Geomorphology 103 (2009) 533–540

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Do river deltas in east India retreat? A case of the Krishna Delta

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ARTICLE INFO

Article history:
Received 7 July 2007
Received in revised form 27 July 2008
Accepted 31 July 2008
Available online 14 August 2008

Keywords:
Coastal erosion
Environmental impact
Reservoir
Sediment load
Krishna
Godavari

ABSTRACT

The construction of multiple dams and barrages in many Indian River basins over the last few decades significantly reduced river flow to the sea and affected the sediment regime. More reservoir construction is planned through the proposed National River Linking Project (NRLP), which will transfer massive amounts of water from the North to the South of India. The impacts of these developments on fertile and ecologically sensitive deltaic environments are poorly understood and quantified at present. In this paper an attempt is made to identify, locate and quantify coastal erosion and deposition processes in one of the major river basins in India—the Krishna—using a time series of Landsat images for 1977, 1990 and 2001 with a spatial resolution ranging from 57.0 m to 28.5 m. The dynamics of these processes are analyzed together with the time series of river flow, sediment discharge and sediment storage in the basin. Comparisons are made with similar processes identified and quantified earlier in the delta of a neighboring similarly large river basin—the Godavari. The results suggest that coastal erosion in the Krishna Delta progressed over the last 25 years at the average rate of 77.6 ha yr^{-1}, dominating the entire delta coastline and exceeding the deposition rate threefold. The retreat of the Krishna Delta may be explained primarily by the reduced river inflow to the delta (which is three times less at present than 50 years ago) and the associated reduction of sediment load. Both are invariably related to upstream reservoir storage development.

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1. Introduction

As in much of the world, the Indian water planning and management approach was to harness river waters through dams and other structures to the extent that was technically feasible. Most Indian rivers, at present, are highly regulated (Agrawal and Chak, 1991). Hundreds of multi-purpose reservoirs for water supply, irrigation, hydropower and fisheries have been constructed, as well as numerous barrages for water diversion. Nevertheless, river basins in the southern and western states of India are experiencing physical or economic water scarcity. Basins in the east of the country are, in contrast, often perceived as having surplus water and encounter recurrent floods. The National River Linking Project (NRLP) has been proposed as a solution to water related problems in India. The NRLP envisages transferring waters of the Ganga and Brahmaputra to water deficient basins in the south and west, but remains a contentious issue in Indian society (Jain et al., 2005). Many argue that assessment of water surplus/deficits in Indian River basins, conducted as part of the NRLP proposal, has ignored environmental impacts.

Inter-basin water transfers are normally associated with the construction of new storage reservoirs. A lot has been said and written about land submergence and population resettlement (upstream), and impacts of changing flow pattern on fish (downstream) due to the construction of reservoirs (Revenga et al., 2000; Rosenberg et al., 2000; Bouwer et. al., 2006; Biggs et. al., 2007). At the same time, in-stream storages anywhere in a basin have impacts on sediment transport and, consequently, on river estuaries and deltas (Chakrapani, 2005; Syvitski et al., 2005; Fan et al., 2006). These issues tend to be ignored in water resources planning worldwide. At the same time, depending on the river and the magnitude of upstream reservoir construction, such impacts may be significant. Although they may not be immediate and are difficult to quantify unambiguously, they may be eventually detrimental to the economy and ecology (Stanley and Warne, 1998; Rosenberg et al., 2000; Vorosmarty et al., 2004; Nilsson et al., 2005).

This study attempts to identify the recent changes in the delta of the Krishna River Basin in India and examine their possible causes in the context of continuing new storage development and planned inter-basin water transfers. The Krishna River (Fig. 1) is one of the major basins in Peninsular India with a catchment area of almost 259,000 km^2 and a long-term natural mean annual flow of 78 billion cubic meters (BCM). Its water resources are already significantly developed (Smakhtin and Anputhas, 2006; Biggs et. al., 2007), but water supply shortages continue to manifest themselves. The basin is located en route of the many planned NRLP water transfers.

River basins located to the north of the Krishna (such as the Godavari, Fig. 1) are often perceived as more water abundant and less developed at present. Malini and Rao (2004) examined the recent changes in the Godavari River Delta, called the “rice bowl” of Andhra Pradesh State, using remote sensing images. They discovered that the

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doi:10.1016/j.geomorph.2008.07.022

