Monitoring of Eco-Restoration of Mangrove Wetlands through Time Series Satellite Images: A Study on Krishna-Godavari Delta Region, East Coast of India

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Abstract Comparative analysis of time series satellite images spread over the past four decades indicated significant changes in the mangrove environment of the Krishna-Godavari twin deltas along the east coast of India. We analyzed Landsat-MSS, TM and ETM images from 1977, 1990, and 2000, respectively, and Indian Remote Sensing Satellite images from 1992, 2001, and 2013, which indicated that the mangrove cover in the region increased from 35,058 ha in 1977 to 39,283 ha by 2013. In spite of loss of mangrove vegetation over 8,036 ha due to coastal erosion, deforestation, decline and aquaculture encroachments, several mangrove-restoration projects taken up during 1991–2008 led to an overall increase in its area. Various mangrove eco-restoration techniques were adapted in the region.

Key words mangrove degradation, coastal erosion, aquaculture, mangrove eco-restoration, Krishna-Godavari delta region, east coast of India

Introduction

Mangroves are halophytic woody plants adopted in intertidal brackish-water habitats at the land-sea interface adjoining landforms such as lagoons, estuaries and bays in the tropical and subtropical latitudes. They occupy about 8% of the world’s coast and 25% of the tropical coastline (Selvam et al. 2003) accounting for about 0.7% of the world’s tropical forest area (Donato et al. 2011; Kolka et al. 2016). South and Southeast Asia has the most extensive and diverse mangrove systems representing about 41.4% (Singh et al. 2012) of the total 15.236 million hectares (Mha) of the global mangrove area (Spalding et al. 2010). In India, mangroves spread over 0.4661 Mha accounting for 3.1% of the global cover (Singh et al. 2012).

Mangroves are important coastal habitats for several ecological, economical, and protective functions (Biswas et al. 2009; Cavanaugh et al. 2014; Nortey et al. 2016) and act as barriers against storm surges, floods and tsunamis (Alongi 2008; Kulkarni 2009; Teh et al. 2009; Yanagisawa et al. 2009; McFadden et al. 2016). They have a highly efficient nutrient retention mechanism (Alongi 2002) and serve as breeding and nursery grounds for a wide range of aquatic and terrestrial species (Kumara et al. 2010). They are among the world’s most productive ecosystems, and carbon sinks contributing significantly to the global carbon cycle (Hutchison et al. 2014), besides being source of wood for construction and energy, tannins and medicines, and even contributing to the burgeoning ecotourism industry (Kathiresan and Bingham 2001).

Despite being an important coastal wetland ecosystem and main focus of study of the international wetland biodiversity conservation and ecological protection (Song et al. 2011), mangrove forests, however, are being degraded globally (Bayraktarov et al. 2016) and the rate of loss was estimated to be 1–2% yr\(^{-1}\) (Malik et al. 2016). According to a recent report, around 30% to 50% of global mangrove forests have been lost during the past 50 years (Godov and De Lacerda 2015) for various natural forces (storms,
tsunamis and coastal erosion), and anthropogenic factors (pollution, deforestation for various purposes including firewood and construction materials, aquaculture, reclamation and dredging). Initiated in Indonesia in 1960s (Soemodihardjo et al. 1996), number of mangrove restoration efforts have been reported successful from different countries (e.g. Ramasubramanian and Ravishankar 2004 from India; Mukhtar and Hannan 2012 from Pakistan; Schmitt et al. 2013 from Vietnam; Taylor et al. 2013 from Mexico).

