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Akhil Kallepalli
Nageswara Rao Kakani
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Digital shoreline analysis system-based change detection along the highly eroding Krishna–Godavari delta front

Akhil Kallepalli,[a,*] Nageswara Rao Kakani,[b] David B. James,[a] and Mark A. Richardson[a]

[a]Cranfield University, Centre for Electronic Warfare, Information, and Cyber, Shrivenham, United Kingdom

[b]Andhra University College of Engineering, Department of Geo-Engineering, Visakhapatnam, India

Abstract. Coastal regions are highly vulnerable to rising sea levels due to global warming. Previous Intergovernmental Panel on Climate Change (2013) predictions of 26 to 82 cm global sea level rise are now considered conservative. Subsequent investigations predict much higher levels which would displace 10% of the world's population living less than 10 m above sea level. Remote sensing and GIS technologies form the mainstay of models on coastal retreat and inundation to future sea-level rise. This study estimates the varying trends along the Krishna–Godavari (K–G) delta region. The rate of shoreline shift along the 330-km long K–G delta coast was estimated using satellite images between 1977 and 2008. With reference to a selected baseline from along an inland position, end point rate and net shoreline movement were calculated using a GIS-based digital shoreline analysis system. The results indicated a net loss of about 42.1 km^2 area during this 31-year period, which is in agreement with previous literature. Considering the nature of landforms and EPR, the future hazard line (or coastline) is predicted for the area; the predication indicates a net erosion of about 57.6 km^2 along the K–G delta coast by 2050 AD. © *2017 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.JRS.11.036018]

Keywords: shoreline change; sea level rise; hazard line demarcation; coastal zone management; coastal erosion; global warming.

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1 Introduction

Global warming, one of the consequences of climate change, caused due to increased carbon dioxide emissions, is increasing the threat of sea level rise. This, in turn, affects the delicate balance of coastal ecosystems and livelihood. Continued sea level rise is heavily dependent on the sustenance of these emissions.[1] Locally, any increases are dependent on land conditions; for example, sea level rise impact would be greater for a region experiencing land subsidence.[2] The global warming trend over the past 50 years was reported by the Intergovernmental Panel on Climate Change (IPCC) to be in the order of 0.13°C per decade.[3] Global sea level has been observed to rise at a rate of 1.8 mm/year over the period from 1961 to 2003 and an accelerated rate of 3.1 mm/year over the period through 1993 to 2003 as a response to global temperature rise.[4] Although IPCC 2007 estimated a rise of about 59 cm, subsequent semiempirical models using the past sea levels and temperature data suggested a rise greater than 1 m by 2100 AD.[5] More recent estimates by the IPCC (2013)[1] have classified the possibility of increase as "very likely." The immediate implication of increased global warming due to variation in temperatures[1,6] directly relates to rise of the sea level. The paleo-sea level from periods warmer than the current time has evidently been 5 m higher,[1] indicative of the impact of disturbance on the balance of the quantity of water on the Earth.

*Address all correspondence to: Akhil Kallepalli, E-mail: a.kallepalli@cranfield.ac.uk

The effects of worldwide sea level rise will be spatially nonuniform. First, global sea level changes are superimposed on local vertical crustal movement (e.g., an area where land is rising is at less risk when compared to regions that are subsiding) to assess its landward impact. Second, characteristics of any shoreline depend on the interaction of the sea with the various landforms of the coast[2] whether it is lithological, structural, or any other characteristic that has an impact on the rate of sea level rise locally. Therefore, it is imperative that studies should be made in order to assess the relative vulnerability of different sectors of the coast, taking into consideration the various features and phenomena that characterize the coastal sector in question. Many attempts[7–10] have been made in this direction from different parts of the world using different methods.

This study is an assessment of the vulnerability of the Krishna–Godavari (K–G) delta coast along the east coast of India using the Digital Shoreline Analysis System (DSAS).[11] The vulnerability of the coast is the susceptibility of the coastal landforms to the changing sea levels. The study also predicts a future coast line, known as the hazard line, to 2050 AD. The novelty that this research conveys is an application-based method using the tools of GIS to extrapolate a future coastline. The simplistic method of shoreline change quantification and flexibility of utilizing additional information in future research adds to the variety of coastline modeling literature.

2 Study Area

The twin delta system of the Krishna and Godavari rivers, draining the catchment into the Bay of Bengal, is shown in Fig. 1. Geographically, the Godavari delta front is 170 km, compared to 140 km of the Krishna delta. These deltas and the 26-km interdelta region characterize the study area for this work.