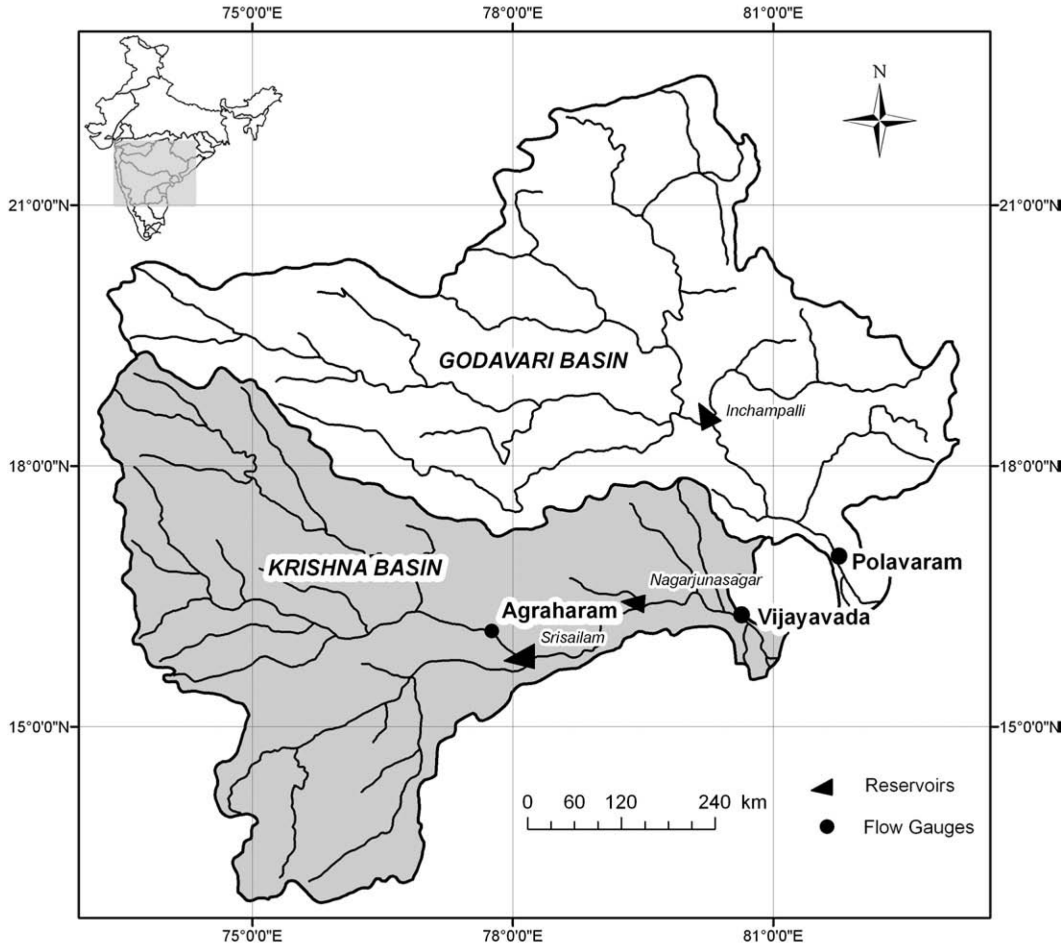

Fig. 1. Map of the Krishna and Godavari River basins in India.

Godavari Delta has regressed landward with the total net land loss of 1836 ha over the period of 1976–2000 (at a rate of 73.4 ha yr^{-1}). It was suggested that reduced inflow of sediments, associated with upstream reservoir construction in the Godavari Basin is the main cause of reduced vertical accretion at the delta coast and of the shoreline retreat.

A number of reservoirs and barrages in the Krishna Basin, both already constructed and planned, detrimentally affect the sediment flow regime in the basin and sediment delivery to the delta (Subramanian et. al., 1985; Ramesh et. al., 1990). It is therefore vital to examine the impacts of water resources development on the Krishna Delta, although the issue has not been addressed in detail.

2. Data and methods

The study first illustrates the dynamics of river flow, sediment loads and reservoir storage growth in both the Krishna and Godavari basins. The comparative analysis of the two basins allows quantitative understanding of water and sediment dynamics. The major problem which adversely affects quantitative assessments in water resources is the lack of observed data and access to existing data—which is often the case in India. Some internet resources provide very limited (past) observed flow data for a few Indian rivers, including the Krishna (http://webworld.unesco.org/water/ihp/db/shiklomanov/index.shtml). The monthly flow time series for the terminal stations on both rivers (Polavaram on the Godavari and Vijayawada on the Krishna, Fig. 1) for the available periods of record from 1930 to the late 1970s have been downloaded from this source. More recent observed flow data for Vijayawada have been provided by the Central Water Commission (CWC) of India. Long-term observations on sediment loads for the Krishna at Vijayawada are unavailable; the only available data are for the period from 1991 to 2000 (CWC, 2006). The available sediment load data for the Godavari at Polavaram (Fig. 1) covers the period from 1970 to 1997 and have been taken from the published study of Malini and Rao (2004). The information on existing and planned reservoirs and their storage is available from the ICOLD register (http://www.icold-cigb.org) and from published feasibility reports (http://nwda.gov.in/indexab.asp?langid=1).

To examine the morphological changes in the Krishna Delta itself, several remote sensing images of the delta area were analyzed. The images were free products obtained from the Earth Science Data Interface (ESDI) at the Global Land Cover Facility (GLFC; http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp) and were selected from the period of 1977 to 2000 to form a time series. They include:

- Landsat 2 Multispectral Scanner (MSS) image dated 1 June 1977 with a spatial resolution of 57 m (Note that GLFC resampled the original MSS image with a slightly lower resolution),
- Landsat 5 Thematic Mapper (TM) image dated 10 November 1990 with a spatial resolution of 28.5 m, and
- Landsat 7 Enhanced Thematic Mapper (ETM+) image dated 28 October 2000 with a spatial resolution of 28.5 m.

