Deltaic Expansions of the Mahanadi Tri-delta and the Chilika Lagoon: Geospatial Approach

Binod Kumar Sethi\(^1\), Siba Prasad Mishra\(^2\), Kabir Sethi\(^1\) and Kamal Barik\(^2\)

\(^1\)Department of Geography, Utkal University, Vani Vihar, Bhubaneswar, Odisha, India.
\(^2\)Department of Civil Engineering, Centurion University of Technology and Management, Bhubaneswar, India.

Authors' contributions

This work was carried out in collaboration among all authors. Authors BKS and SPM designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors KS and KB managed the literature searches, GIS works and collection of data. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/CJAST/2020/v39i3431036
Editors:
(1) Dr. Rui Xiao, Southeast University, China.
Reviewers:
(1) Ayuba Abubakar Fusami, Abubakar Tafawa Balewa University Bauchi, Nigeria.
(2) Zagbayou Nakpoh Nadege Barbara, University Felix Houphouet Boigny, Côte d'Ivoire.
Complete Peer review History: http://www.sdiarticle4.com/review-history/62226

Received 24 August 2020
Accepted 29 October 2020
Published 09 November 2020

ABSTRACT

Prelude: The major river deltas are sinking, shrinking which accommodate ≈40% of global population. The Mahanadi tri-delta along the east coast of India consists of three river deltas i.e. the Mahanadi, the Bramhani and the Baitarani. The tri-delta encompasses many ecological hubs and the 2\(^{nd}\) largest lagoon of Asia, the Chilika Lagoon lies in the southern corner of the delta. Presently the Mahanadi tri-delta and its coastal environments are under threat due to coastal vulnerability, population growth, urbanization and industrialization but the expansion of the delta towards south is observed.

Scope: Present research is ubiquitous to know the quantity of sinking, shrinking and subsidence of the Mahanadi tri-delta under congregation of different geological setting, damming, LULC changes, soil erosion, regional sea level rise, and anthropogenic pressure. Also geospatial geomorphic changes in the anastomosis of the rivers and drainage channels are studied along with expansion of the delta to its southern fringe

Methodology: The causes of vulnerability of the delta are estimated from sediment inflow and marine transgression is evaluated. The land use and land cover changes has been evaluated and analyzed by using satellite imageries, remote sensing, GIS tools and ERDAS softwares.

*Corresponding author: E-mail: 2sibamishra@gmail.com;
Results: The study revealed that due to effect of relative sea-level rise, paucity of sediment influx @ 66.7% to the delta are the main causes for the delta vulnerability accompanied by geo-mining and urbanization. The extention of delta to the south is due to emergence of the Makara river system which carries more flood flow than the existing Daya river. Prominent changes in LU & LC are observed from the satellite imageries of two different period. Changes in the LU &LC of the tri-delta has shown the extension of the Mahanadi tri-delta towards south and shifting of deltaic boundary from 20 m to 50 m contour line in l landward direction during last four to five decades (recasted).

Keywords: Mahanadi tri-delta; Chilika, Daya river; land use and land cover; GIS/RS; geospatial; rivers.

1. INTRODUCTION

The deltas of major rivers are fluvial landmass formed by deposit of sediments when arrive the coastal plains at the mouth of the estuaries transported from inland. Globally the riverine deltas accommodate ~ 500 million people (~61% present projected to rise to 75% in 2025) [1]. Deltas are the hotbeds to array of climate changes (CC) and challenges vulnerable to meteorological extremes and climatic traumas. Syvitski et al. [2,3] has cautioned 33major deltas the modern world in the globe are plummeting at very fast rate during the golden spike period (from 1980 onwards) due to anthropogenic activities. There is a strong coordinating relation between climate change (CC), erratic SW-monsoon, heat wave, lighting, tropical cyclone, varying intensity of rainfall, floods, coastal erosion and finally the LU/LC of the area [4,5,6,7,8,9,10,11,12].

Identification, delineation, mapping and land use and land cover (LU/LC) classification are the key features of the Geographic information system (GIS) and remote sensing (RS) applications for scientific monitoring of supply chain, resource control, policy making and proper planning by knowing the spatial/temporal LU/LC changes of an area. Availability of land records from federal institutions are mainly tabular, Soil maps from National Bureau of soil survey and land use planning of Indian council of agriculture and research (ICAR-NBSS&LUP) are project specific, TOPO Sheets issued from Survey of India (SOI) provides topographic features, Land use atlas issued by National Atlas and Thematic Mapping Organization (NATMO) are micro scaled topographic representation. The LU/LC classified visual maps of an area are versatile and blend the collective advantages of the above.

