Automatic shoreline detection and future prediction: A case study on Puri Coast, Bay of Bengal, India

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Abstract
Shoreline prediction models have the capability of integrating geoinformatics within them. The present study is conducted on the 142 km-long coastline of Puri district, India. It aims to analyze the change in coastline due to erosion/accretion and provide best estimate of future shoreline positions based on past shorelines. A simple mathematical model, End Point Rate (EPR), has been used to calculate the rate of change of shoreline and its future positions, based on empirical observations. The erosional/accretional scenario has also been analysed by delineating the shoreline from Landsat imageries of 1972, 2001 and 2010. It is found that the northern part of Puri, in the vicinity of Kushabhadra estuary and Chandrabhaga beach undergo high rates of erosion. Based on the delineated shoreline, the short term (2015) and long term (2025) shoreline positions have been predicted.

Keywords: Shoreline prediction, EPR model, erosion, Puri, Orissa, India.

Introduction
The coast is a highly dynamic environment with many physical processes, such as tidal fluctuations, wave and longshore current, littoral cell circulation, ridge and runnel system and rip currents. These processes play an important role in modifying the coast and shoreline changes. Shoreline is the line of contact between land and sea and its nature is dynamic [Cui and Li, 2011]. Shoreline change is considered one of the most dynamic processes and the change in shoreline, due to physical as well as anthropogenic processes, has large environmental significance [Chen et al., 2005]. Detection of shoreline change, the rate of positional change and future prediction play an important role in any coastal zone management such as hazard zonation, island development studies, marine transport,
Shoreline change is the direct result of coastal erosion / accretion, the effect of nearshore currents. With respect to the sediment supply, a given length of coastline may have surplus, be in balance, or have a deficit in its sediment budget. A large scale reduction or increase in the sediment supply, in a short period of time or a long period, creates a deficit/surplus in the sediment budget which causes shoreline change.

Multi-year shoreline mapping is considered to be a valuable task for coastal monitoring and assessment. In recent years, satellite remote sensing data in conjunction with Geographic Information System (GIS) is being used in shoreline extraction and mapping [Lee and Jurkevich, 1990; White and El Asmar., 1999, Bertacchini and Capra, 2010]. Several studies have already been done on shoreline change and prediction, such as empirical analysis relating to hard stabilization structures to beach dynamics [Wright and Pilkey, 1989; Basco, 1991], analysis of natural beach loss and gain [Paine and Morton, 1989], identification of relative changes among coastal units [Siddiqui and Maajid, 2004], process response of a shoreline [Fenster et al., 1993]. Change in shoreline and rate of change of shoreline position has also been predicted by various studies. The common process in this regard includes field observations such as tide and wave measurements, detection and comparison of shoreline from toposheets, aerial photographs and multi date satellite imageries. Several models have been proposed for prediction of shoreline from comparison with historical data such as End Point Rate (EPR) model [Fenster et al., 1991], Average of Rates (AOR), Linear Regression (LR) and Jackknife (JK) [Dolan et al., 1991]. The EPR model is based on the assumption that observed historical rate of change is the best estimate available for predicting future while LR model is based on robust linear prediction method in order to detect short term changes in the long term trend. This process identifies the linear and high-order polynomial model which best fits the data according to that Minimum Description Length (MDL) criterion that discovers the regularities in observed data. The length of the data by which the data itself can be described is used for measuring such regularities [Rissanen, 1978].

Prediction of future coastlines, from multi-temporal satellite images, using these models are dependent on several influencing factors like accuracy of shoreline detection (accuracy of satellite data and method used), time duration of shoreline data acquisition, number of data points taken into consideration during the measurement of shoreline position and temporal variability of shoreline etc. [Douglas and Crowell, 2000; Maiti and Bhattacharya 2009].