In India, the major mangrove zones are along the east coast, west coast and Andaman-Nicobar Islands. According to a Forest Survey of India report (FSI 1999), the east coast has about 275,800 ha with Sundarbans (Ganges-Brahmaputra delta) accounting for 212,500 ha and the Krishna-Godavari twin delta region being a distant second with 39,700 ha followed by Mahanadi delta with 21,500 ha. The major mangrove area along the west coast is in Gujarat accounting for 90% (102,600 ha) of the total 114,200 ha (FSI 1999). Andaman-Nicobar Islands contain about 96,600 ha mangrove forest (FSI 1999). In fact the Sundarban mangroves spread over more than 0.60 million ha in a contiguous zone in India and Bangladesh fringing the Ganges-Brahmaputra delta (Ifeekhar and Islam 2004), is a complex and dynamic socio-ecological system with dense mangrove forests and human population (DasGupta and Shaw 2015). A remote sensing study by Giri et al. (2007) revealed that the net mangrove area in Sundarbans decreased by 1.4% during 1970–1990 but increased by 2.5% during 1990–2000 due to restoration efforts, in spite of its degradation by various natural and anthropogenic impacts. Pattnaik and Narendra Prasad (2011) estimated that about 2,606 ha of mangroves were lost in the Mahanadi delta area during 1973–2006. Our field observations along the Krishna-Godavari (K–G) delta coast indicated considerable destruction of mangroves on one hand and its restoration activities on the other hand. An attempt is made in this study to trace the spatio-temporal changes of mangrove forests in the K–G deltas using geospatial technologies, because monitoring of changes in mangrove wetlands provides valuable information for ecologists and forest managers to improve management strategies for mangrove ecosystems (Son et al. 2016).

**Study Area**

The Krishna and the Godavari rivers originate in the Western Ghats and flow eastward across the Indian peninsula for 1,400 km and 1,465 km, respectively, before decanting into the Bay of Bengal. With the drainage areas of 258,948 km² and 312,812 km², respectively, the Krishna and Godavari are the third and second largest river basins in India, after the River Ganga (Ganges). Both these adjacent rivers built extensive deltas on the east coast of India, which are coalesced into one large delta complex covering 12,700 km² characterized by strand plains, lagoons, mudflats and mangrove swamps. This twin delta region is a relatively low-energy marine environment (Nageswara Rao et al. 2008) with micro-tidal (spring tide range is <1.5) and low to moderate wave conditions (significant wave height is <2 m). The 336-km long Krishna-Godavari (K–G) twin delta coast has mangrove forest mainly on both sides of the three distributaries of the Krishna River that constitute its main delta lobe and on both sides of the Gautami distributary of the Godavari River. Mangrove vegetation also prevails on both sides of the fourth (easternmost) distributary of the Krishna and to the east of Machilipatnam, besides a few smaller patches near Nizampatnam in the western part of the Krishna delta (Figure 1). Mangrove vegetation is absent in the rest of the twin delta region including the estuarine parts of the Vasishta and Vainateyam distributaries of the Godavari River. Thirty five mangrove species occur in this region, of these 16 are true mangroves with 19 associates. *Avicennia marina* and *Excoecaria agallocha* are the dominant mangrove species in the region along with certain varieties such as *Rhizophora* and *Bruguiera* species (Ravishankar et al. 2004).

**Methods of Study**

**Satellite images and processing**

We estimated the spatio-temporal changes in the extent of mangroves of the entire K–G delta complex using time series satellite images of the period from 1977 to 2013. Landsat Multi Spectral Scanner (MSS) images (1977), Thematic Mapper (TM) images (1990) and Enhanced Thematic Mapper (ETM) images (2000), and the Indian Remote Sensing Satellite (IRS) Linear Imaging Self-Scanning (LISS) II image (1992), LISS III image (2001) and LISS IV images (2013) were used in the study. The specifications of the images used are provided in Table 1. All the satellite images were geo-referenced for easy comparison with one another. As mangroves are distributed along the coast, shoreline changes were also analyzed for estimating loss of mangroves by coastal erosion. For this purpose, the near infra-red band images were chosen (Band 6 of MSS: electromagnetic radiation (EMR) range of 0.7–0.8 µm, Band 4 of TM and ETM: EMR...
range 0.76–0.90 µm), and Band 4 of LISS-II, LISS-III and LISS-IV (EMR range of 0.77–0.86 µm) since the landwater boundary is sharper in these band of images. The selected images were edge-enhanced and then resampled using cubic convolution method in the image processing software (ERDAS Imagine 9.2) to smoothen the pixels, so that the shoreline could be traced through onscreen digitization by using the overlay techniques in geographic information system (GIS). The mangrove vegetation was identified on the satellite images based on the typical fine-texture and bright red tone exhibited by the mangrove vegetation on the false colour composite images, besides the presence of intricately meandering tidal channels across the forest and the proximity to the distributary mouths supplemented by extensive field investigations.