The Godavari and Krishna rivers originate in the eastern slopes of the Western Ghats and flow across the peninsula; these are joined by multiple tributaries along the way before reaching the

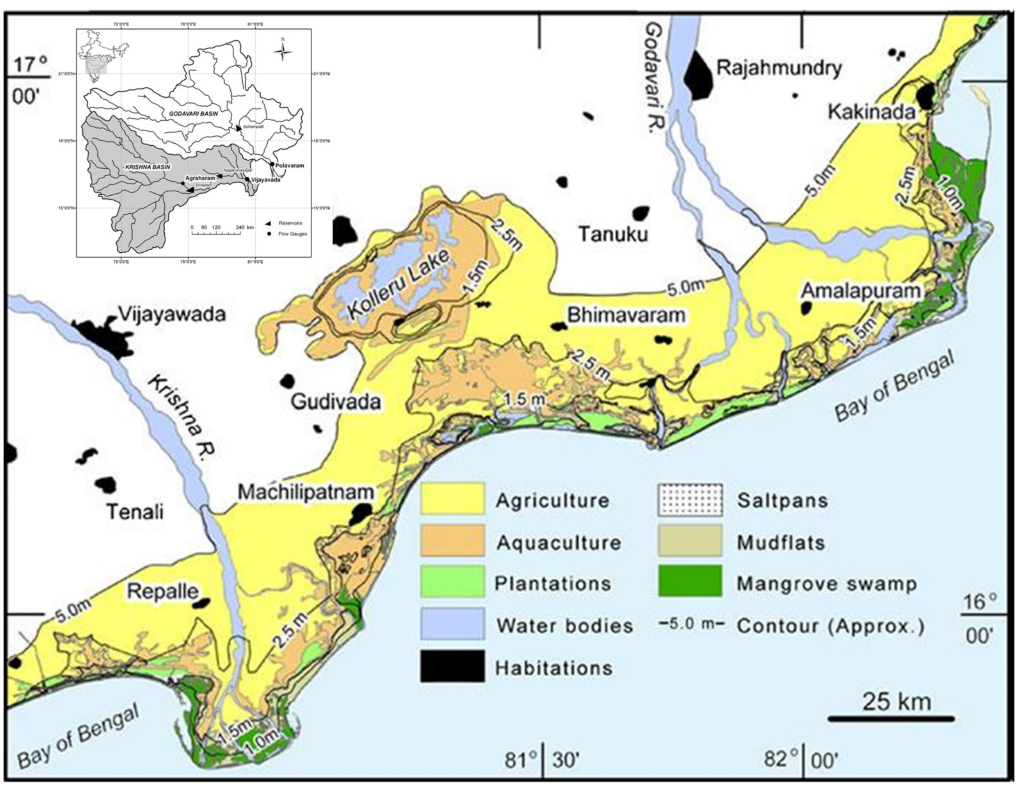

Fig. 1 Land use/land cover of study area.[12] Inset indicating the locations of the dams and reservoirs.[13]

Bay of Bengal. This semiarid region receives an average rainfall of 1100 mm in the Godavari delta[14] and 840 mm in the Krishna delta,[15] and the rivers cumulatively drain a catchment equal to the area of India. Built into a pericratonic basin, both the rivers form a contiguous and complex delta system which is known as the K–G sedimentary basin.[16,17] This twin delta complex (12,700 km^2 in area) is composed of the Godavari (5200 km^2 in area) and Krishna (4800 km^2 in area) deltas and an interdelta plain of 2700 km^2 area which is significantly influenced by the sediment flow into the deltas and the transport of these along the shore. The interdelta plain is characterized by a series of lagoons including the Kolleru Lake (a former lagoon turned into a freshwater lake, Fig. 1) and Goguleru Creek (present lagoon) separated by several beach ridges.[18,19] The varied landforms and resourceful nature indicate the potential loss to life and property due to inundation of the region.

The region experiences a marine environment influenced by relatively low-energy tidal conditions (spring tide range is <1.5 m) and low to moderate wave conditions (significant wave height is <2 m).[20] However, placed in the Bay of Bengal region that experiences frequent cyclones, this delta region is prone to severe cyclonic activity accompanied by strong waves and storm surges which reach many kilometers inland, because of its extremely low lying nature and gentle gradient. These densely populated deltas have an average population of 729 persons per square kilometer (km^2). The great loss of life and damage to property in the Godavari delta region caused by the 1990 and 1996 storm surges are evidence to the low-lying and populated nature of region.

It is also important to note the geomorphology of the coastline, as the features that fringe the study area define the erosion and deposition patterns and trends. From previous studies,[2,20] it can be understood, for example, that rocky terrains tend to obstruct erosion, while mudflats tend to erode comparatively easily. The geomorphology of the study area[20] was considered in the sections of hazard line generation after the statistical calculations of shoreline change were completed. The shoreline has various degrees of vulnerability. As mentioned before, regions of strong lithology such as Visakhapatnam are under less risk of impact due to the presence of rocky terrain, while regions that are relatively flat and have lesser obstruction to the oncoming sea impacts are at a higher risk, like the K–G delta basin, the study area in this case.[20] When considering the impacts of storm surges, which may be sudden and of short duration, or slow and long spanning erosion of deltas due to sea level rise, the K–G delta region is a vulnerable region with the majority of its area being considered to be at "high risk."[20]

3 Method of Study

This study was carried out with the tools of GIS (ArcGIS) and image processing, using multidate satellite products. Figure 2 shows the methodology adopted for this study.