Spatial modelling along with efficient temporal representation of the dynamic coastal environment is a very demanding and challenging research. A wide range of applications can be made possible with the accurate estimation of historical shoreline change rates. The calculations involved in the trend analysis of the shoreline are very complex due to spatio-temporal variability. Future shoreline prediction models are essential to effectively determine the changes in the coastline and to allow us to keep the structural and financial losses in the coastal region. In this process, it is necessary to create a digital database of historical shoreline position, implementation of standardized remote sensing and GIS technology as well as create a data inventory that can be used to facilitate current and future analyses of shoreline change. In this study, an attempt has been made to evaluate an analytical model for predicting the future shoreline in order to monitor the shoreline change along the coast in Puri district of Orissa, India.
Study area and data set
Accelerated rate of erosion of the beach at Puri has been a matter of recent investigation by the researchers. The present study is conducted in the 142 km long coastal area (19° 25’ 50.42” N / 85° 07’ 23.58” E to 20° 00’ 29.13” N/86° 24’ 55.20” E) of Puri district, Orissa (Fig. 1). This coastal area has various geographical and geological divisions, on the basis of the available rock types, soil, vegetation, water bodies and climate. The study area falls under the tropical monsoon climate type with mean annual temperature of 27° C which varies between 37°C to 13°C. The mean monthly rainfall is 120mm, maximum rainfall occurs during the monsoon period (June – October) and the average wind speed is 16.5 km/h (Indian Meteorological Department).

The variation of annual average high and low tide height is 2.31 and 1.08 m (2009) respectively. The mean monthly tide height variation in the year 2009 has been shown in (Fig. 2). The whole district may be divided into two distinct natural divisions - the littoral track and the alluvial track. Inland dunes and barriers are found along the sea coast, which stretches into the districts of Jagatsingpur and Ganjam. One such sandy spit divides the Lake Chilka from Bay of Bengal. These sandy ridges and dunes are by the strong monsoon
current which blows over the area for nearly eight months of the year. The ridges vary from few meters to 7 km in width and prevent most of the rivers of the district from finding their way into the ocean. Being a part of coastal Orissa, the area is famous for its historical antiquities, architectural grandeur and sea-scape beauty.

Three satellite data were taken into consideration spanning over 38 year time period (1972 – 2010). Multi resolution satellite data such as Landsat MSS and Landsat TM-5 are used in this study because of the unavailability of same resolution imagery over the chosen period. The details of the satellite imagery, acquisition details and resolutions are given in the Table 1.

Table1 - Details of satellite data, date of acquisition and resolution.

| Satellite and Sensor | Date of acquisition | Path/ Row | Band used         | Spatial resolution |
|----------------------|---------------------|-----------|-------------------|--------------------|
| LANDSAT MSS          | 1972-11-07          | 150/046   | Visible and NIR   | 60m                |
| LANDSAT TM           | 2001-11-29          | 140/046   | Visible and NIR   | 30m                |
| LANDSAT TM           | 2010/1/19           | 140/046   | Visible and NIR   | 30m                |

Methodology
The methodology adopted in this study to delineate the shoreline and future position prediction is given in the sequential manner as follows:

Data processing
Three satellite imageries of the years 1972, 2001 and 2010 have been taken into consideration in this study. Landsat MSS and TM-5 data sets have been acquired from USGS [website...
http://glovis.usgs.gov]. Landsat MSS image of 1972 has been resampled to 30m to match
the spatial resolution of Landsat TM-5 images of 2001 and 2010. All the data sets are
projected in UTM projection with zone no 44 and WGS 84 datum. The MSS imagery of
1972 has been considered as base data and TM-5 image of 2001 and 2010 have been co-
registered using first order polynomial model with base data with 0.5 pixel Root Mean
Square Error (RMSE) accuracy.

**Shoreline delineation**
Automatic shoreline delineation is a complex process due to the presence of water saturated
zone at the land-water boundary [Ryu et al., 2002; Maiti and Bhattacharya, 2009]. In order to
determine the actual coastline position, two methods have been explored- image classification
and vegetation indexing. The histograms of MSS and TM images have been found to be bimodal
in nature with two different peaks for land and water. Based on the histogram observation, images
have been classified using the ISODATA classification (Unsupervised) technique and two classes
(land, water) have been taken to demarcate the land water interface. In the vegetation indexing
processes, Normalized Difference Vegetation Index (NDVI) has been used to differentiate the
land water boundary. The pixels representing the shoreline have been converted into vector
layer to get the actual coastline. The coastline (year 2010) obtained by the above method has
been compared with the 40 ground survey points (taken from the field with the help of GPS).

