Impact of River Dams on Littoral Cells Located Adjacent to the River Mouth

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Abstract

Terrestrial sediment is a major source of sediment to all coasts. Suspended sediment is carried away by the rivers and supplied to the coast to maintain sediment budget. The construction of dams across the rivers arrest sediment behind it and affect the sediment budget of littoral cells along the coast. Reduction in sediment supply induces ecological as well as geomorphological changes along the shoreline. Coastal erosion may accelerate due to reduced sediment influx. With the growing number of cross-river dams and water diversion projects, it has become a major concern before the scientific community to measure, understand and find solutions to multi-fold geo-environmental problems that are arising out of river damming. The present study aims to find out the impact of dams on the coast. It examines how the changes in the suspended sediment supply of an Indian river impact the coast in terms of loss of area due to erosion. Temporal analysis of geomorphological changes along the shoreline in relation to sediment influx holds immense importance to coastal management essential for the sustainable life and livelihood of coastal communities. Scientific investigation into the impact of river dams on the coastal environment is likely to provide a strong ground to reconsider the way present basin development projects function. Areal changes in littoral sediment cells adjacent to the river mouth have been quantified and correlated with changes in sediment influx. Changes along the shorelines have been detected through multispectral satellite images of Landsat belonging to different dates. Image processing and quantification of changes have been performed in QGIS 3.14 "Pi" platform. Virtual raster, raster calculator, field calculator and other required tools in QGIS were used during image processing.

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Introduction

Constructions of dams, reservoirs, water diversion projects etc. arrest sediment flux and decrease its supply to the coast.[1-3] Large rivers all over the globe are affected by dams. According to the International Commission on Large Dams (ICOLD), 45000 large dams all over the globe are obstructing the natural flow of rivers. Dam changes discharge volume of water and sediment and affects the entire river system. Sediments are arrested behind the dam and the coast receives reduced influx. Such reduction alters the coastal sediment budget. Impacts of reduced sediment influx may be visible near the estuary and littoral sediment cells adjacent to the river mouth. Coastal erosion, shifting of the river mouth and marine bar are geomorphological manifestations of reduced sediment influx.

Suspended sediment influx by rivers is a major source of sediment to the coasts.[4] Terrestrial sediment is carried away by the river and deposition takes place wherever carrying capacity of river falls below threshold limit.[5,6] Low-lying alluvial plains, estuaries and coastal zones are the major reservoirs of terrestrial sediment. The process of sedimentation in the river mouth and coastal zone brings morphological changes[7] Warrick *et a*l. (2019)[9] have studied the process through which terrestrial sediment brings changes to the coast. According to them, sedimentation begins in "intertidal and subtidal deltaic lobes". In due course of time river mouth bars are formed by wave action and these bars gradually g*et a*ttached to the main land. Large deltas all around the world have been formed by sediment discharge and deposition by large rivers and all deltas are sensitive to fluctuation in sediment flux.[10]

Rozengurt *et a*l. (1993)[11] have studied the impact of a barrage in the Nile delta and concluded that the prograding phase of the Nile delta was replaced by retro grading with the construction of barrage. Aswan dam across the Nile reduces sediment influx further and these two events result in erosion of delta coast line up to 125-175 m/yr. Stanley (1996)[12] has measured the impact of Aswan and other dams across the Nile on the coast. He pointed out that reduction in sediment discharge depends upon the design, purpose and operation of the dam. Another example of the effects of dams on coastal geomorphology may be cited from

the study on the Pearl river in China by Dai *et a*l. (2008).[13] Sediment discharge from this river has decreased significantly since the mid-1980s with the construction of large dams and consequent deposition of sediment behind those dams.