1.1 Study Area

The Mahanadi tri-delta extends from the Dhamara Port in northeast to the Harachandi area adjacent to the Chilika Lagoon in south. The tri-delta accommodates the major rivers the Mahanadi system, the Bramhani system and the Baitarani system (Fig. 1). The districts housed by the delta and drainage systems are Bhadrak, Kendrapada, Jagpur, Cuttack, Jagatsinghpur (JS Pur), Khurdha and Puri, Fig 2 (A).

Southern part of the largest brackish water lagoon, the Chilika is the estuarine pear-shaped water body of the river Daya and the Bhargovi. The huge Lagoon swells during flood and shrink in summer to cover average area ≈1020sqm and separated from adjacent Bay of Bengal by a length 64.3 km partly fragile towards north and more stable to south with developed agricultural land.

The sediment flow observations of these rivers indicate there is gradual diminishing of the quantity of sediment influx from upper basin in all rivers/rivulets of the Mahanadi tri-delta. A little study has been done about sinking, shrinking and subsidence of the tri-delta either by physical methods or modern GIS and remote sensing techniques. Present study envisages the impact of paucity of sediment influx to delta by introduction of hydraulic structures, urbanization, industrialization and modernization along with natural impressions of sun-earth geometry or meteorological extremes.

The major river course outer embankments, the deltaic boundaries, divide the compound delta with different geomorphologic parameters segregate the compound delta into six important districts. The complex changes caused in land use and land cover pattern and threats of life, migration and pecuniary penalties is foreseen to our upcoming generation in the tri-delta.
Fig. 1. The index map of the study area of the Mahanadi Tri-delta and the Chilika lagoon

Fig. 2(A) & (B). The Chilika lagoon (A) and Mahanadi tri-delta (B) The rivers/drainage system: GIS Imagery

1.2 Scope of Study

The research focuses on the anastomosis of the drainage pattern, climatological anomalies, soil changes, sediment influx, vegetation patterns and area wise changes of geomorphologic parameters. It is observed that there is extension of the delta to southern and western fringes. There is a large conversion of wet and fallow lands to agricultural land, township and settlements; waste land. An argument for a combined strategic plan is focused to save the
deterioration of the tri-delta from climatic vulnerability Fig. 2(B).

1.3 The Rivers and Major Drainage System Tri-delta

The riverine and major drainage system consists of four subsystems South Mahanadi Delta (SMD), Central Mahanadi Delta (CMD), North Mahanadi Delta (NMD) and conjoined Brahmani-Baitarani Delta (BBD). The major drainage systems are the Daya, the Bhargovi and the Kushabhadra rivers in SMD, the Devi, the Biluakhai, and the Alaka in CMD, the Paika, the Nuna, the Suka, the Chitrotpala, the Karandia, the Bada genguti in NMD and the Brahmani, the Tanti, the Kani, the Badua, the Rudtara, the Kelua in Brahmani system and the Reba, the Kapali, the Kochila, the Genguti, the Salandi in the Baitarani system.

These rivers, their estuaries, and deltas are in combination form the Mahanadi tri-delta. For the LU/LC changes these rivers play pivotal role for the natural resources which must be studied which is the main research objective.

1.4 Deltaic Sediment Disparity

Major deltas from the Ganga Brahmaputra delta, Mississippi delta to the Yellow river delta, about two third of deltas are sinking mainly due to human (anthropogenic) interventions like damming, due heavy land subsidence over exploitation of ground water (formation of deltas) or due to LU and LC changes for excess soil loss [3,13,14], (SOURCE given). They have reported about all most all major deltas of India are sinking [13,14,15]. Indian Rivers along east coast are under considerable threat. They are the Bramhani, the Mahanadi, the Godavari and Krishna deltas, [16,17,18,19] (SOURCE given). Delta along east coast (EC) India with no aggradation but under peril is the Krishna delta. The list of the deltas in EC of India undergoing the process of sedimentation is given in Table 1.