Three basic layers were used to detect morphological changes in the delta: band 4 (NIR), band 2 (Green) and band 1 (Blue). These bands have characteristics that are suitable for coastal mapping, differentiation of vegetation from soil, reflectivity of vegetation vigor, and delineation of water bodies. The images have been enhanced for better brightness and clarity using ERDAS 9.0 software. The

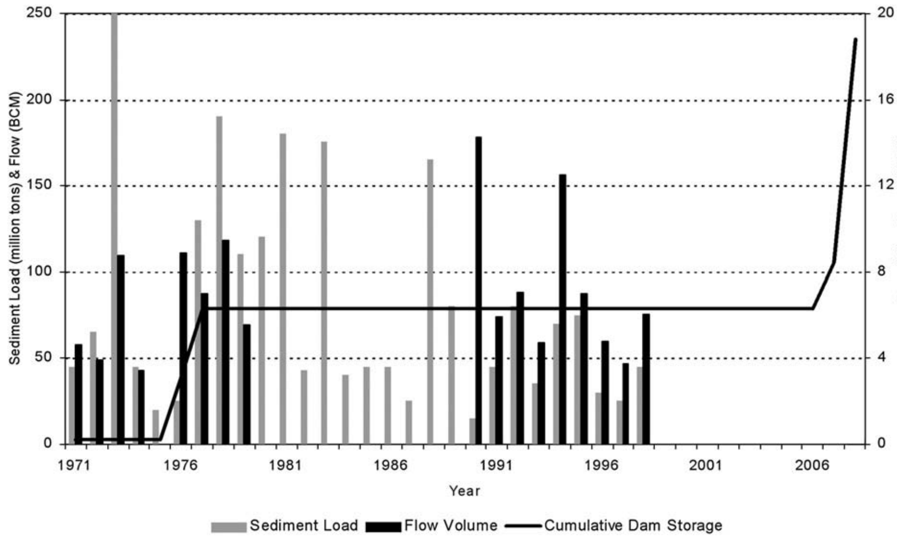

Fig. 2. Time series of annual flows and sediment loads at Polavaram, at the outlet of the Godavari basin, with basin-wide cumulative storage.

methodology employed in the study was similar to that applied by other coastal zone researchers in different parts of the world (e.g. Azab and Noor, 2003; Malini and Rao, 2004; Turner et al., 2006; Huh et al., 2007; Kumar et al., 2007). First, land area was demarcated in all images using same projection system (UTM), unique band combination with the same magnification level to avoid the imbalance of spatial resolution from 1977 to 2000. This consideration was to avoid over or underestimate of the land area due to changing level of the information with varying spatial resolution from 1977 to 2000. Then "oldest" image was assumed to be the reference condition against which changes in the other two images were detected. The entire Krishna Delta shoreline of 134 km was examined to demarcate the zones of coastal erosion and accretion (deposition) between 1977 and 2000. The enhanced images were subsequently analyzed using GIS tools. The delta coastline from each image was presented in a vector form. These lines were subsequently superimposed to identify zones of erosion and deposition and calculate the areas of these zones.

3. Results and discussion

3.1. Water and sediment inflows to the Godavari and Krishna deltas

Fig. 2 illustrates the dynamics of flow and sediment load at the outlet of the Godavari (at Polavaram) and reservoir storage growth in the entire Godavari Basin since 1970. The flow time series has missing data during 1980–1990 and neither flow nor sediment data were available after 1998. Cumulative dam storage increased significantly in the early 1970s but remained relatively constant until 2006. However, it will increase abruptly again after the construction of the Polavaram Barrage and the large Inchampalli Dam. To illustrate this abrupt growth in Fig. 2, the year of completion for both dams is assumed to be 2010.

While trends in the flow of the Godavari River cannot be ascertained from the available disrupted flow time series, the decreasing trend in annual sediment loads are clear from the sediment data (Fig. 3, also shown by Malini and Rao, 2004). The mean annual sediment load has decreased from 100 million tons in 1978 (effectively an ending point in noticeable reservoir growth in the basin so far) to 46 million tons at the end of the 1990s. The current cumulative reservoir storage in the Godavari Basin remains relatively low (6.3 BCM, i.e. approximately 6% of the mean annual flow at the outlet—Amarasinghe et al., 2005; Smakhtin and Anputhas, 2006). The storage growth is not the only aspect of significance because much of the water is also diverted from barrages, i.e., structures without storage. A relatively small storage in the basin (Fig. 2) and still a noticeable decreasing trend in sediment load (Fig. 3) imply that the basin sediment regime is very sensitive to reservoir installation. Further reduction in sediment inflow may therefore be expected after the construction of the Polavaram and Inchampalli storages, which will increase the storage/flow ratio in the basin to 19% (Amarasinghe et al., 2005; Smakhtin and Anputhas, 2006).