**Shoreline prediction using EPR model**
Open ocean shorelines undergo both erosion and accretion over a wide range of spatio-
temporal scales. The prediction accuracy of shoreline position depends on the historical
processes (assumed to be captured by shoreline sample data) and gives the best information
regarding future shoreline locations. In coastline analysis research, extrapolation of a
constant rate of change is the most commonly used method to predict the shoreline [Eliot
and Clarke, 1989]. Shoreline position change rates are frequently applied to summarize
the historical shoreline movements and their future prediction. Several methods have been
used for prediction of shoreline position as a function of time, rate of erosion and deposition
or sea-level rise such as non-linear mathematical models e.g. higher order polynomial,
exponential model, cyclic series models [Li et al., 2001]. Among them, the most simple and
useful ones are the End Point Rate (EPR) and the Linear Regression (LR) models. In the
present study, the EPR model has been adopted to predict the future shoreline. The model
is based on the assumption that the observed periodical rate of change of shoreline position
is the best estimate for prediction of the future shoreline [Fenster et al., 1993] and no prior
knowledge regarding the sediment transport or wave interference is required because the
cumulative effect of all the underlined processes is assumed to be captured in the position
history [Li et al., 2001]. The position of the future shoreline for a given data is estimated
using the rate of shoreline movement (slope), time interval between observed and predicted
shoreline and model intercept which can be expressed as

\[
\text{Shoreline Position} = \text{Slope} \times \text{Time interval} + \text{Intercept} \quad [1]
\]

The mathematical structure of the model which is necessary for model calibration is
described in the following manner.
Step-1: The EPR model utilizes the shoreline extracted from the two end points of satellite imageries, the earliest ($Y_1$) and the recent positions ($Y_2$). If we use $\overline{Y}$ to denote predicted shoreline positions, $X$ for time interval / date, $B$ for model intercept and $m_{EPR}$ for the rate of shoreline change, then the [1] can be written as

$$\overline{Y} = m_{EPR} \times X + B_{EPR} \quad [2]$$

Step-2: The rate of shoreline movement for a given set of samples, $m_{EPR}$ can be calculated as

$$m_{EPR} = (Y_i - Y_j) / (X_2 - X_1) \quad [3]$$

Step-3: $EPR$ intercept can be calculated as

$$B_{EPR} = Y_i - (m_{EPR} \times X_i) = Y_i - (m_{EPR} \times X_i) \quad [4]$$

Step-4: Since the end point line can extend beyond the most recent point ($t$), [2] can be rewritten to use that position ($Y_2$) and the elapsed time ($X_i - X_2$)

$$\overline{Y}_i = m_{EPR} \times (X_i - X_2) + Y_2 \quad [5]$$

Hence, the shorelines extracted from 1972, 2001 and 2010 images are segmented into 250m interval and the location of the midpoint of each segments are sampled for the entire 142 km Puri shoreline. The UTM coordinates(x and y) for each sample point were used to calculate $m_{EPR}$ for both x and y locations of each point. Initially, the model was calibrated based on 1972 and 2001 shoreline sample and the rate of movement ($m_{EPR}$) was calculated to predict the shoreline of 2010. Then the model was again calibrated with 1972 and 2010 shoreline sample points and based on the historical position and derived shoreline change rates, the shoreline of the study area for short term (2015) and long term (2025) was predicted.

The positional shift in the model (estimated shoreline of 2010) was validated with respect to actual image (extracted shoreline of 2010). The estimated shoreline was also validated with the 40 Ground Control Points (GCPs) collected from the field during the satellite overpass time and during high tide. The validation (location error in model estimated shoreline) was carried out in terms of RMSE [6]. The location errors at each sample point can be plotted as error vectors, which have the constituents in x and y directions and the length of the average vector are measured. RMSE gives a measure of accuracy which exhibits, how far, on average, the observed values are from the assumed true value. The equations are listed below.

$$RMSE = \left[ n^{-1} \sum_{i=1}^{n} (X_{MOD} - X_{ORG})^2 + (Y_{MOD} - Y_{ORG})^2 \right]^{1/2} \quad [6]$$

Where $X_{MOD}$ and $Y_{MOD}$ are the model generated and $X_{ORG}$ and $Y_{ORG}$ are the actual x and y coordinates of the shoreline sample points.
In order to minimize the error, an experimental step has been introduced in this study. Positional shift in each sample points has been calculated by comparing the actual and estimated shoreline of 2010. The future shoreline prediction was tested by applying the error estimated at each sample points.

**Result and discussion**

*Shoreline change during the period 1972 – 2010*

The 142 km long Puri shoreline has been delineated from the satellite imageries of different years (1972, 2001 and 2010) using the vegetation cover (NDVI) and image classification technique (Fig. 3).