With the growing need for freshwater, the numbers of dams are likely to increase in future dates. The natural flow of rivers continues to be obstructed more with an increasing number of dams.[14] The sediment supply from the river to the sea will decrease further. The scientific community should pay more attention to measuring the environmental impacts of such a decrease in sediment supply and suggest management techniques.[14] The present research examines how the increase in the number of dams across an east-flowing Indian river (Subarnarekha) impacts sediment influx and consequent changes along the coast. A number of studies have already linked up the relationship between dam construction and a decrease in sediment influx to the coast due to sediment arrest behind the dams.[15-18] Misra (2017) has prepared a stochastic model of flow and sediment of the rivers at delta head.[19] Lowering of sediment influx to the coast and consequent acceleration in erosion has also been studied in scientific investigation.[20-22] For example, Jana *et a*l (2016) have calculated the rate of coastal erosion on the North-Eastern coastal tract of the Indian peninsula based on Landsat images in the Digital Shoreline Analysis System (DSAS) platform.[23]

However, the available literature regarding the impact of river dams on coastal geomorphology is limited to calculating the rate of shoreline shifting and identifying erosion-affected zones. There is little research that emphasises areal gain and loss in relation to the continuous decrease in sediment influx. The present study has also taken littoral sediment cells as a natural geomorphological unit while analysing the impact of an increasing number of dams on the coastal environment. Using littoral cells as a unit of the study may provide us significant insight into the differential behaviour of adjacently located cells under identical changes. Again, the periodic breakup of total investigation time in the present study is likely to contribute significantly to understanding the lag time between commissioning a dam and its impact to be visible on the coast. In the present study, changes in suspended sediment influx

were studied first and such changes were correlated with coastal erosion and accretion.

Study Area

Subarnarekha river originated in the Indian state of Jharkhand and flows through West Bengal and Odisha before debouching into the Bay of Bengal. The geographical extension of the basin ranges from 85° 8' to 87° 32' E and 21° 15' to 23° 34' N. The river basin of Subarnarekha has a total area of 29,196 km2. The basin receives a Mean Annual Rainfall of 1458 mm and most of the rainfall takes place during the South-West monsoon. A total of 38 dams including 16 large dams and water diversion barrages (Fig. 1a) has been commissioned so far. The numbers of dams and barrages have increased since 1974 and sediments continue to arrest behind the dams.[24] The river enters the Bay of Bengal through the northern coastal zone of the

Indian state of Odisha. According to Mohanty *et al* (2008), this coastal tract is highly vulnerable to tropical cyclone.[25] Areal loss and gain along the shoreline adjacent to the mouth of this river in response to the decreasing amount of sediment influx have been observed for a time span of 38 years. The observed length of the coast is extended from the left bank of Bardaia river mouth (87° 12' 20.02''E and 21° 32' 45.17"N) in the south to Udaypur (87° 31' 48.57''E and 21° 37' 27.42"N) in the north for a length of about 36 km. Coastal stretches on either side of the river mouth have been assumed to be in two different littoral cells. Such an assumption was based on the idea of "fixed absolute boundaries of a cell" as proposed by Malcolm *et al*. (1995)[26]. Littoral sediment cells located adjacent to the river mouth have been named LCLS (Littoral Cell to the Left of Subarnarekha) and LCRS (Littoral Cell to the Right of Subarnarekha)
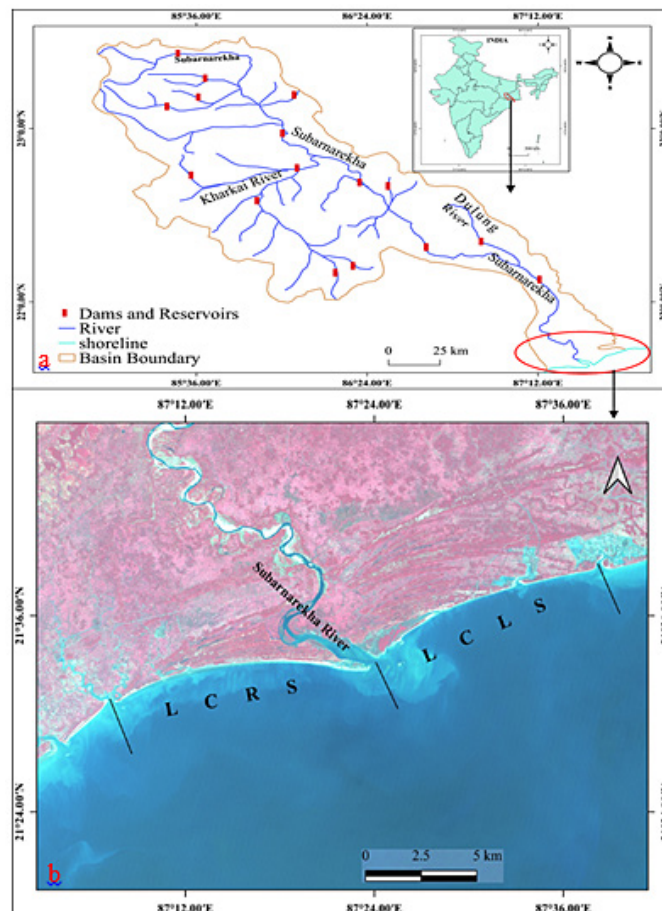
Fig.1: Location of study area (a) Subarnarekha Basin (b) Subarnarekha coast with two littoral cells (Littoral Cell to the Left of Subarnarekha mouth, LCLS and Littoral Cell to the Right of Subarnarekha mouth, LCRS)