The imagery was referenced to a projection system, UTM-projection, and WGS84-datum. The images were then coregistered in ArcGIS. Once the images are registered, the workflow of the study proceeds to GIS extraction of shorelines using the tools of ArcGIS. The DSAS workflow begins with construction of a baseline, mirroring the shape of the shoreline, to act as a reference for shoreline change quantification. Estimation of change statistics for the prediction of the future shoreline is carried out. The predicted shoreline, known as the hazard line, is constructed on the basis of rate of change and physical coastal conditions.

Georeferenced satellite imagery (Table 1) forms the base data for extraction of the temporal configuration of the K–G delta front shoreline during the past four decades from 1977 to 2008.

The workflow of estimation of the hazard line begins with referencing the datasets to a common datum and projection system. In the absence of a common projection system, the estimations of the shoreline would not be accurate. In this case, UTM-projection and WGS84-datum are chosen. The imagery datasets are referenced to this system before GIS demarcation of individual shorelines. The multispectral datasets are considered as false color composites for demarcation of the shorelines, as the usage of the infrared bands allows relatively easier distinction of water boundaries. The shorelines are extracted as individual line shapefiles using ArcGIS. The "date" data type must be saved in the shapefile (line vector data), as this is needed for the change statistics that DSAS[11] would utilize. DSAS, the change detection application developed by

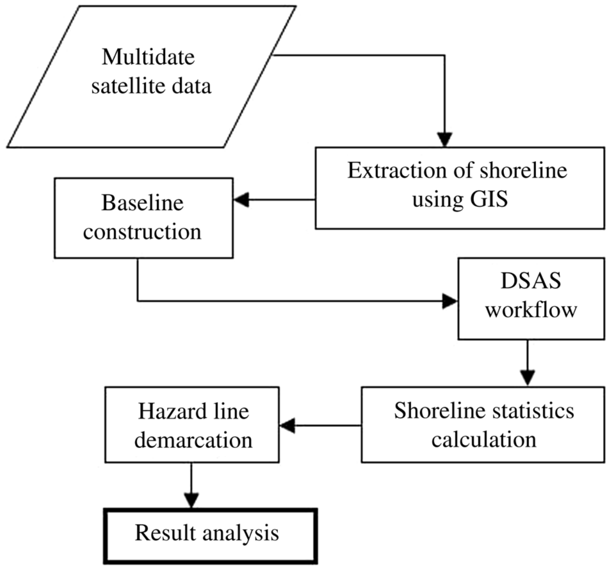

Fig. 2 Methodology flowchart.

Table 1 Satellite data used in the study.

Dataset information	Date of imagery
Landsat MSS	01-May-1977
Landsat TM	10-November-1990
Landsat ETM+	28-October-2000
IRS-P6 LISS III	13-December-2004
IRS-P6 LISS III	25-January-2006
IRS-P6 LISS III	03-March-2008

USGS, is an add-on product to ArcGIS which constructs transects from a predefined baseline for estimating shoreline changes.

The DSAS application requires an arbitrary baseline for the construction of transects. This baseline was drawn in the landward direction of the water body as the change of shorelines is the intention. In order to quantify the movement of the shoreline with respect to the standard baseline, perpendicular transects are constructed. With due consideration of past change patterns in the region,[12] the georeferenced baseline was established 2.5 km landward from the shoreline position in 1977 and used for every combination of consecutive datasets. The measuring elements of the DSAS workflow (for detailed explanation regarding the workflow, refer to Thieler et al.[11]) involve the construction and spacing of transects. The decision of the number of transects is task-specific and subjective. If the number of transects is low, the regions encountering high erosion or deposition may not have an acceptable number of transects passing through them, thereby resulting in the loss of valuable statistics of change. If the number of transects is excessive, then the density of transects through each region might be different, leading to over or under-estimation of information. Therefore, for this study, a combination of the optimal number of transects and manual validation of spacing and density of transects is performed. Simple transects are cast along the baseline at 2000 m spacing and 8000 m in length. The length of transects is not a value of concern as the change along the region of intersection is calculated, wherein the length of transects will not play any role. Due to the irregular nature of a shoreline, the transects constructed from the baseline are of different orientations. To ensure a distributed transect presence, a manual verification was carried out for the automated creation by DSAS.

Table 2 Weights of coastal geomorphology and their impacts on the erosion/deposition rates.[20]

Coastal geomorphology	Rocky coasts	Indented coasts	Beach ridges, vegetated dunes	Low dunes, estuaries, and lagoons	Mudflats, mangroves, beaches, barriers/spits
Rank	1	2	3	4	5
Degree of influence (%)	20	40	60	80	100

Shoreline statistics are pivotal in understanding the movement of the shoreline in a given time interval. This movement is an indication of the direction of change in this region. Erosion and deposition are the two main shoreline altering factors of coasts. Transects previously generated are used to generate the following statistics along the coasts of the K–G delta and interdelta region, along each transect in order to estimate a trend.