Apart from the extents of mangrove, saltpans, aqua-
culture and mudflat (bare surface) areas were separately extracted using the on-screen digitization on all the georeferenced images and vector layers were created for each of the digitized features from the four satellite images of 1977, 1990, 2000, and 2013 covering the Krishna delta, and from the four images of 1977, 1992, 2001, and 2013 covering the Godavari delta. Then using the union analysis of ArcMap, the vector layers in 1970s were compared with that of the 1990s. With this analysis, any changes from mangrove into other land cover are extracted. Similar changes from 1990s to 2000s, 2000s and 2013 were also extracted and their extents are estimated.

**Field survey**

Field investigations were carried in the mangrove areas in the K–G deltas during 2008–2012 using a hand-held Global Positioning System (GPS) device supplemented by detailed on-site observations and enquiries for ground truth on the mangrove and associated vegetation, deforested as well as reforested areas, aquaculture ponds, and other land use/land cover features.

**Results and Discussion**

Analysis of satellite imagery has revealed the changes in the extent of mangrove vegetation in the entire K–G deltas. In the Krishna delta, the mangrove cover had decreased initially from 17,966 ha in 1977 to 16,110 ha by 1990, and then to 16,055 ha by 2000 but increased thereon to 20,156 ha by 2013 (Table 2). In the Godavari delta, the area occupied by mangrove vegetation increased initially from 17,092 ha in 1977 to 18,550 ha by 1992. However, it decreased to 16,543 ha by 2001. Again the area increased later to 19,127 ha by 2013 (Table 2). The changes in the extent of mangrove vegetation in the K–G delta region are the net result of decrease in the extent of mangroves by degradation and increase by mangrove restoration programs.

**Mangrove degradation**

Although the total area of mangroves showed relative increase in both these deltas, there was considerable destruction of mangrove forests in the K–G delta region by various processes, which we categorize as 1) mangrove degradation by coastal erosion, 2) mangrove deforestation and decline, and 3) mangrove degradation for aquaculture.

**Mangrove degradation by coastal erosion** Coastal erosion is one of the major causes of mangrove destruction along the Krishna delta (Figures 2-a and 2-b) and the Godavari delta (Figure 3-a) (Hema Malini and Nageswara Rao 2004; Nageswara Rao et al. 2010). Our study showed that coastal erosion along the Krishna delta coast led to loss of land (mangrove) of about 2,470 ha (610 ha) between 1977 and 1990, and about 2,210 ha (129 ha) between 1990 and 2000 followed by a further loss of 1,706 ha (294 ha) during 2000–2013. In the Godavari delta, the loss of land (mangrove) by coastal erosion was 3,380 ha (176 ha) during 1977–1990 and 2,200 ha (321 ha) between 1992 and 2001 followed by a further loss of 1,290 ha (231 ha) during 2001–2013.

**Table 2.** Data on temporal changes in mangrove extent in the Krishna and Godavari deltas

| Year | Mangrove extent (ha) | By coastal erosion | For aquaculture | By deforestation & decay | Total loss | Mangroves gained by restoration (ha) | Net loss/gain of mangrove cover (ha) |
|------|---------------------|-------------------|----------------|--------------------------|-----------|-----------------------------------|----------------------------------|
| **Krishna Delta** | | | | | | | |
| 1977 | 17966 | — | — | — | — | — | — |
| 1990 | 16110 | 610 | 335 | 911 | 1856 | — | −1856 |
| 2000 | 16055 | 129 | 680 | 936 | 1745 | 1690 | −55 |
| 2013 | 20156 | 294 | 297 | 70 | 661 | 4762 | 4101 |
| Total | 1033 | 1312 | 1917 | 4262 | 6452 | 2190 |
| **Godavari Delta** | | | | | | | |
| 1977 | 17092 | — | — | — | — | — | — |
| 1992 | 18550 | 176 | 306 | 561 | 1043 | 2501 | 1458 |
| 2001 | 16543 | 321 | 132 | 1821 | 2274 | 267 | −2007 |
| 2013 | 19127 | 231 | 158 | 68 | 457 | 3041 | 2584 |
| Total | 728 | 596 | 2450 | 3774 | 5809 | 2035 |
On the whole, the Krishna delta (Godavari delta) lost 6,386 ha (6,870 ha) of land during the thirty-six year period from 1977 to 2013, at the rate of 177.4 ha (190.8 ha) yr⁻¹ due to coastal erosion, which included 1,033 ha (728 ha) at 28.7 ha (20.2 ha) yr⁻¹ of mangrove covered area.