Materials and Methods

Time series data on annual sediment load has been collected from the "Water Year Book" published by Hydrological Observation Circle, Bhubaneswar (Ministry of Water Resource, River Development & Ganga Rejuvenation, Govt. of India). Information on the number of dams in river basins and the year of completion has been collected and compiled from "National Register of Large Dams-2019", published by Dam Safety Monitoring Directorate, Central Water Commission, Govt. of India. An increase in the number of dams and a decrease in sediment influx have been examined for a period of time from 1978 to 2016.

Shifting of shorelines adjacent to the river has been detected through Landsat images for the said period of time (Table 1). Landsat images have been collected from the USGS (United States Geological Survey) website (https://glovis.usgs.gov). The selected set of images have been acquired under similar rising tidal situations and image scenes were processed with the Standard Terrain Correction (Level 1). Almost the same acquisition time of the day and similar tidal condition was basic criteria while selecting image scenes. Tidal conditions during an image scene acquisition were accounted for with the help of daily tide chart archives of the INCOIS (Indian National Centre for Ocean Information Service), an autonomous body of Govt. of India. Landsat level-1 products are precision registered and ortho rectified. It includes ground control points and a digital elevation model.[27] These products are useful for coastal mapping.[28]

Table 1: Specifications of Landsat images

Satellite	SENSOR	Grid Cell Size Reflective (Meter)	PATH/ ROW	Date of acquisition	Time (GMT+5:30)	Scene Identifier
LANDSAT-3	MSS	60	149/045	17-12-1978	03:56:38	LM31490451978153AAA03
LANDSAT-5	TM	30	139/045	23-12-1990	03:56:57	LT51390451990357ISP00
LANDSAT-7	ETM+	30	139/045	10-12-2000	04:27:42	LE71390452000345SGS00
LANDSAT-7	ETM+	30	139/045	19-12-2009	04:28:25	LE71390452009353SGS01
LANDSAT-8	OLI_TIRS	30	139/045	14-12-2016	04:37:35	LC81390452016349LGN01

For the purpose of study, the entire time duration has been sub divided into four segments (From 1978 to 1990, 1990 to 2000, 2000 to 2009 and 2009 to 2016). Such unequal sub-division of observation duration was due to availability of good quality Landsat images in those years. The year 1978 has been taken as the base year and subsequent changes in sediment load has been calculated based on average annual sediment load during a time period. As 1978 was taken as a base year, "zero" change was assigned to it. After calculating the amount of changes from one time period to another, total change was obtained by adding up all periodic changes. To make the amount of changes unit free, all amounts were converted into percentage values and the cumulative changes were determined by adding up percentage values of change from one time point to next.

Changes in sediment flux due to dam construction across the river over a period of time have been measured carefully in a way as mentioned in Table 2. "x" was taken as the average annual sediment load for a time period. To identify the change, "x1"was taken as a base year. Changes in average sediment load could be negative or positive or zero. Summation of changes would always be a positive number as modulus function ($|x|$) has been used to calculate the total changes ($|xd0, xd1…xd4|$). As a result, the percentage of total change may or may not be hundred. Similarly, while calculating cumulative changes it could be hundred percent or less than hundred depending on pattern of changes.

QGIS 3.14 "Pi '' has been used to process Landsat data to derive shoreline and quantifying changes. Individual Landsat bands were stacked together by using the "Virtual Raster" function in QGIS 3.14 "Pi" to develop multispectral images. Interpretability of multispectral images have been enhanced by using "band rendering" and "contrast enhancement" and "colour rendering" tools in QGIS (Fig 2a).