2. REVIEW OF LITERATURE

According to Ericsson et al. [20], have reported that reduction of sediment flux to deltas by retention in dams and hydraulic structures resulting in disparity in consumptive use of runoff from irrigation is the cause of 70% ESLR rise in EC-deltas of India. The Mahanadi and the Bramhani delta of Odisha, India are sinking under the category of deltas at grander risk: decline in aggradation under rates is not exceeding RSLR (relative sea-level rise). According to Dandekar P. et al. [13], the hydraulic intervening structures across rivers have reduced the sediment entry to the deltas of the rivers the Krishna’s (94%), the Narmada, (95%), the Cauvery and the Indus (80%), the Sabarmati (96%) and, 74% reduction in the Mahanadi, and the Godavari, whereas 50% reduction the Brahmani, Syvitski et al. [3].

The sediments transport is a slow process and major dams are constructed in the 20th century, it is estimated that 33 major deltas of the globe shall affect 8.7million people and 28000 Km² area shall be under threat to coastal flooding and augmented salt water intrusion by 2050 and shall increase by 50% towards end of 21st century [3]. Report of IPCC [21,22] had mentioned about 75% decrease of sediment flux covering basin area of 19000 TKm² in last 5decades due to sediment trap by damming. As prints of Anthropocene, the shoreline is receding at places like Ramachandi, Satabhaia coast, @ 10 to 15 m/year since 2004 which signifies the delta is prograding, Mukhopadhyay et al. [23]. Like the neighbor Ganga-Brahmaputra and the Godavari-Krishna delta, the Mahanadi tri-delta consisting of the rivers the Mahanadi, Bramhani and Baitarani is suffering from paucity of sediment and affected for its natural delta building process due to construction of dams, barrages and many hydraulic structures Rao SMK et al. 2015 (SOURCE given). The thickly populated coastal districts politically covered under the Mahanadi tri-delta are Baleshwar, Bhadrak, Jaipur, Kendrapada, Cuttack, Jagatsinghpur, Khurda and Puri. Ecologically, hydrologically, and geographically the tri-delta are partitioned as the Bramhani-Baitarani delta (BBD), the North Mahanadi delta (NMD), the Central Mahanadi delta (CMD) and the Southern Mahanadi delta (SMD) [12].

The changes of sediment flux, population explosion in the lower deltas and the anthropogenic activities have altered the Land use and Land cover of the deltaic area. Monitoring fluctuations in Land use (LU) and Land cover (LC) is very difficult to access by traditional surveying methods. Whereas use of geospatial satellite data is an accurate and easier (GIS and RS) methods provide LU/LC changes of an area is an accurate, cost and time efficient technique, [24,25,26,27]. About 83% of the deltas get flooded which lies below 5m...
contour line [24,25]. After construction of the Hirakud dam over the Mahanadi and the Rengali dam over the river Brahmanji, major portion of sediment is retained in the reservoir and there is paucity of sediment influx to the deltas by 66.7% and 75% respectively [28].

The present regional sea level rise (RSLR) occurring due to climate changes such as global warming and reduced sediment influx to deltas has become threat for coastal submergence. The ameliorative action may be plan and accommodate with the aggradation and progradation by shifting the settlement considering optimized impact, using land retrieval, coastal protection using soft measures and hard coastal structures.

2.1 Population in the Mahanadi Tri-delta

The population of tri-delta had faced the stagnation period (1901 to 1921), steady growth period (1921-1951), rapid high rise (1951 -1981), high growth with geospatially slowing (1981-2001) and constant rate (=13%) except capital city Bhubaneswar. The Mahanadi tri-delta consisting of the districts Bhadrak, Jajpur, Kendrapada, Cuttack, (J S Pur), Khurda and Puri are thickly populated and economically strong districts. Since last three decades there were drastic changes in the areas due to urbanization and industrialization. The migration of rural settlement to the urban and interior districts to the coastal districts is seen. The rate of population rise of Orissa is 14.05% in the decade (2001-2011) to decade (1991-2001). The Census data report is in Table 2.

As per state Government data there is an increase in forest cover by 865 Km² area in Odisha and the Mangrove increase in the Mahanadi tri-delta is 44 Km² only. According to Census India the persons/Km² were 325, 382 and 502 respectively and area occupied per person according G. Ravi Sankar from NRSC were 0.307Ha, 0.260Ha and 0.199Ha respectively in the years 2001, 2011 and projected 2050. All districts in the Mahanadi delta at present have population density is above the world standards.