A subsequent attempt has been made to examine whether similar trends exist in the Krishna Basin, where the proportion of storage to annual flow is much larger than in the Godavari. The comparison of the two short (1991–2000) time series of sediment loads at Agraharam (upstream of major reservoirs) and at Vijayawada (downstream of them) revealed a significant decrease in sediment downstream of

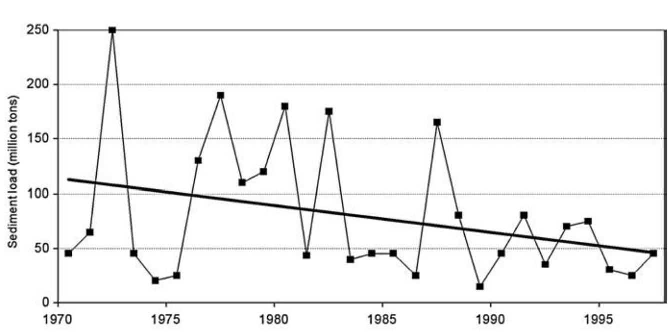

Fig. 3. Time series of sediment load at Polavaram with a decreasing trend line (source: Malini and Rao, 2004).

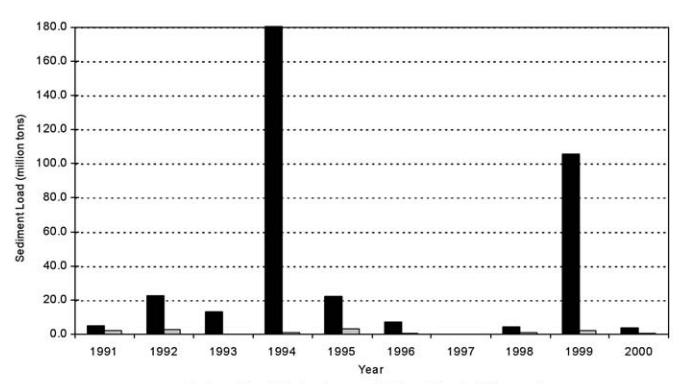

Fig. 4. The time series of sediment loads at Agraharam and Vijayavada in the Krishna River basin.

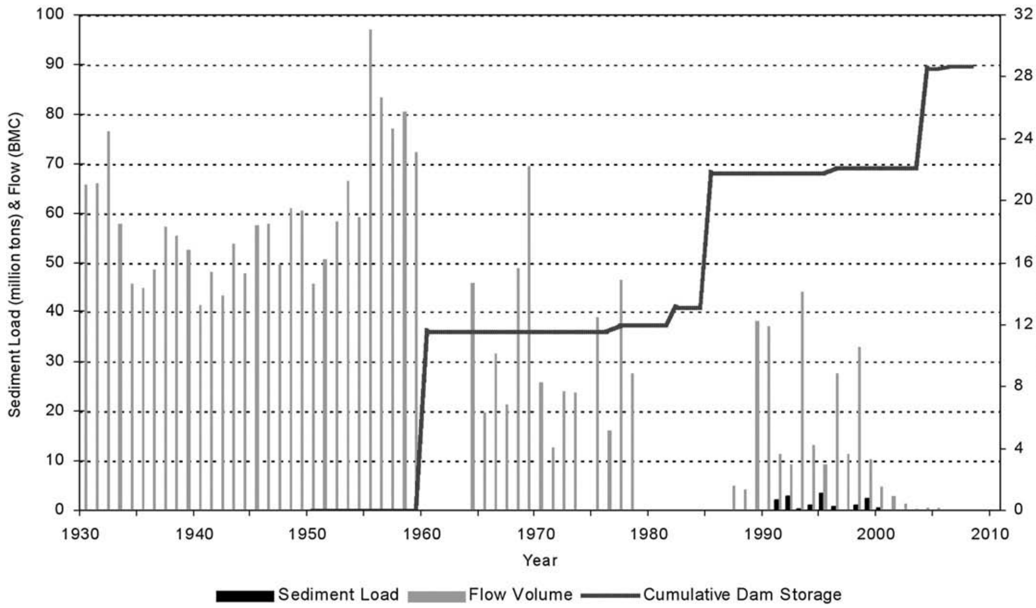

Fig. 5. Time series of annual flows and sediment loads at Vijayavada, at the outlet of the Krishna basin, with basin-wide cumulative storage.