Normalised Differences Water Index (NDWI) function[29] has been applied to Landsat images to differentiate between land and water in satellite images.

Table 2: Methods applied to derive cumulative percentage of change

x	Changes in x (xd)	% xd (x)	Cumulative % of x'
x1	xd0=0	x0=∑│xd0,xd1…xd4│/100×xd0	x' 0
x2	xd1=x1-x2	x1=∑│xd0,xd1…xd4│/100×xd1	x' 0+x'1
x3	xd2=x3-x2	x2=∑│xd0,xd1…xd4│/100×xd2	x' 0+x' 1+x'2
x4	xd3=x4-x3	x3=∑│xd0,xd1…xd4│/100×xd3	x' 0+x' 1+x' 2+x'3
x5	xd4=x5-x4	x4=∑ │xd0,xd1…xd4│/100×xd4	x^' 0+x^' 1+x^' 2+x^' 3+x'4
Total	∑│xd0,xd1…xd4│	∑ x0,x1…x4	
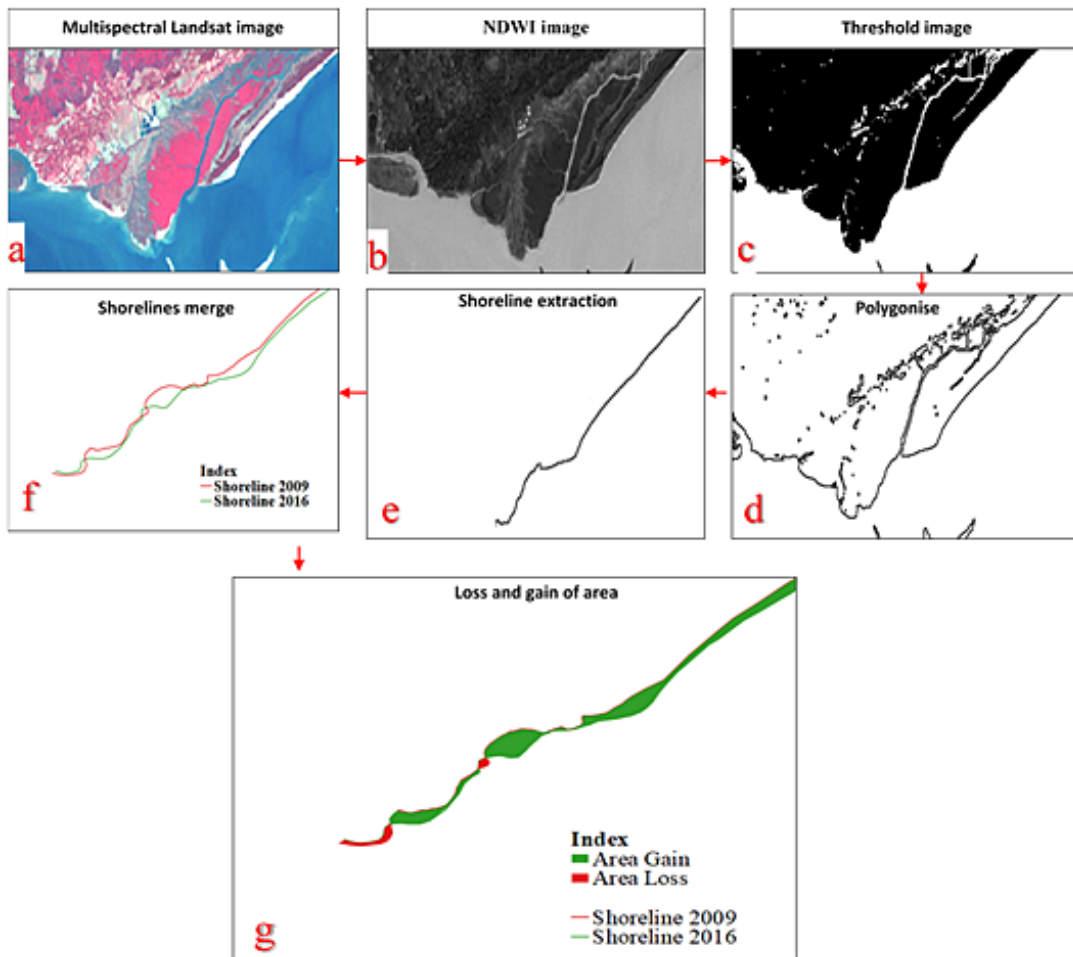
Fig. 2 (a) Multispectral Landsat image, (b) NDWI image, (c) Threshold image, (d) Polygonise, (e) Shoreline extraction, (f) Shorelines of two different dates merge together (g) Loss and gain of area during a period of time