2.2 Geography of the Study Area

East coast (EC) of India had gone through manifold oceanic transgressions/regressions geospatially tectonic activities of crustal plates, MSL rise/fall based on alternate warm periods and ice ages under climatic anomalies. Geomorphic proxies of these physical advances are depicting the past paleo macro-climate conducive for conservation and sustenance of natural resources from Jurassic age to present Anthropocene (under debate). The geomorphology, limnology and fluvial landforms have exhibited five sets of strandlines along the coastline with intermittent inner Beach Ridges, Paleo-channels, lagoons and swamps, either exposed or relict as coastal features of past. The GIS technology has unveiled the scales of changes, source, extent, positioning, timeline of the spit growth and also about the formation and extension of deltas inland. The past tectonic, volcanic, meteorological, climatic and oceanic disturbances have brought these changes along shorefront due to erosion and accretion of coastal attributes along with anthropogenic activities along coast line. Rout et al. [29]. In the southern fringes lies the Chilika estuarine Lagoon covering about 1500 Km² inclusive of the swamps, Spits, sand dunes and the huge water body with two interconnected parallel channels where the outer channel is open to Bay of Bengal by one or more tidal inlets(TI) [30].

2.3 Formation of the Mahanadi Tri-delta

The paleo Stratigraphy, geology, climatology and ecology of the East Coast (EC) of India reveals that it was evolved as a result of reconstruction of Gondwana, Ender bay and Mac Robertson lands of Antarctica during Permian – Cretaceous –Jurassic period [31,32,33] (SOURCE given). The basins along EC of India is having NE-SW trend and the rivers formed are Subarnarekha, Baitaran, Brahmani and Mahanadi, Godavari-Krishna, up to the river Vaigai which are pericratonic [31,34] (SOURCE given). The architecture of horst-graben type Mahanadi tri-delta basin is emergent since post Jurassic Vulcanization [33] (SOURCE: given). The Mahanadi tri-delta basins are contiguous with Gondwana land of Antarctica. But the Chilika Lake is in resemblance with Cape Darnley of Antarctica [31,32,34,33]. The Mahanadi tri-delta is a composite tri-delta with all the rivers originating from different directions. The Mahanadi originates from west Maikel range, Brahmani and Baitarani from east Maikel range of Satpura Hills at different heights. The basins were enlarged all through Paleocene period because of deltaic sedimentation, [33] (SOURCE given).
Table 1. The deltas in east of India under peril due to damming the Mahanadi tri-delta & Krishna – Godavari delta

| Delta of the river | Area < 2 m above MSL (km²) | Stormsurge area (km²) | Recent area flooding (km²) | Sediment drop (%) | 20th/ 21st century deposit rate mm/yr | RSLR m | Dams/ barrages built | Deltaic erosion or shoreline recession, Average Sediment MMT |
|--------------------|-----------------------------|------------------------|-----------------------------|-------------------|---------------------------------------|--------|--------------------|----------------------------------------------------------|
| Bramhani           | 640                         | 1100                   | 3380                        | 50%               | 2/1                                   | 0.5-2  | Mandira & Rengali Dams, two barrages Samal and Birupa | 5.23 MMT bet. 1986-2011, 4.973 MMT, 1993-2014 |
| Godavari           | 170                         | 660                    | 220                         | 40%               | 7/2                                   | -3     | 10 dams and 15 barrages/ Irrgn projects                | 76 Km²: 336 Km coast 1965-2008), 1983-2012 Sed.Flux45.57MM |
| Mahanadi           | 150                         | 1480                   | 2060                        | 74%               | 2/0.3                                 | 13     | Hirakud, Hasdeo-Bango, Ravishankar Sagar, Tandula and Dughawa Lower Indravati dams | 28.48MMT 1980-84, & 10.702MMT 1993-2014 |
| Krishna (Under peril) | 250                        | 840                    | 1160                        | 94%               | 7/0.4                                 | ≈ 4    | Dams: Dhom, Almatti Narayanpur, Amar, Kanur, Srisailam, Jurala, Nagarjuna Sagar, Nagajuna Sagar tail pond, Puli chinthala: Prakasam, Hippagiri barrage, | 5.145 MMT bet 1993-2012 |