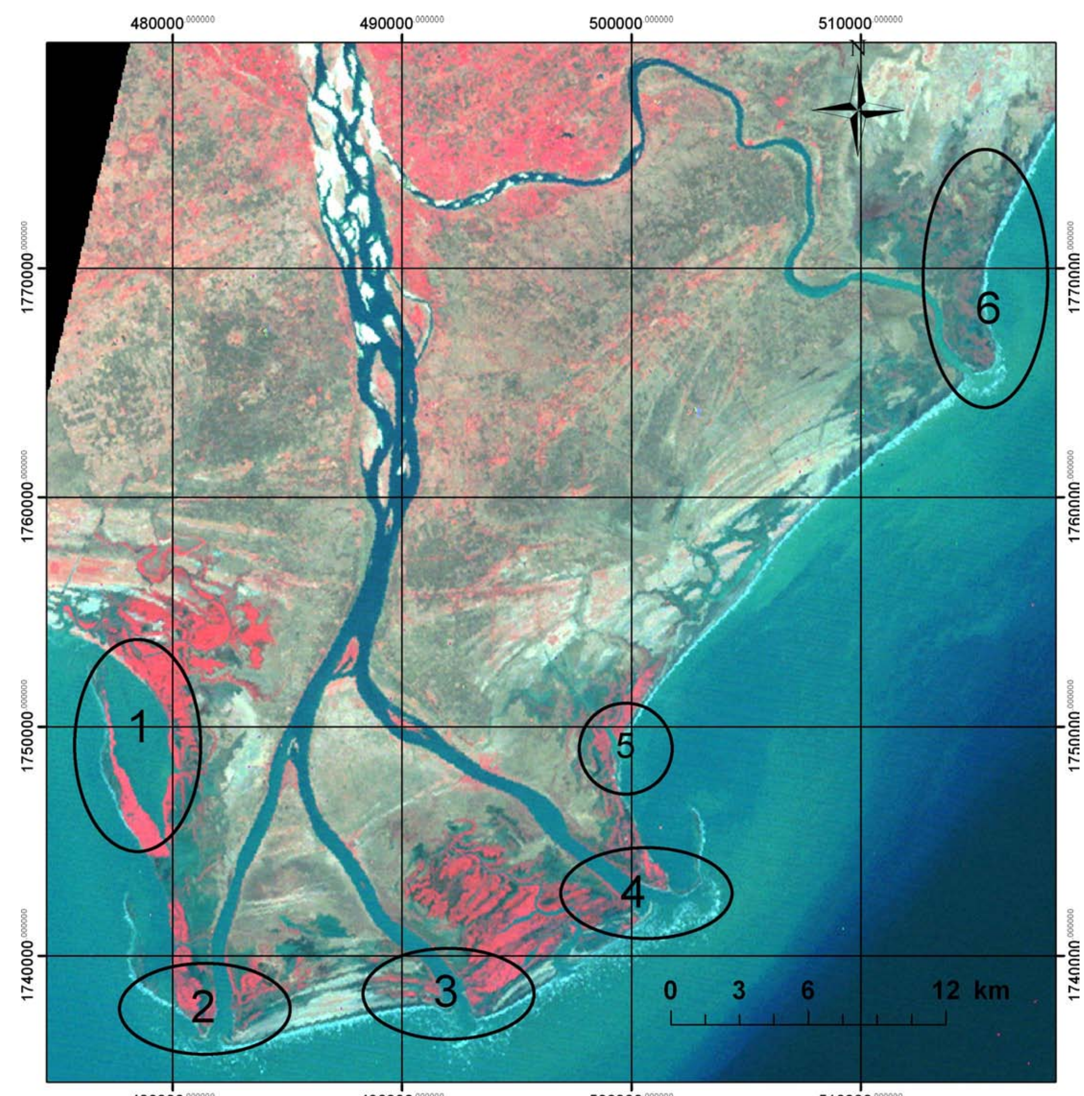

Fig. 6. An image of the Krishna River delta showing several areas (numbered) where detailed analyses of erosion and deposition have been made.

the reservoir system (Fig. 4). The differences are particularly noticeable in high-flow years (1994 and 1999), when more sediment reaches Agraharam from the relatively unregulated upstream basin but all sediments are likely being trapped by the existing reservoir system (Srisailam and Nagarjuna-Sagar) upstream of Vijayawada. The absence of sediment data prior to 1991 does not allow further consideration on changes in the sediment regime. However, these changes are most likely very significant due to marked reduction of river flow at Vijayawada over the last 70 years (Fig. 5). This reduction is due to various water diversions, groundwater development (Biggs et al., 2007) and increased cumulative small farm dams' and large reservoir storage in the basin, which has grown from almost zero in 1960 to 28.5 BCM at present (Fig. 5). This present cumulative storage, made up primarily of large dams, represents 36% and 132% of the natural and present-day mean annual flow of the Krishna River, respectively (Amarasinghe et al., 2005; Smakhtin and Anputhas, 2006; Biggs et al., 2007).

3.2. Erosion and deposition in the Krishna Delta

Fig. 6 shows the image of the Krishna Delta with several selected areas where erosion and deposition were examined in detail. Figs. 7 and 8 display the sequence of images for years 1977, 1990 and 2000 for some of the selected areas circled in Fig. 6. The black lines in each image represent the reference position of the land mass—in 1977. Fig. 9 shows areas of predominant erosion and deposition during the period between 1977 and 2000 for the entire delta shoreline, and Table 1 summarizes the calculated characteristics of these processes for the entire delta over the same period.

The results suggest that while areas of predominant erosion and deposition interchange, the overall tendency is towards the regression landward with losses of land to the sea—the situation similar to that in the Godavari Delta. The annual net loss rate of 77.4 ha is almost the same as that in the Godavari Delta (73.4 ha yr^{-1}; Malini and Rao, 2004). One noticeable feature of the Krishna Delta is also its higher ratio of erosion to deposition (3.05 versus 1.6 in the Godavari) over the same period, suggesting that coastal erosion is more distinct in the Krishna Delta than in the Godavari, despite the slightly smaller area (4700 km^2 versus 5100 km^2) and shorter shoreline of the former (134 versus 160 km). Erosion is also a dominant process through most of the coastline, while the deposition is only limited to certain sections (Fig. 9).