1. Net shoreline movement (NSM) reports the distance of shoreline movement. The NSM statistic is associated with the dates. It reports the distance between the oldest and youngest shorelines, with positive or negative symbols indicative of deposition or erosion.

$$\text{Net shoreline movement} = \text{distance between oldest and youngest shorelines.}$$

2. End point rate (EPR) is calculated by dividing the distance of shoreline movement by the time elapsed between the oldest and most recent shorelines. The major advantage of the EPR is the ease of computation and minimal requirement of two shoreline dates.

$$\begin{aligned}&\text{End point rate}\\&\quad = [\text{distance(NSM)in meters}]/(\text{time between oldest and most recent shorelines}).\end{aligned}$$

While the knowledge of change is established by EPR, it is vital to account for the encountered landforms on the coastline. A trend of high erosion in a location where the morphology is that of a marshland would change if it encountered a rocky terrain within the time frame of this study. The hazard line in this study is to be estimated to 2050, and under this time frame, the erosion trend encounters a single morphology only. In order to estimate their impacts, a linear relationship between the rate of erosion/deposition is assumed with the rank of the terrain. A geomorphological feature like rocky cliffs along the coastline would be attributed a rank of 1, while highly eroding and unstable features like mudflats would be attributed a rank of 5.[20] The corresponding ranks were given to the geomorphological features and the erosion and deposition patterns were extrapolated along these features, with their respective weights (Table 2). It must be noted that these weights are study area specific, and with a change of study area, an investigation of coastal morphology is vital.

The shoreline is divided into sectors of erosion and deposition depending on the change statistics. Multiplying the degree of influence of each encountered geomorphology along the coast, the movement of the coastline was extrapolated to 2050 and the hazard line (shoreline at a future date) is drawn. Using a polygon-based area calculation, the loss and gain of land due to erosion and deposition along the K–G delta can be calculated.

4 Results

The shoreline change statistics calculated are NSM and EPR. It is to be noted that NSM gives the amount of change with respect to time and EPR calculates the rate of change. In the context of the current study where the hazard line demarcation and the estimation of change to a future date are being examined, EPR stands out as the most important. Therefore, further analyses (trend investigation and hazard line construction) are done using EPR. The statistics, along all transects cumulatively, are presented in Table 3.

Table 3 EPR statistics for 1977 to 2008.

Period	Krishna delta			Interdelta region			Godavari delta		
	Min	Max	Net	Min	Max	Net	Min	Max	Net
1977 to 1990	−62.34	32.07	**−13.99**	−18.4	28.85	**−2.42**	−148.7	77.25	**−3.85**
1990 to 2000	−41.1	166.26	**7.21**	−27.52	48.79	**2.73**	−107.6	35.77	**−0.33**
2000 to 2004	−154.1	132.74	**12.23**	34.84	89.05	**60.26**	60.03	134.81	**45.25**
2004 to 2006	−502.5	411.1	**−122.5**	−122.5	144.37	**−23.53**	−389.4	979.2	**−40.58**
2006 to 2008	−234.6	189.49	**50.45**	−74.18	64.61	**−6.16**	−505.7	219.4	**30.49**
1977 to **2008**	**−32.06**	**87.62**	**−1.72**	**−25.53**	**26.87**	**1.75**	**−101.9**	**39.07**	**−3.32**

The nomenclature of the table statistics: the minimum column is indicative of the least occurrence of the phenomenon (erosion or deposition), whereas the maximum indicates the opposite. The negative sign (−) indicates erosion, whereas the positive (+) indicates deposition, with net EPR illustrated along all transects in the entire study area. Although EPR measurement is at individual locations, it is a dependable source of information as it is estimated from well distributed transects in all sectors along the study area.

Periodical analysis of trends along the transects indicates the variations of erosion and deposition in different sectors of the study area. The entire region has experienced a significant amount of erosion during the 2004 to 2006 period, due to the tsunami of December 2004. The imagery of 2004 (before the tsunami) and the subsequent dataset of 2006 provide an insight into the localized impact of the tsunami. In summary, however, it is noted that the Krishna and Godavari deltas are impacted severely by the forces of the sea, and the shoreline movement is erosion and incursion-dominant. Deposition in the interdelta plain is attributed to alongshore sediment movement and to the “bay-like” configuration of the delta combination. The results are presented as proceeding from the Godavari delta, through the interdelta plain, to the Krishna delta. The graphs also present the nature of change (erosion or deposition) with a legend indicating the amount of shoreline movement.

During the period from 1977 to 1990, the region predominantly experienced erosion. The NSM was landward (Fig. 3 and Table 3), indicating erosion in all sectors, including an erosion