Source: Syvestky et al., [3], Dandekar P., [13], Gupta et al. [14], Mishra S. P. [15]
Table 2. The statistics of different coastal districts in the Mahanadi Tri-delta

| District | Area (Km²) | Coast length (Km) | Populace density (Per/Km²) | Populace 1991 | Populace 2001 | Populace 2011 | Decadal Increase area rise 21st Century | All forest area (% of area) |
|----------|------------|------------------|-----------------------------|--------------|--------------|--------------|----------------------------------------|---------------------------|
| Bhadrak  | 2,505      | 52.61            | 601                         | 1105834      | 1337349      | 1506337      | 12.94                                  | 75/2                      |
| Jajpur   | 2899       | 2899             | 630                         | 1386177      | 1624341      | 1827192      | 12.49                                  | 303/3                     |
| Kendrapada | 2644    | 83.55            | 545                         | 1149501      | 1302005      | 1440361      | 10.63                                  | 305/14                    |
| Cuttack  | 2505       | 56.95            | 682                         | 2053000      | 2340832      | 2624470      | 12.10                                  | 796/11                    |
| J S Pur  | 1668       | 58.95            | 800                         | 934000       | 1057891      | 1136971      | 07.50                                  | 136/6                     |
| Khurda   | 2813       | 2813             | 800                         | 1502014      | 1877395      | 2251673      | 19.94                                  | 457/00                    |
| Puri     | 3479       | 136.48           | 488                         | 1305365      | 1502682      | 1698730      | 13.05                                  | 214/8                     |

Source: [http://www.citypopulation.de/php/india-odisha.php](http://www.citypopulation.de/php/india-odisha.php), [https://archive.india.gov.in/know_india/districts/andhra1.php](https://archive.india.gov.in/know_india/districts/andhra1.php), [https://www.census2011.co.in/census/state/districtlist/orissa.html](https://www.census2011.co.in/census/state/districtlist/orissa.html), [http://sis.nic.in/isfr2017/odisha-isfr-2017.pdf](http://sis.nic.in/isfr2017/odisha-isfr-2017.pdf)

2.4 Coastal landform Odisha

Mahanadi tri-delta in Odisha has a long coast line of 331.6 Km witnessing severe climatic changes due to fronting meteorological extremes and impact of inland anthropogenic alterations affecting the development and growth of the people and Ramachandran et al. [35], Ramesh et al. [36] (SOURCE: included). Disaster intensity has increased than post 20th century like rainfall, floods, drought, heatwaves, lightening and the 2013, Hudhud 2014, Fani 2019 has shattered the lifeline of the coastal inhabitants and the ecology during the study period [37] (SOURCE included). Coastal erosion has washed out the southern and central Mahanadi tri-delta coasts (~46.5%) and accretion has dominated the Northern Mahanadi and the Bramhani &Baitarani -deltaic districts (~62%) [36], (SOURCE included). Totally erosion and accretion length along Odisha coast are 199 km and 205 km respectively and the rest stable coasts are 32.1 km (data: 1989-91 and 2004-06) [http://iomenvis.nic.in/index3.aspx?sslid=782](http://iomenvis.nic.in/index3.aspx?sslid=782). Increased coastal inundation has helped in salinity intrusion of the coastal districts puri & Jagatsinghpur of the Mahanadi tri-delta. The coastal agriculture and the mangroves area has been drastically affected due to population growth and urbanization and natural events [28,38,39] (SOURCE included).

3. METHODOLOGY

Various methods used for mapping patterns of land are by ground survey, aerial photogrammetry or from high resolution imageries received via satellites. Land Use (LU) is the land utilities like, agriculture, water sheds, water bodies, settlement, shrubs etc. This involves reference line mapping and monitoring till gathering of land use information at a particular time to assess LU changes over a period. The information about LU changes helps us in strategic planning, sustenance conservation and uses during disparity of issues and progressive pressure. The Land cover (LC) of an area includes township, water bodies, vegetation, beaches, sands, barren lands, laterite covers and used to identify, delineate, map for planning and resource usages. Knowing the land cover the monitoring accomplishment of the area can be done. The procedures followed are data source, data downloading, geo-referencing, layer fixing as per classification and analysis of the data.

