	178.52	105.59	507.35
Max	−270.07	−163.59	−175.59	−222.89	−176.76	−156.70
Total	384	138	156	162	228	180

Negative values indicate erosion and positive values indicate accretion

transects) during both seasons. The last cell, LC7, shows both erosion (16.7 and 29.4 % of transects) and accretion (83.3 and 70.6 % of transects).

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