NDWI=(Green – NIR)(Green + NIR)

Equation for NDWI was written in "Field calculator" of QGIS and the multi spectral images were transformed into NDWI (Fig. 2b). Band-1 and band-3 of Landsat-4 MSS (Multispectral Scanner) have been used as green and NIR respectively to generate NDWI images. For the Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) of Landsat 5, band-2 and band-4 have used for the same purpose. Selection of those bands (to be used as green and NIR) was based on the wave length of the bands. Information on band wave length has been derived from the USGS website (https://glovis.usgs.gov).

Image thres holding by raster calculator was performed to make land and water boundaries more clearly identifiable (Fig. 2c). Pixel values less than zero (< 0) are assigned zero and rest of the pixels are assigned one (zero for land and one for water). Output images after thres holding were transformed into vector format through "polygonise (Raster to Vector)" tool in QGIS (Fig. 2d). Polygon features were then converted into line and except shorelines all others features were eliminated (Fig. 2e). After extracting the shorelines, "merge" tool in QGIS was used to unite shorelines of two different dates (Fig. 2f). Ends of shorelines were closed by adding line features and again converted into polygon by "polygonise" tool to calculate areal loss or gain along the shoreline (Fig. 2g).

Based on such differentiation, shorelines of different dates have been detected and extracted from the image as line vectors. Shorelines of different dates were superimposed to calculate loss and gain of land due to erosion and accretion along the shoreline during a specific time segment. The geometric function in the Field Calculator of QGIS has been used to calculate areal loss and gain. All maps were prepared in Layout of QGIS and line graphs in MS Excel professional 2013.

Table 3: Dams and sediment discharge in Subarnarekha basin

Year	Cumulative Time Period	No. of Dam	% of growth	Cumulative % of Growth	Avg. Annual Load (M.T)	% of Changes in Avg. Annual Load	Cumulative % of Changes in Avg. Annual Load
1978	0	0	0.00	0.00	7486769	0.00	0.00
1990	12	21	87.5	87.50	3911678	-55.61	-55.61
2000	22	0	0.00	87.50	3406113	-7.86	-63.47
2009	31	2	8.33	95.83	2803126	-9.38	-72.85
2016	38	1	4.17	100.00	1057624	-27.15	-100.00
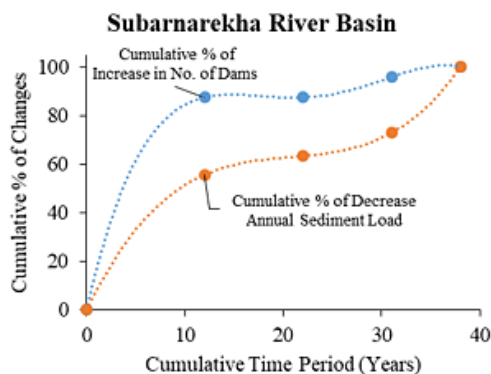
**Fig. 3 : Impact of river dam on sediment load**

Results

It is evident that the decrease in sediment influx was in tune with the increasing number of dams. During the entire time period from 1978 to 2016, suspended sediment load has decreased. Although there was no new dam recorded between 1990 and 2000, sediment discharge has been reduced by 7.86 percent. Such reduction may be viewed as an after-effect of dams which were constructed before 1990 (Table 3). Again, with the increase of the number of dams from 2000, suspended sediment load started to decrease (Fig. 3.).