The LU/LC classification of the Mahanadi tri-delta was (done past tense) done by the help of the satellite RS data considering its repetitive landscape is very useful in mapping of the geomorphologic design and their geospatial changes. The decadal geomorphology changes (LU/LC) considering the years 2007 and 2017 have been studied district wise taking the GLOVIS data. The digitalized maps of the districts were made considering the rivers in the tri-delta such as SMD (Puri district), CMD (Jagatsinghpur), NMD (Jagatsinghpur and Cuttack), Bramhani (Kendrapada and Jajpur) and Baitarani (Bhadrak district). GLOVIS 4 & 5 for the geomorphology map of 2007 and Glovis -8 have been used to find the base map of the Mahanadi tri-delta avoiding cloudy timing. The different layers (eight layers) are stacked by layer stacking methods and atmospheric corrections were made to get clear visible image. Then geo-referencing followed by digitization is done to get the geomorphologic map of the area by the help of Arc GIS to attach data base and image.
processing by using Erdas software (Recasted)). The LULC plot (vectored) for 2007 was made ready on-screen by visual version and digitized (1:50000 scale) based upon interpretation by adopting a standard classification arrangement. The ERDAS imagine (be specific with, and, or both) software is used for the image processing which was conceded by on-screen digitization. Both the LU/LC maps of the year 2007 and 2017 the % of error evaluated, and are found to be within 5% (recasted).

3.1 Bhubaneswar

The image Derived Digital Cadastral Maps showing available LU/LC of the area was (done past tense) prepared from satellite imageries for the period 2007 and 2017 in GIS formats and the comparison of agriculture land, built up / transport, forest, waste Land, water bodies and wet lands has been done. The70 years old latosol covered temple city have witnessed many LU/LC changes after becoming the capital city Odisha from 1950. The major changes are in increase in forest area due to federal initiation to develop more forest area in the Chandka forest belt in the west of Bhubaneswar city and Nandankanan area. After expansion of the capital city, and creation of smart city, the urban area has been expanded. The concept of twin city of Bhubaneswar and Cuttack has increased the built up area further. The city’s expansion with constructions have reduced mainly the agricultural land and the waste land of the twin city areas. (Recasted).

The matrix of the area is a city which is under constant expansion from 1950 onwards with present optimum population density of 2131 per/Km² and occupied by a large numbers of multistoried buildings, satellite townships and slums. The city is highly prone to cyclones, urban floods, and minimal tremors, Fig. 3(a), Fig. 3(b) & Table 3.

| BBSR City                  | FY 2007 % of total area | FY 2017 % of total area | Increase (+)/ decrease (-) Major Causes |
|----------------------------|-------------------------|-------------------------|-----------------------------------------|
| Agricultural Land          | 4973.4                  | 4570.2                  | -0.18529                                |
| Built up & Roads           | 21002.9                 | 19627.6                 | -0.42302                                |
| Forest                     | 13295.5                 | 25442.7                 | 14.02271                                |
| Westland                   | 7287.98                 | 27.93014                | 14.02271                                |
| Waterbodies                | 2674.31                 | 2571.82                 | -0.027462                               |
| Wetland                    | 929.49                  | 860.72                  | -0.027462                               |
| Others                     | 45436.4                 | 38001.9                 | -5.8104                                 |
| Total                      | 95600                   | 91094.08                | 100                                      |
3.2 Khurdha District

Khurdha District (19°55’ to 20°25’ Lat. N and 84°55’ to 86°5’ Long E was born on 1st April 1993, on segregation Puri district. The bio-climate is influenced by brackish water environment of Chilika lake in the east. Khurdha enjoys SW monsoon rainfall of 1408 mm/year with temp ranging 42.2°C in summer and 11.1°C winter normally with humidity ranging from 46% to 89%.

The district is laden with 3 municipalities and 57 colleges / institutions. The Khurdha district depicts assortment of coastal terrain, high lands with sporadic, deltaic alluvial plains of the south Mahanadi delta and bordered by the coasts of the Chilika lagoon. The soil of the district is lateritic and granite bedded of Eastern Ghats Belt hills range. The LU / LC of the area is given in Fig. 4 (a), 4 (b), and Table 4.

The major changes are in increase in forest area due to deforestation and formation of a new district headquarter offices of Government of Odisha and construction of many educational hubs in the area Like NISER, IIT Bhubaneswar and many engineering and other institutions. The economically advanced urban district has highest density with equal share of population (>800per/Km2), less forest, tourism excellency with various eco-sensitive areas. But the district is highly sensitive to cyclones, urban floods, and little prone to tremors of earthquake.