Mangrove deforestation and decline  Presence of mangrove vegetation in an image and absence of it in the same area in images of subsequent years suggest removal or decline of mangroves. Number of bare patches appears in dark tone reflecting recent deforestation exposing the wet mudflats in the K–G delta region (Figure 2-c). Most of the deforestation is by local communities for using the mangrove logs for construction of their houses (huts) and as firewood, as our field enquiries revealed. At some locations, the bare ground appears in light (white to pale blue) tone (Figure 2-c) due to salt encrustation in the areas where the mangrove vegetation declined and the land dried out, because extreme salinity can lead the death of mangrove plants (Chen and Ye 2014). The main reason for increased salinity regime in certain parts of mangrove ecosystem is construction of dams and barrages across rivers and consequent reduction in freshwater inputs into the system through the rivers (Spalding et al. 1997). Identification of such bare patches from time series satellite images indicated loss of mangroves in both the deltas.

In the Krishna delta, mangrove loss by deforestation and decline was 911 ha between 1977 and 1990 (70 ha yr⁻¹) including 238 ha under salt encrustation, followed by 936 ha during 1990–2000 out of which salt encrustation appeared in 392 ha. The loss of mangroves during 2000–2013, however, was very low with only 70 ha was lost including 39 ha under salt encrustation. Although exact reasons for this decrease in the rate of mangrove decline by salt encrustation during 2000–2013 are difficult to ascertain, probably the areas dried out of freshwater reach from the river inputs were limited in extent as most of such relatively higher topographic areas within the mangrove forest were already dried out in the earlier periods. As such only a few more smaller extents were added since 2000. In the Godavari delta, mangrove degradation by deforestation (salt encrustation) was 561 ha (61 ha) during 1977–1992, about 1,821 ha (465 ha) more during 1992–2001 and another 68 ha (39 ha) during 2001–2013. On the whole, the loss of mangrove vegetation under this category was 1,917 ha in the Krishna delta during 1977–2013 at a rate of 53.3 ha yr⁻¹ of which 34% (669 ha) by salt encrustation, whereas in the Godavari

Figure 2. Land use/land cover map prepared from the satellite image (Resourcesat-1 LISS IV) from 2013 showing the mangrove forest (in dark green colour) in the Krishna delta fringing the three terminal branches of the Krishna River. Black coloured dotted line represents the shoreline position in 1977 indicating coastal retreat by erosion between 1977 and 2013. The two photographs to the right of the figure show the nature of coastal erosion leading to destruction of mangroves at the mouth of the western distributary (a), and exposure of clay beds by removal of overlying mangroves between the eastern and central distributaries (b). The light blue coloured patches amid the mangrove forest are the bare patches with salt encrustation (c).
delta, the mangrove loss under this category was comparatively higher at 2,450 ha during 1977–2013 at a rate of 67 ha yr$^{-1}$ including 565 ha (23%) under salt encrustation. Progressive increase in mangrove loss by salt encrustation is perhaps a consequence of manifold decrease in water discharges and sediment loads through the Krishna and Godavari rivers due to impounding of water at the burgeoning dams in the respective drainage basins (Nageswara Rao et al. 2010), depriving the estuarine regions of the freshwater inputs and nutrients.