3.3. Possible causes and implications of coastal erosion

The regression of both deltas cannot be explained by the rise in the sea level. According to Malini and Rao (2004), analysis of the available sea level data in the region, for the periods overlapping with that of the present study, did not reveal any significant rising or falling trends. Therefore, coastal erosion in the Krishna and Godavari deltas can most likely be explained by the reduced sediment supply, which, in turn, is due to upstream flow regulation. In addition, human activities in delta regions (e.g. conversion of cropland and mangrove swamp areas into aquaculture ponds) may also be responsible for sea transgression leading to coastal erosion and shoreline retreat in both deltas (e.g. Sarma et al., 2001).

Analysis of the longer series of sediment load data for the downstream parts of the Krishna and the use of more recent and more

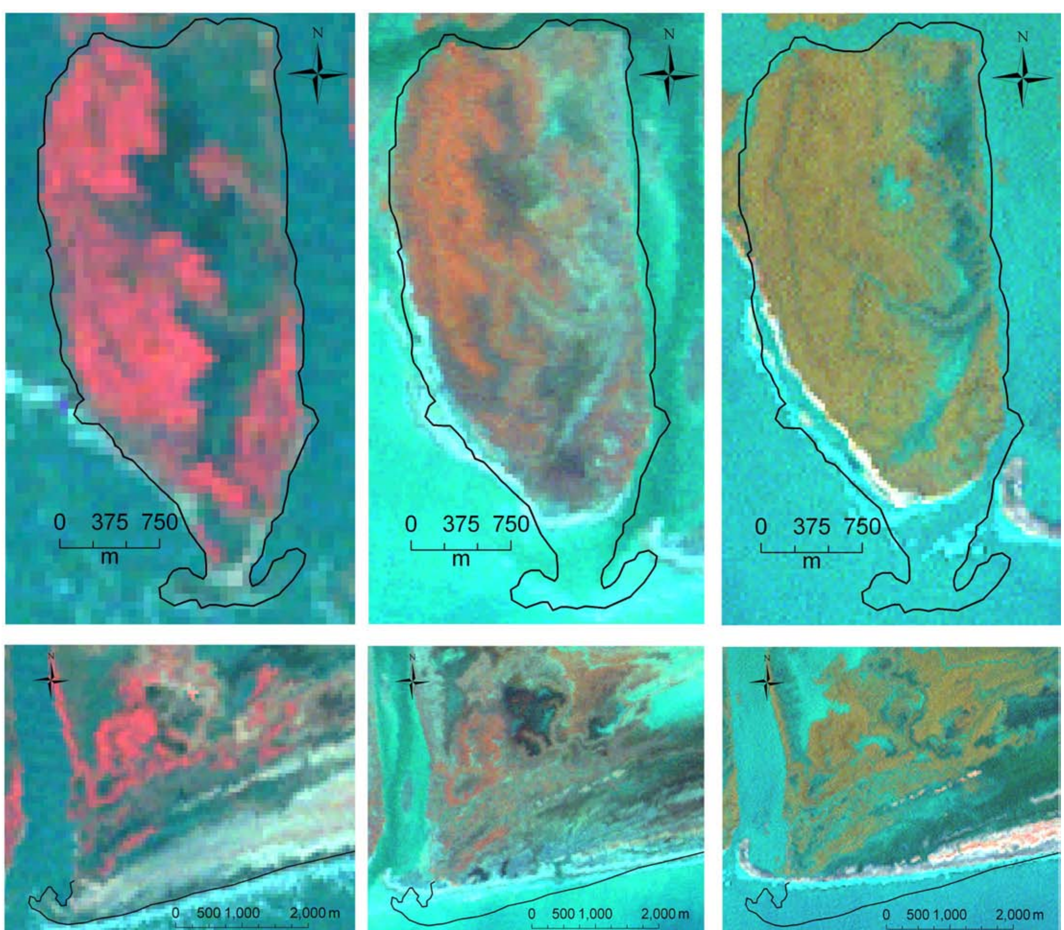

Fig. 7. Changing morphology of area #2 (Fig. 6) in 1977 (left two images), 1990 (middle two images) and 2000 (right two images). The top and bottom rows of images show the dynamics of the right and left banks of the river channel, respectively.

resolute remote sensing images could result in more detailed quantification of delta erosion. However, even with the existing limited data, it is possible to suggest that upstream basin storage development leads to the said retreat of deltas. The Krishna River is already a "closed basin" because only occasional high flows with almost no sediment spill into the delta (Fig. 4). Therefore, the storage that is already constructed in the Krishna will have a long-lasting detrimental effect on the delta and its agricultural productivity. The situation in the Godavari Delta will most likely deteriorate after the construction of the additional storages (Polavaram and Inchampalli, Fig. 2) planned as part of the NRLP.

Detailed sedimentation modeling studies would be useful in all major deltas of India in order to develop a better understanding and quantification of the links among upstream runoff reduction, sediment discharge reduction, upstream storage growth and man-induced changes in deltas. Such studies could allow the specification of necessary environmental flow releases to be made for the maintenance of delta sediment regimes.