A cumulative analysis of littoral cells on either side of Subarnarekha mouth was performed to relate coastal changes with decreasing sediment influx to the shore. It was observed that LCLS lost area and shoreline moved back towards land on account of net cumulative erosion over an area of 0.97 km^2 whereas LCRS accumulated sediment and shoreline advanced towards sea on account of net cumulative accretion over an area of 3.97 km^2. LCLS was dominated by erosional activities from 1990 to 2009 (Fig. 4b). A reverse trend has been noted since 2009 (Fig. 4c). Although loss of area

was not regained completely between 2009 and 2016 (Fig 4d). On the other hand, a significant loss of area (1.55 km^2) in LCRS has been noted from 1978 to 1990 (Fig 4a). Such an erosional trend had been replaced with accretion in from 1990 to 2000 when n*et a*rea increased maximum (5.18 km^2). Such a change in LCRS was contrary to the direction of change in LCLS during the same time. Net loss of area in LCRS from 1978 to 1990 and 2000 to 2009 was adjusted by deposition during the rest of the time. By the end of 2016 this cell gained an area of 3.97 km^2 with respect to base year (Table 4).

Table 4: Cumulative net area change in LCLS and LCRS between 1978 and 2016

Date	Time period (Years)	Cumulative time period (Years)	LCLS		LCRS	
			Net areal changes (km2)	Cumulative net areal changes (km2)	Net areal changes (km2)	Cumulative net areal changes (km2)
1978	0	0	0.0000	0.0000	0.0000	0.0000
1990	12	12	0.2077	0.2077	-1.5481	-1.5481
2000	10	22	-1.0957	-0.8881	5.1801	3.6320
2009	9	31	-1.0247	-1.9128	-1.9532	1.6788
2016	7	38	0.9403	-0.9725	2.2909	3.9696
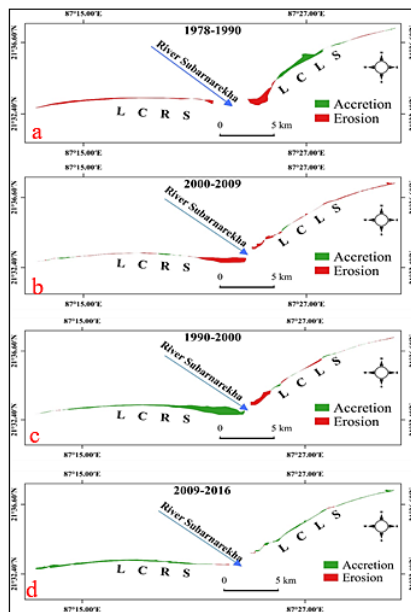
Fig. 4 : Erosion and accretion along the shoreline during different periods of time (a) 1978-1990, (b) 1990-2000, (c) 2000-2009, (d) 2009-2016

Absolute values of areal changes along the shoreline have been converted into unit free value i.e. percentage (Table 5) to detect coastal response to decreasing influx. It has been observed that response of LCLS is more in tune with decreasing sediment load (Fig. 5). From 1978 to 2016 sediment load decreased continuously while loss of area in LCLS was detected only between 1990 and 2009. However, in LCRS n*et a*rea was added between 1978 and 2016 (net cumulative 36 percent of total Change due to more accretion than erosion). Thus, changes in sediment load in Subarnarekha remain unrelated to the changes in this cell for the entire time duration (from 1978 to 2016). Although, periodic break up indicates that loss of area in LCRS surpasses area gain by accretion between 1978 and 1990 and between 2000 and 2009.

Discussion
Differential response of littoral cells in terms of areal changes may be attributed to seasonal reversal of longshore current (Fig. 6). Coastal

current in the western margin of Bay of Bengal (BoB) become northerly under the South-West Monsoon (S-E Monsoon) regime and southerly under North-East Monsoon (N-E Monsoon) regime.[30-31] River Subarnarekha being a rain-fed river, brings maximum sediment to the coast during summer monsoon (June to August) which is a rainy season in India. River sediment carried away by northerly coastal current and influences the sediment budget of LCLS. On the other hand, southerly coastal currents (During the months of November to January which are cold and dry) have much less amount of sediment to carry and influence the sediment budget of LCRS. Thus, geomorphic evolution of this cell may be assumed as independent of sediment influx from river mouth.