![Figure 3 - Shoreline detected from satellite image using NDVI and classification techniques.](image-url)
The delineated shoreline of 2010 was validated using 40 GCPs and the positional shift in each GCP is plotted in the Figure 4, which shows that classification technique does better delineation of shoreline in comparison to NDVI. The positional shift is also expressed in terms of Root Mean Square Error, which is 2.55 m and 4.62 m for the classification and NDVI techniques respectively. It has been found that the shift in the classification-detected shoreline varies from 1.4 to 3.75 m while in NDVI the shift varied from 2.0 to 9.31 m. Based on this analysis, classification technique for delineating shoreline has been used for all other application.

It has also been found that the coast line of Puri is experiencing erosion. Figure 5 shows the shifting of coast-line inland. Figure 6 also shows the erosional scenario of Puri coast for the period from 1972 to 2010 indicating significant erosion in the northern part of the coast line (near Kusabhadra River estuary) whereas southern part (near Chilka and Puri City) is considerably stable.

![Positional shift in image delineated shoreline from GCPs](image)

**Figure 4 - Positional shift in NDVI and classification technique with respect to GCPs.**

It has been observed that the annual net longshore sediment transport rate (LSTR) is 940000 cubic meter / year at Gopalpur and Puri towards north, which corroborates with observed data between Prayagi and Puri. The gross LSTR is about 1000000 cubic metre / year along south Orissa.

**Validation of EPR model**

The End Point Rate (EPR) model has been used for estimating the future shoreline. But before the prediction of future shoreline, the model has been validated with the present scenario. The rate of shoreline movement calculated from shoreline position in 1972 and 2001 was applied and based on this, the estimated shoreline of 2010 was calculated. The estimated shoreline was compared with the actual shoreline delineated from satellite imagery of 2010. The model error or positional shift at each sample points is shown in the Figure 6. The positional error varies from -3.70 m to 239.41 m. It has been found that model prediction error is higher in the central and southern part.
of the coast line. The overall error for the entire predicted shoreline was found to be 51.34 m (RMSE).

**Future shoreline prediction using EPR model and error adjustment**

Using the EPR model, the shoreline of the study area has been predicted for short term (2015) and long term (2025). In this prediction, shoreline change rate has been computed from historical observations and catastrophic impacts like tsunami and storm have not been considered. Figure 7 shows the past, present and future shorelines.

![Figure 5 - Shifting of shoreline inside the coast.](image)

The predicted shoreline indicates that the maximum erosion will take place in the northern part and no significant change will occur in rest of the study area. The same observation was found in the change scenario (Fig. 8) of shoreline from 1972 to 2010, which suggests that the cumulative effect of various processes like sediment transport system, littoral process, which is captured in the observed rate of change is relevant to predict the future shoreline. An error adjustment procedure of EPR model has been proposed in this study. The positional shifts in $x$ and $y$ direction were calculated by comparing the actual and estimated shoreline of 2010. The calculated shift was applied or adjusted to predict the future shoreline of 2015 and 2025. The shift adjusted shoreline is shown in the Figure 9.
Figure 6 - Positional shift in between actual and estimated shorelines of 2010.

Figure 7 - Past, present and future (predicted) shorelines of Puri.

Conclusion
Analysis of the obtained results suggests that the use of remote sensing data with the integration of GIS technology is very suitable for extraction of shoreline and change detection. Simple ISODATA binary classification technique is useful for delineation of shoreline. The spatial modeling along with temporal representation of dynamic coastline of Puri district signifies that the coastline is suffering erosion and it has shifted inside. The magnitude of erosion is higher in the northern part of the coastline in the area of Kusabhadra river estuary and Chandrabhaga beach which is seen from the imagery of 1972 to 2010 and the model predicted shoreline also depicts the same.
Figure 8 - Erosional scenario of Puri shoreline from 1972 to 2010. The red colour depicts erosion, which is maximum in the north east part of the beach.

Figure 9 - Error adjusted shorelines of 2015 and 2025.
The southern part of the shoreline near Chilika and Puri is considerably stable, indicated by the same model. The validation of EPR model with image delineated shoreline was found to be useful. The cross validation shows that the model can predict reliable estimate of the shoreline position with acceptable accuracy. The trend of the future shoreline is matched with the present scenario.

Further study can be carried out based on high resolution satellite data in which shoreline detection will be more detailed. EPR model has been used in this study but comparison of different models like Linear Regression (LR) & Average of Rates (AOR) etc. for shoreline prediction and its validation can be carried out. The modification of EPR model can also be worked out for future shoreline prediction. A procedure for adjustment of model error is suggested in this paper which can be validated to understand its effectiveness.

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