Fig. 4(a). LU/LC map Khurdha except BBSR 2007 Fig. 4(b). LU/LC map Khurdha except BBSR 2017

Table 4. The LU/LC changes in the Mahanadi tri-delta (2007 and 2017) of Khurdha district except BBSR (SMD)

| BBSR City       | FY 2007 Total area | FY 2017 Total area | Increase (+)/Decrease (-) | Major Causes                  |
|-----------------|--------------------|--------------------|---------------------------|--------------------------------|
|                 | Ha %               | Ha %               |                           |                                |
| Agricultural land | 17677.5 53.40634 | 14587.9 44.07221 | -9.334139                 | Minimal change                 |
| Built/transport | 2658.5 8.031722   | 3677.05 11.10891  | 3.07719033                | was noticed in the last decade. Most |
| Forest          | 6223.5 18.80211   | 6261.2 18.91601   | 0.11389728                | of the city waste of            |
| Waste Land      | 5200.65 15.71193  | 6913.3 20.8861    | 5.17416918                | BBSR is dumped in               |
| Water bodies    | 68.33 0.206435    | 213.8 0.645921    | 0.4394864                  | Khurdha area so                |
| Wet land        | 1176.04 3.552991  | 1097.5 3.31571    | -0.237281                  | major change is seen           |
| Others          | 95.48 0.288459    | 349.25 1.055136   | 0.76667674                 |                                |
| Total Area      | 33100 100         | 33100 100         |                            |                                |
3.3 Puri District

Puri district lies adjacent to BoB ever itinerant coast line of length 138.46 Km with 40.5% erosion and likely to face probable maximum storm surge (PMSS) of 4.3m as per National assessment of shore line changes (NASC), FY2012.

The largest brackish water lagoon of Asia, the Chilika lake is in the southern part occupying average about 1000 Km2 posing threats of sedimentation, downsizing, depleting and changing its fragile ecosystem. The population growth, hydraulic infrastructures and recurrent intensified flood and storm activities from 1999 onwards (drought 2001, flood 2004, 2006, 2008) and storms (2013, 2014 and 2019) have completely changed the LU/LC pattern of the district.

The district has less forest cover, sand dunes, waterlogged areas, dune forests, eco-beach tourism potential, with eco-sensitive zones, and controversial LU/LC of Lord Jagannath. The changes occurred in between 2007 to 2017 is shown in Fig. 5(a), Fig. 5(b) and Table 5.

![Fig. 5(a). LU/LC map Puri district 2007](image1.png)

![Fig. 5(b). LU/LC map Puri 2017](image2.png)

Table 5. The LU/LC changes in the Mahanadi tri-delta FY 2007 and FY2017 of Puri district (SMD)

| Puri City (without Chilika lagoon) | FY 2007 | % of total area | FY 2017 | % of total Area | Increase (+)/ decrease (-) | Major Causes |
|-----------------------------------|---------|----------------|---------|----------------|---------------------------|-------------|
| Ha                                | %       | Ha             | %       |               |                           |             |
| Agricultural land                 | 168474  | 69.96428571    | 165206.3| 68.17947      | -1.78482                  | Change of wet lands to agri-culture due to extension of SMD, Rise of population so more houses |
| Built up / transport              | 28615.3 | 11.88343023    | 30554.2 | 12.6095       | 0.726072                  |             |
| Forest                            | 13374.1 | 5.554028239    | 13219.7 | 5.455677      | -0.09835                  |             |
| Coastal waste                     | 494     | 0.205149502    | 1296.64 | 0.535114      | 0.329965                  |             |
| Water bodies                      | 7717.1  | 3.204775748    | 8223.4  | 3.393739      | 0.188963                  |             |
| Wet land                          | 19285.9 | 8.009094684    | 16537.48| 6.824901      | -1.18419                  |             |
| Others                            | 2839.6  | 1.17923588     | 5262.2  | 2.171673      | 0.992437                  |             |
| Total Area                        | 240800  | 100            | 242310.9| 99.17007      |                           |             |
Built up area has been increased due to increase in population and growth of the city. Water bodies and coastal waste land has increased due to erosion and effect of devastation caused by Phailine and Hudhud in the years 2013 and 2014 respectively. Though water bodies have increased along the coastal are but there is conversion of lacustrine area in Sakhigopal, Brahamagiri and kanas block being converted to agricultural land. Coastal waste land has increased due to formation of lateral channels along coast and outer channel of Chilika Lake.