Table 5: Net changes in area along the shoreline in response to decreasing sediment influx

| Year | Cumulative Time Period | Net Changes in Area along the shoreline due to erosion or accretion | | | |
| | | LCLS | | LCRS | |
		% of Net Change	Cumulative % of net Change	% of net Change	Cumulative % of net change
1978	0	0	0	0	0
1990	12	6.35	6.35	-14.11	-14.11
2000	22	-33.52	-27.17	47.21	33.1
2009	31	-31.35	-58.52	-17.8	15.3
2016	38	28.77	-29.75	20.88	36.18
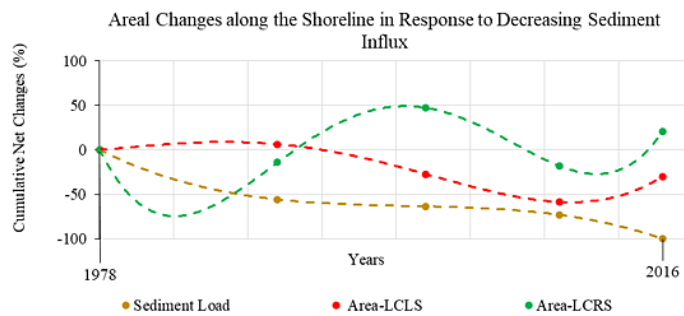
Fig. 5 : Coastal response to decreasing sediment load in Subarnarekha

In addition to long shore coastal currents, perpendicular components of coastal currents such as rip currents may be responsible for differential behaviour of adjacently located littoral cells. Variations in wave height and wave breaking along the shore due to undulation of shore-zone topography may give rise to rip currents. Such currents directed towards open sea and carried away suspended sediment deep into the sea.[32-34] Predominance of such current may neutralise effects of suspended sediment influx on coast.

Scientific research should pay attention to these aspects of coastal currents as further steps towards assessing impact of dams on the coastal morphology through reduction in sediment influx to the coast.

Investigations into the impacts of dams on coastal environments primarily had a geomorphological focus. This study attempted to address the indirect effects of dam on shoreline shifting and consequent areal changes along the littoral cells adjacent to river mouth. There have been relatively few studies that have addressed the causal relationship between dams and areal changes in littoral cells in response to damming.
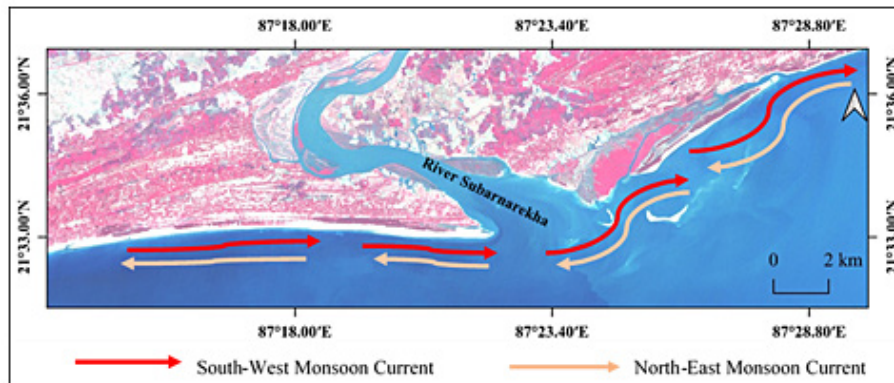
Fig. 6 : Seasonal reversal of coastal currents under the prevailing South-West and North-East monsoon wind regime.

The present study found that the coastal response to decreasing sediment influx is not uniform. Different parts of the coast respond at varying degrees. Study reveals that reduction in sediment influx does not necessarily lead to coastal erosion. Shoreline shifting and consequent area loss and gain depends upon a number of factors like sea level changes, river mouth shifting, longshore drift and construction of port and harbours etc. 35-36. Reduction in suspended sediment influx could be an important factor in controlling shoreline changes and consequent area loss and gain in a littoral cell but it cannot be taken as the single most important factor. However, as the present study relies upon Landsat images which provides very coarse resolution (30 m), it is difficult to capture any sub-meter level changes along the coast. With the availability of sub-meter level data with more temporal frequency may reveal more minute changes.

There is a pressing need to measure not only areal changes in littoral cells but also other factors which control the morphological evolution of the coast. The role of Regional Sea Level Rise (RSLR) in altering or moderating coastal morphodynamic processes is also very poorly understood and needs to be studied in connection with decreasing sediment influx. A number of observations need to be increased to provide new insight into how coastal processes respond to upstream dam construction.

Conflict of Interest
The authors declare that they have no conflict of interest.

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