Mangrove degradation for aquaculture  Encroachment for aquaculture is one of the major causes of mangrove destruction in recent decades in many countries (e.g. Thu and Populus 2007; Stuart 2013; Karstens and Lukas 2014). Satellite image analysis substantiated by field observations revealed that mangrove vegetation was extensively damaged for aquaculture encroachments in the K–G delta region. Figure 3 shows the stages of removal of mangrove vegetation (Figure 3-b), construction of fishponds (Figures 3-c and 3-d) in the Godavari delta region. About 335 ha of mangrove area in the Krishna delta was converted into aquaculture ponds during 1977–1990 (25.8 ha yr$^{-1}$), which increased to 680 ha (68 ha yr$^{-1}$) during 1990–2000, followed by a further encroachment over 297 ha (22.8 ha yr$^{-1}$) during 2000–2013. In the Godavari delta, mangroves were removed over an area of 306 ha (20.4 ha yr$^{-1}$) for aquaculture during 1977–1992, 132 ha (14.7 ha yr$^{-1}$) during 1992–2001 and 158 ha (13.2 ha yr$^{-1}$) during 2001–2013. On the whole, the Krishna delta lost

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**Figure 3.** Land use/land cover map prepared from the satellite image (Resourcesat-1 LISS IV) from 2013 showing the mangrove forest (in dark green colour) in the Godavari delta south of Kakinada city.

Black coloured dotted line along the delta front represents the shoreline position in 1977 indicating the coastal retreat by erosion (between 1977 and 2013), leading to mangrove destruction and withering (a). Mangrove vegetation is cleared (compare b and c) for creating aquaculture ponds (d).
1,312 ha of mangroves for aquaculture during 1977–2013, at an average rate of 36.4 ha yr\(^{-1}\), while the Godavari delta lost 596 ha (16.5 ha yr\(^{-1}\)) during 1977–2013. The rate of destruction was higher during the 1990–2000 at 68 ha yr\(^{-1}\) in the Krishna delta and 20.4 ha yr\(^{-1}\) during 1977–1992 in the Godavari delta.

**Mangrove restoration**

While the mangrove vegetation was being degraded by several natural and anthropogenic causes, considerable efforts are also being made for conservation, restoration and sustainable use of mangroves, which in turn improves the carbon stocks (Tang et al. 2016). Mangrove reforestation programs need to consider selection of suitable species for a given environmental conditions such as the topography and soil condition (Miyagi et al. 2014). A massive mangrove reforestation program taken up by the Ho Chi Min City Forest Department in the Can Gio Mangrove Biosphere Reserve (MBR) since 1978 resulted in spread of mangrove forest (Miyagi et al. 2014). In fact, *Rhizophora apiculata*, which was chosen for reforestation in the MBR not only established in the region but also promoted sedimentation in the surrounding areas which in turn facilitated colonization of *Avicennia alba* and *Avicennia officinalis* resulting in a diversified mangrove ecosystem (Miyagi et al. 2014). Several agencies took up mangrove restoration projects in the K–G delta region. The Forest Department of Andhra Pradesh has taken up the mangrove afforestation in 1991, and non-governmental organizations (NGO) such as M. S. Swaminathan Research Foundation (MSSRF) during 1997–2007, and Coastal Environmental Rehabilitation Programme (CERP) during 2004–2008 also participated in the mangrove reforestation work in the region.

The reforestation methods in the region involved digging of networks of canals across the mudflats and bare patches in mangrove swamps linking the main canal with the river distributary or major tidal channels for a free flow of brackish water. Mangrove saplings were planted along the water front on both sides of these canals. Two types of canal networks were attempted. Initially, the Forest Department and MSSRF used ‘fish-bone’ type of canals in which the branch canals were dug at 30° angle to the main feeder canal (upper panel in Figure 4-a). However, CERP followed altogether a new method called ‘snake’ method of canal network (upper panel in Figure 4-b) in which all the canals were dug as sinuous meanders almost replicating the natural meandering of the tidal channels for ensuring a better flow of water. Based on the salinity levels of the soil, mangrove species namely *Avicennia marina*, *Avicennia officinalis* and *Excoecaria agallocha* were selected for planting in the degraded areas (Ramasubramanian and Ravishankar 2004). Both the methods have been successful in restoring mangrove vegetation in the region as indicated by a comparison of middle and lower panels in Figures 4-a and 4-b, respectively. The Forest Department has planted mangroves over 2,000 ha, and MSSRF over 520 ha in the K–G deltas whereas CERP took up afforestation over 264 ha in the Krishna delta using *Avicennia marina*, *Avicennia officinalis*, *Rhizophora mucronata* and *Rhizophora apiculata* species. But the actual increase in mangrove extent as estimated from the satellite image analysis was much higher than the total area in which mangrove reforestation was taken up. The mangroves have grown not only where they were planted but also spread to the adjacent areas as well. The dispersal mechanism of mangrove propagules by water to wider areas where they anchor the favourable ground (Van der Stocken et al. 2015) has apparently led to spread of mangroves in the K–G deltas.