Coastal erosion may be seen as a slow process. However, there are a few aspects which promote negative environmental impacts associated with it. One is the saltwater intrusion. Bobba (2002) conducted a numerical modeling study of the Godavari Delta and inferred that saline intrusion may become a major factor of reduced agricultural productivity in the delta due to increased groundwater pumping and reduced freshwater inflow. Coastal erosion, caused by similar factors, facilitates saltwater intrusion deeper in the delta adversely affecting the productivity of land. An additional problem is the potential rise in sea level in the next 50 years due to climate change, although the limited available observations so far do not detect it. This rise can lead to even more coastal erosion and deeper saltwater penetration, accelerating degradation of the deltas. Research on this aspect was not the scope of the current study, and needs to be carried out as a separate detailed project. While quantification of the above impacts will be developing, even limited environmental flow releases from existing reservoirs in the Krishna and the Godavari will delay the adverse environmental processes in both deltas. New storage reservoirs need to be planned to allow sediments to reach deltas. Construction of the most downstream reservoirs, particularly as large as Inchampalli, will definitely not serve this purpose.

4. Conclusions

Reservoir construction in river basins have multiple ecological impacts such as the significant decrease in sediment supply to downstream deltas, which are often referred to as the "rice bowls" of India because of their high land productivity. It has been demonstrated that the Krishna Delta has been in retreat for the last 25 years, with areas of erosion dominating over deposition. This retreat is due mainly to reduced water and sediment inflow to the delta, related to the development of upstream reservoir storage development and barrages.

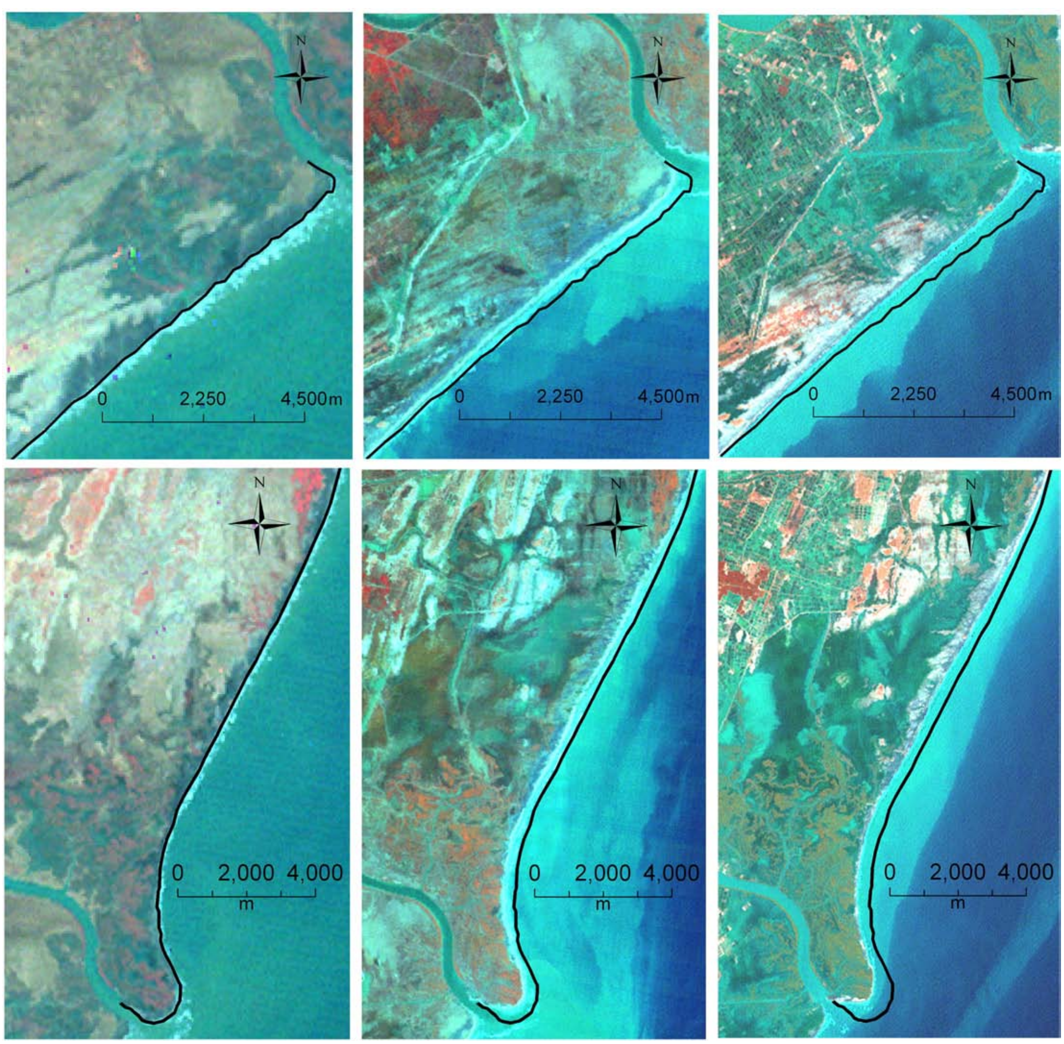

Fig. 8. Changing morphology of area #4 (Fig. 6) in 1977 (left two images), 1990 (middle two images) and 2000 (right two images). The top and bottom rows of images show the dynamics of the southern and northern parts of the area, respectively.