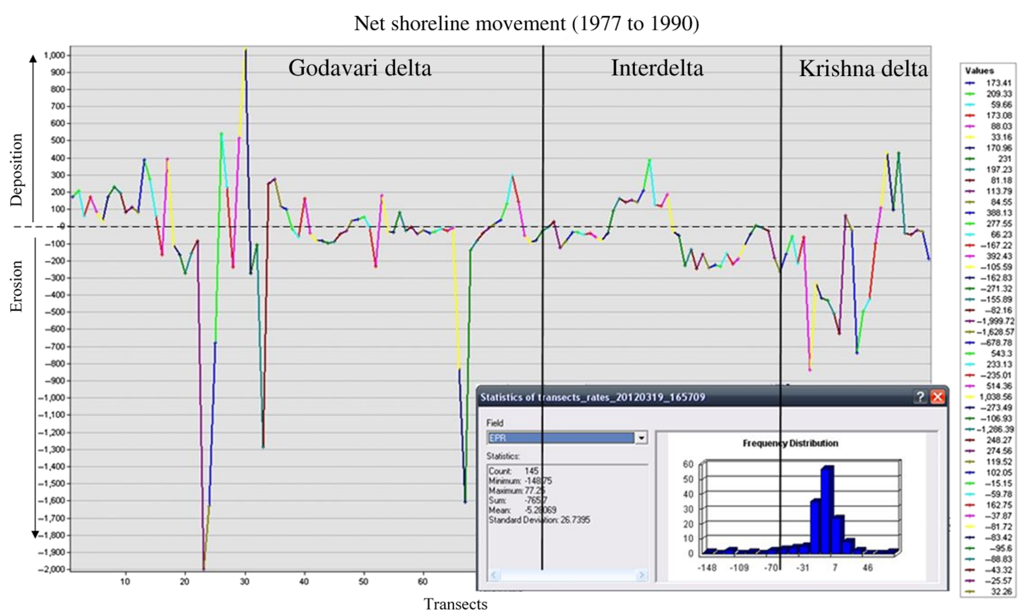

Fig. 3 NSM/EPR trend of study area in the period 1977 to 1990.

rate of 2.42 m in the interdelta region. The decade of 1990 to 2000 and through to 2004 experienced localized erosion in the Godavari delta, only to the tune of 0.33 m (Table 3). The frequency distributions of the transect-calculated EPR also shifts toward the deposition rates (Figs. 4 and 5). Net erosion is observed in the 2004 to 2006 period, attributed to the increased erosion trends being coupled with the impacts of the tsunami of 2004 (Fig. 6). The overall trend in the following two-year period shows net deposition in the deltaic regions, but erosion only in the interdelta region (Fig. 7). The statistics presented in each of the mentioned figures showing the NSM distribution describe the overall trend of the region, along all transects. This assists in making interpretations regarding the impact of the sea on the whole study area, such as the highest erosion experienced by the region in 2004 to 2006 due to the impact of the tsunami.

Considering the occurrence of natural phenomena, the overall trend in the K–G delta basin, including the interdelta region, implies a trend of erosion more than deposition. The overall

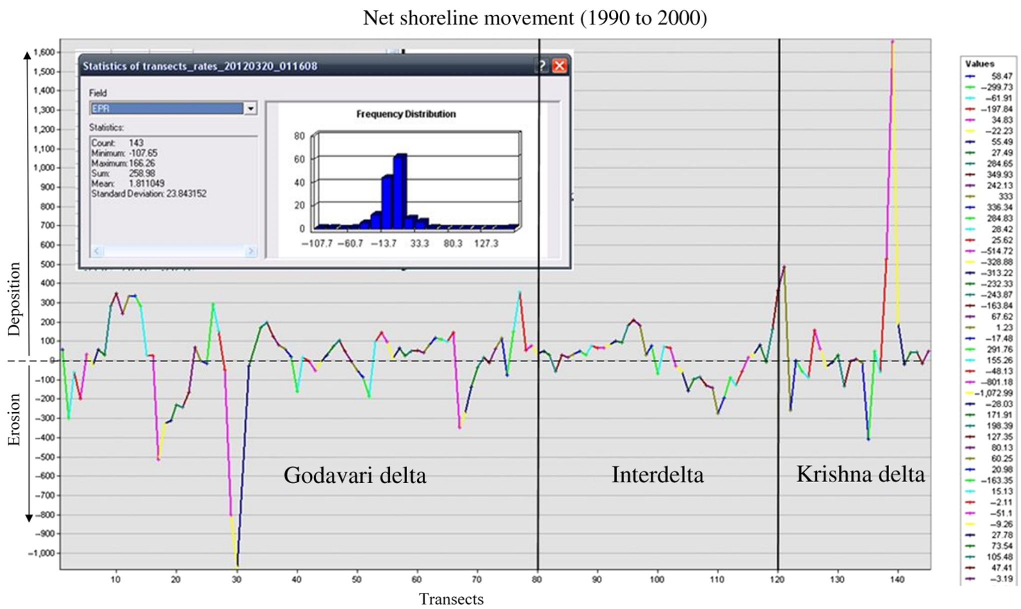

Fig. 4 NSM/EPR trend of study area in the period 1990 to 2000.