**Net increase of mangrove area**

In spite of cumulative loss of mangrove vegetation in both the deltas due to several causes, there has been a net increase in mangrove cover in the region, obviously as a result of afforestation measures by allowing flow of brackish water into the degraded areas through artificial canal networks. Analysis of time series satellite images revealed that the mangrove cover in the Krishna delta decreased from 17,966 ha in 1977 to 16,110 ha by 1990 as a direct result of the mangrove degradation. During 1990–2000, however, the net loss was only 55 ha from 16,110 ha in 1990 to 16,055 ha in 2000, despite the fact the mangroves degraded over 1,745 ha due to various factors mentioned above. That means the restoration programs led to a total addition of 1,695 ha thereby covering up for most of the mangrove loss. Later, during 2000–2013, the net increase of mangrove cover was 4,101 ha from 16,055 ha in 2000 to 20,156 ha by 2013. On the whole, the net gain of mangrove extent was 2,190 ha in the Krishna delta during 1977–2013 (Table 2).

In the Godavari delta, mangroves occupied an area of about 17,092 ha in 1977. The cumulative loss of mangrove was 1,043 ha during 1977–1992 due to various causes of degradation. But the actual area has increased by 1,458 ha, which indicates that the mangroves were restored over 2,501 ha during the period after offsetting the loss by degradation of 1,043 ha (Table 2). Later between 1992 and 2001, the mangrove cover decreased from 18,550 ha to 16,543 ha showing a net loss of 2,007 ha.
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in spite of the increase of 267 ha by restoration because of widespread deforestation, which alone accounted for a loss of 1,821 ha during 1992–2001. However, mangrove cover increased by 2,584 ha from 16,543 ha in 2001 to 19,127 ha by 2013 completely offsetting 457 ha of mangrove loss by degradation (Table 2). On the whole, mangrove forest showed an increase of 2,035 ha in the Godavari delta during the 36-year period (1977–2013). The total increase of mangroves in both the deltas put together is 4,225 ha offsetting the loss of 8,036 ha by various types of degradation.

Conclusions

Four sets of satellite imagery representing 1970s, 1990s, 2000s, and 2013 were analyzed to reveal the changes in mangrove areas in the K–G delta region. There are several causes for the destruction and degradation of mangroves. The cumulative loss of mangrove vegetation due to coastal erosion, conversion to aquaculture and other deforestation activities was 8,036 ha between 1977 and 2013 in this twin delta region along the east coast of India. The change in hydrological regime of the Krishna River with a sharp decrease in discharge by the construction of dams might have resulted in mangrove decline by salt encrustation, while in the Godavari delta, rampant deforestation led to significant mangrove reduction.

Despite the cumulative loss of mangroves detected from satellite images, total area showed a relative increase in both the deltas during 1977–2013 owing to the afforestation measures taken up by several agencies in the region. The total increase of mangrove cover by 4,225 ha in spite of its loss by various factors highlights the success story of mangrove restoration efforts in the K–G delta region.

While the present study brought out the temporal changes in the mangrove forest cover, future studies based on remote sensing and extensive field observations...
are necessary for a proper appraisal of the mangrove forest expansion by afforestation efforts as well as natural regeneration.

This study emphasized the efficacy of remote sensing and GIS in monitoring the spatio-temporal changes in the mangrove forests besides aiding to decipher the causes and consequences of various human activities in the region.

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