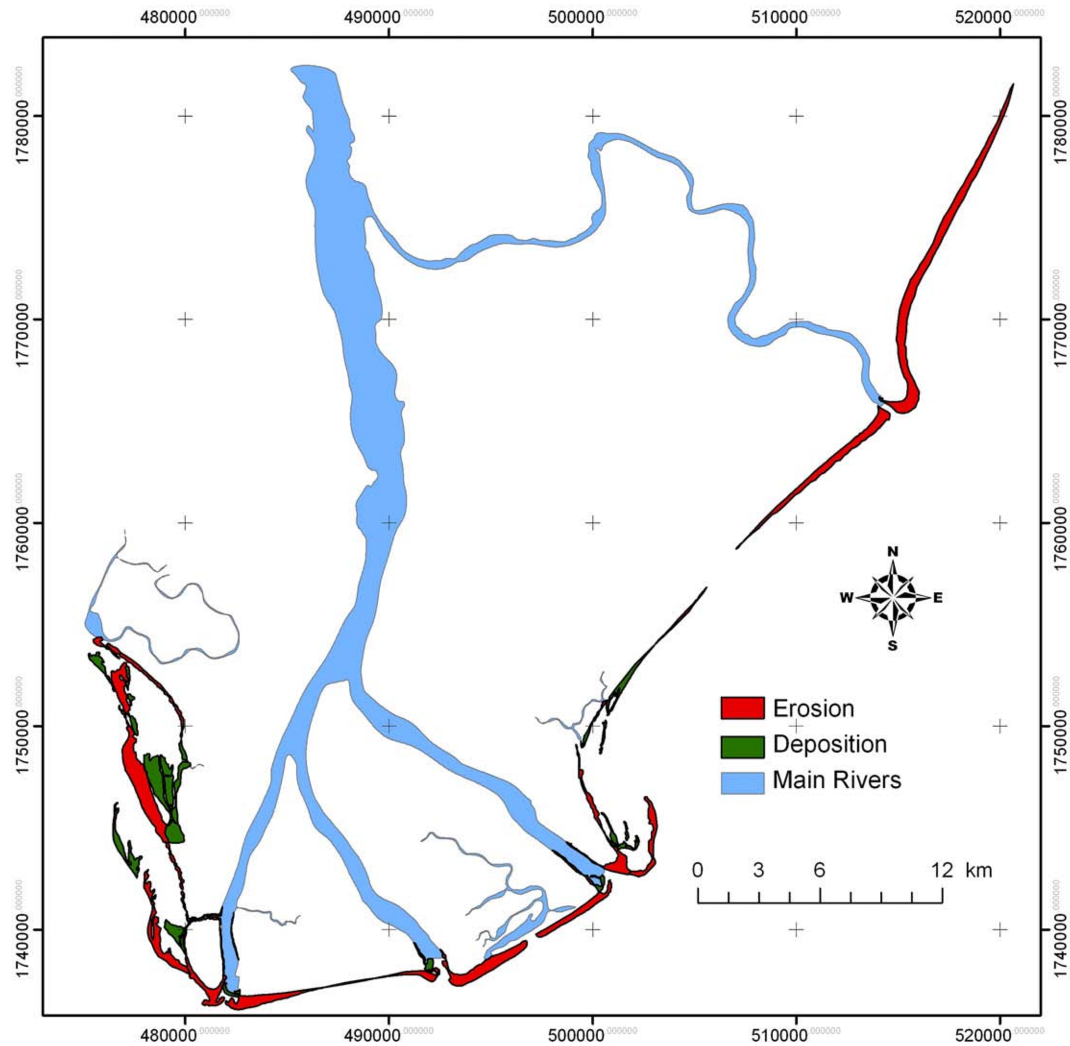

Fig. 9. Map of the Krishna Delta showing areas of erosion and deposition during the period of 1977–2000.

These conclusions, however, have been reached from limited observation data, which are not easily and freely available in India.

Coastal erosion detected in the Krishna Delta may be seen as a slow process. However, it gives some negative environmental impacts such as saltwater intrusion, and the potential rise in sea level caused by future climate change may significantly speed up the erosion. Detailed sedimentation modeling studies need to be conducted in major deltas of India in order to develop a better quantitative understanding of the relationships among upstream water and sediment flow reduction, upstream storage growth and changes in deltas. Such studies could allow the specification of necessary environmental flow releases to be made for the maintenance of deltas and could be a valuable contribution to quantitative justification of environmental water allocations in coastal regions.

Table 1
Areal extent of erosion and deposition in the Krishna Delta over 23 years (1977–2000)

Point number in Fig. 6	Erosion (ha)	Deposition (ha)	Net loss (ha)	Rate of loss/gain (ha yr^{-1})
1	598	483	115	5.0
2	478	178	299	13.0
3	275	31	243	10.6
4	326	74	251	10.9
5	79	98	−19	−0.8
6	894	3	890	38.7
Total (23 years)	2 650	867	1 779	77.4

Acknowledgements

The study forms part of the research project on the assessment of the National River Linking Project in India. The authors gratefully acknowledge the support from the CGIAR Challenge Program on Water and Food (http://www.waterandfood.org), who funded this project.

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