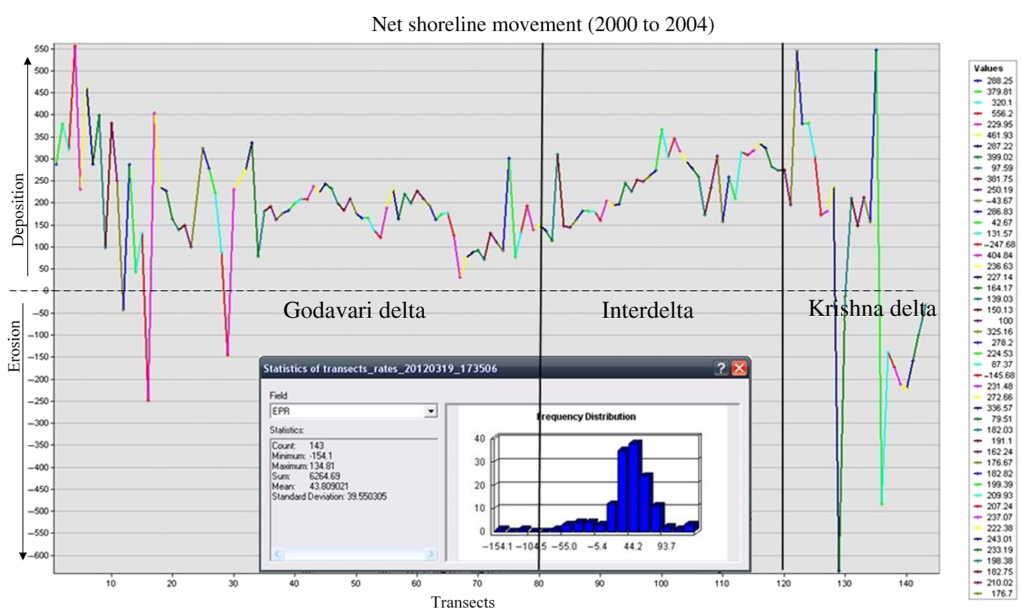

Fig. 5 NSM/EPR trend of study area in the period 2000 to 2004.

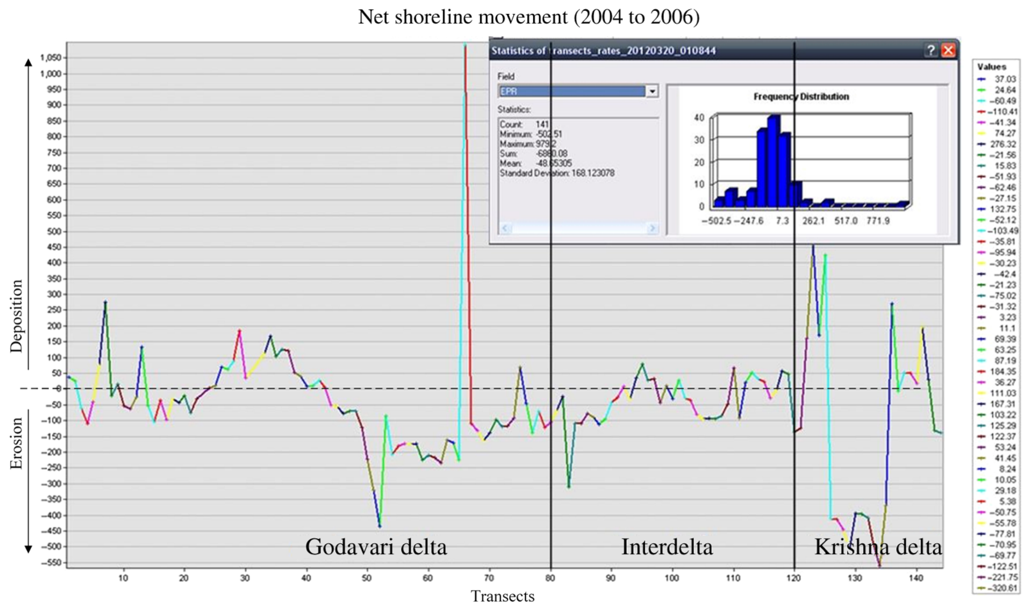

Fig. 6 NSM/EPR trend of study area in the period 2004 to 2006.

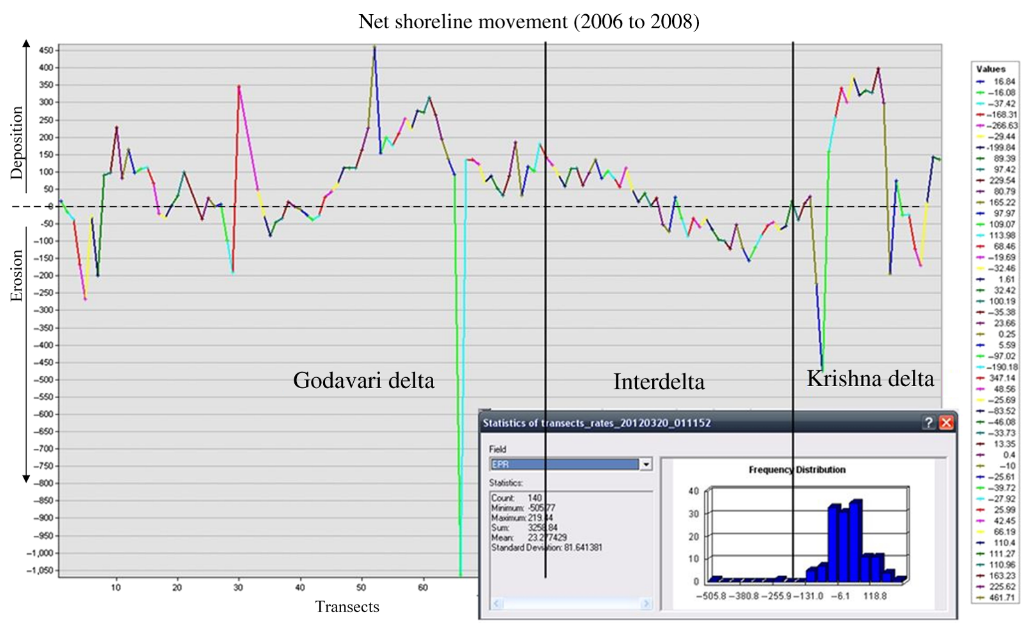

Fig. 7 NSM/EPR trend of study area in the period 2006 to 2008.

implication of microscopic changes in shorter time-frames can be assessed by observing the shoreline changes for the first and final datasets, i.e., 1977 and 2008. The assessment (Fig. 8) indicates a cumulative erosion rate of around 1.7 m/year in the Krishna delta, 3.3 m/year in the Godavari delta, and a deposition of 1.7 m/year in the interdelta plain (Table 3).

Transects beyond 300 (Fig. 8) were constructed to quantify the changes in the Kakinada Spit, a permanent feature of the Godavari delta. Estimating the EPR and plotting the trends of NSM to quantify the change occurring along the study area is vital to understand the degree of impact the sea is having on the delta, a formation created due to the delicate balance of sea and freshwater interactions. This understanding helps in accurately generating the hazard line along the coast to the year 2050.

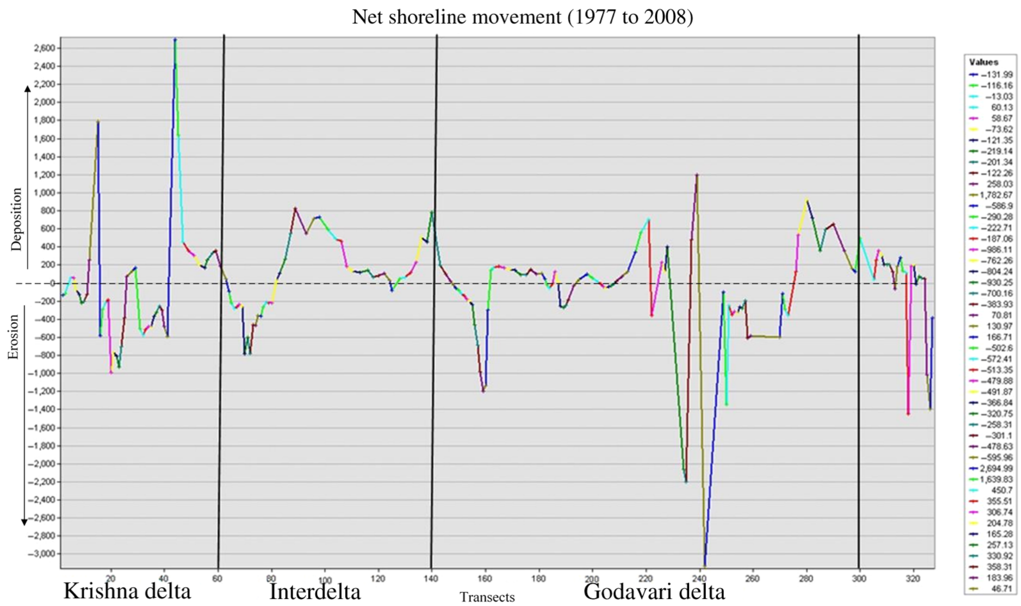

Fig. 8 NSM/EPR trend for K–G delta (1977 to 2008).

As indicated in Table 3, the EPR ranges from −101.9 to 87.6 m/year of erosion and deposition, respectively. The net EPR indicates an erosion rate of 1.6 m/year. This indicates a permanent and ongoing erosion (or sea incursion) in the K–G delta. As mentioned before, EPR is a point location estimate of occurrence of shoreline change. In order to quantify this, in terms of loss or gain of land, the estimation of change of area in this region was done; this showed a loss of 73.1 km^2 due to erosion and 30.9 km^2 gained due to deposition. The net result of loss of 42.1 km^2 from 1977 to 2008 is in agreement with previous studies such as Rao et al.[12]

With the literature-verified estimates of shoreline change in the region, the study now focuses on the main aspect of the post-DSAS workflow analysis; the construction of the hazard line. The prediction of the future shoreline position is done based on the rate of current trends and geomorphology.[20] Geomorphology maps generated by Rao et al.[20] and assigned weights (Table 2) were used to extrapolate a future hazard line. Some significant inferences from the future prediction involve the extended Spit, indicated in the Godavari delta and deposition in the interdelta plain.

A further polygon-based GIS analysis of the area indicates that a comparison between the predicted shoreline and 2008 position would result in an erosion of 121.9 km^2 and deposition of 64.3 km^2, representing in a net loss of 57.6 km^2.

5 Discussion and Conclusions

EPR offered a vital insight into localized variations of erosion and deposition in the K–G delta. As the region encounters higher rates of erosion, as compared to deposition, this delicately balanced region is in danger from the impacts of the sea and its rise. The change statistics have provided a time stamped assessment of the shoreline, the importance of which can be understood in both short- and long-term trends. Short-term trends provide an insight into local variations and events, while the latter provides a more normalized idea of the occurring phenomena. All interpretations and discussions draw inferences from Table 3 and Figs. 3–7. The overall inference of the study area is shown in Fig. 8.

The study begins its evaluation of the coastline from 1977 to 2008. Inclusive of the overall time period of the study, analyses of shorter time periods are considered. The first time period evaluated is between 1977 and 1990. The longest period in the current study (13 years) shows a dominant occurrence of erosion throughout the study area. A combination of erosion and deposition results in net loss of land across all three sectors in the study area (Krishna delta, Godavari delta, and the interdelta region). The Krishna delta region encounters higher net erosion rates in this period. An increase in net deposition was observed from a similar analysis of the next two time periods (1990 to 2000 and 2000 to 2004). However, Table 3 shows localized erosion in some portions of the region. While the Krishna delta region benefits the most from net gain of land from 1990 to 2000, the interdelta region gains relatively significantly (within the limits of the study) in the following four years. The gain can be attributed to the bay-like configuration of the K–G delta shoreline.

The region experiences a significant increase in erosion during the period 2004 to 2006. This is inferred to be a direct implication of the tsunami that affected the Indian Ocean in December, 2004, after collection of the IRS dataset. All sectors of the region experienced higher rates of erosion, with a net loss of land. Although deposition was seen in the region in the next two years, the irreparable damage of the tsunami continued to show its effects.

The nature of the region and its setting in the Bay of Bengal with the erosion patterns illustrate how vulnerable the low-lying region of the K–G delta is to changes of sea level. Area lost in the region due to erosion from the sea, changes in sea level, and construction of dams that block the sediments from reaching and replenishing the delta[12] are evident, with the net loss about 42.1 km^2. Although deposition in the interdelta region is evidence of along-shore movement of sediments, the equilibrium of this tectonically affected region is being disturbed. Following the predictions of the shoreline change to the year 2050, the region is in danger of losing $\sim$57.6 km^2. Local variations of tectonics, coupled with variations of temperature and global-scale changes, only increase the risk to the many inhabitants of the K–G basin.

The changes (erosion and deposition) occurring in this region have been investigated, using change detection of shorelines, extracted from satellite imagery, spanning 31 years. The overall change is estimated during 1977 and 2008 (Fig. 8 and Table 3). Short-term trends indicated impacts of local phenomena, whereas long-term trends calculated overall change, in agreement with previous studies.[12] The net change to the study area was due to erosion (42.1 km^2) during the period of 1977 to 2008. The hazard line was extrapolated using the trends of erosion/deposition and knowledge of geomorphology (assigned ranks based on lithology). Once established, a prediction of 57.6 km^2 loss of land due to erosion was made for the year 2050.

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Akhil Kallepalli received his BTech degree in geoinformatics engineering from Andhra University in 2012 and his MSc degree in geo-information science and earth observation through a joint program of Indian Institute of Remote Sensing, India, and ITC, University of Twente, The Netherlands, in 2014. He is a researcher, currently pursuing his PhD in optical imaging and laser systems applications at the Centre for Electronic Warfare, Information and Cyber, Cranfield University, Shrivenham, at the Defence Academy of the UK. His current research interests include biomedical applications of lasers, hyperspectral image processing, and coastal change detection. He is a current student member of SPIE.

Nageswara Rao Kakani is an emeritus professor in the Department of Geo-Engineering, Andhra University, Visakhapatnam, India. He has more than three decades of teaching and research experience in the fields of morphology and evolution of landforms, land use/land cover analyses, impact of human activities on the coastal/delta environments, coastal zone management, and geospatial technologies. He has published more than 75 research papers, guided 16 doctoral theses, carried out 14 research projects, and visited several countries, including USA, Japan, Thailand, Vietnam, and China on research assignments. His current research involves Holocene sea levels and evolution of river deltas; and changes in the Indian monsoon and early agriculture practices on millennial scale in the Indian peninsula through multiproxy analyses of core sediments from the delta plains.

David B. James received his PhD from the Royal Military College of Science in 2002. He is a senior lecturer and head of the Sensors Group at the Centre for Electronic Warfare, Information and Cyber. He joined MoD in 1989 and worked on nonlinear optical systems and devices. In 2008, he joined Cranfield University, conducting research into innovative laser applications.

Mark A. Richardson received his BSc (first class), MSc (with distinction), PhD, and his diploma degrees from the Imperial College. He is a professor at the Centre for Electronic Warfare, Information and Cyber and the director of Research for Cranfield Defence and Security. He is an associate of the Royal College of Science. His research interests are electro-optics and infrared (EOIR) for electronic warfare, countermeasures, seekers, surveillance and target acquisition, man-portable air-defense systems (MANPADs), laser systems, digital image processing, electro-optical protective measures (EOPM), and electro-optical countermeasures (EOCM).