The Chilika (Ramsar site 229) is the most expansive coastal lagoon in Odisha, India, is shallow, brackish, lagoon, running parallel to Bay of Bengal. The water spread area of the lagoon has downsized from 1165km² during flood and 906 km² in 1950’s to av. area varying from ≈1011 to ≈770 Km², average depth ≈ 1.5m during 2012. Sterling A. [4], Mishra SP. [33]. The coastal stretch has become short from 70.81 km to ≈63.4 km due to shrinkage in spread. The maximum width has been reduced 32.2 km in 19th century to ≈20 km at present. The lagoon divided into four sectors north, south, central sector, and the outer channel. The lagoon has 203 number isles and islands of sand dunes to rocky hills. The marginalized fishing communities, the lake users residing in and around the lagoon consists of about 200K fishermen. There was 393 Km² of water spread area of the lake had been emerged as landmass mostly from NW sector at the fringe of the Lake between Badagaon to Balugaon in Puri and Khurdha district respectively and the land mass generated was 46 Km² [40]. Since anthropogenic intervention were done on the hydraulic system from Naraj barrage to tidal inlets of the lagoon the flushing flow has changed to late 19th century scenario of the lake catchments including the lake physiography.

3.4 Cuttack district

Cuttack district lies at the apex of the Mahanadi delta where the Mahanadi system (NMD), Kathajodi-Devi system (CMD) and Kuakhai system is originated. There are three barrages in the districts that regulate the hydraulic flow and finally the LU/LC pattern of the district. After formation of the twin city i.e. Cuttack and Bhubaneswar, the shifts and migration of people have multifold during last 10-20years increasing the settlement area. The expansion of the city is limited due to existing reserved forests in the area towards Chandaka side near Nanadan Kanan, a natural wildlife refuge (Recasted sentence). The efficient irrigation setup (the Mahanadi Stage I and II) have made the area green and productivity have increased abruptly with significant LU/LC, Fig. 6(a), Fig. 6(b), & Tab-6.

Fig. 6(a). LU/LC map Cuttack 2007 Fig. 6(b). LU/LC map Cuttack 2017
Table 6. The LU/LC changes in the Mahanadi tri-delta during 2007 and 2017 of Cuttack (CMD)

| Cuttack District FY 2007 | % of total area | FY 2017 | % of total area | Increase (+)/ decrease (-) | Major Causes |
|--------------------------|-----------------|---------|-----------------|-----------------------------|--------------|
| Agricultural Land        | 110970          | 61.85619| 105634          | -3.1657409                 | Deforestation and new settlement |
| Built& Transportation    | 31252.5         | 17.42057| 36438.5         | 2.82472966                 |             |
| Forest                   | 8733.06         | 4.867926| 8771.5          | 0.00553526                 | area, new wetland |
| Waste land               | 4260.36         | 2.374783| 8323.7          | 2.24988056                 |             |
| Water bodies             | 21659.2         | 12.07313| 17136.1         | -2.5522837                 | Scrub rise in Surua – Kathajodi doab |
| Wetland                  | 1752.2          | 0.9767  | 2205.5          | 0.24867978                 |             |
| Others                   | 772.68          | 0.430702| 1475.7          | 0.38919932                 |             |

The twin cities, Cuttack and Bhubaneswar has come closure in the decade under study. The agricultural land has decreased by 3 % whereas the homestead land has increased due to accommodate the rising population by 06 %. The dumping area and waste land has been increased by 2% whereas the water bodies have reduced by 6% indicating that most of the water logged areas were converted to settlements.

3.5 Jagatsinghpur District

Jagatsinghpur (J. S. Pur) district (long 86° 3’ E to 86° 45’ E. and between lat. 19° 58’ N to 20° 23’ N) carved out of Cuttack district in 1993 from Cuttack district. It is coastsional located, riverine (Mahanadi system) and with coastal ecosystem and geography.

It is situated in Prachi valley and near the Chitrotpala River, a distributary of the Mahanadi branch with 2nd most populated district in Odisha. Geographically the district has minimum area, Table -2 (clarified); female ratio is higher, economically sound due to port corridor, high yielded paddy crops, fishing, and tourism. The Hukitola bay is constantly changing in its barrier spits and mangrove vegetation and bay area. The LU/LC cover is highly sensitive / vulnerable to disasters like floods, cyclones, storm surges, cyclones and pastes.

Fig. 7(a). LU/LC map J. S. Pur district 2007  
Fig. 7(b). LU/LC map J. S. Pur district 2017
Table 7. The LU/LC changes in the Mahanadi tri-delta during 2007 and 2017 of Jagatsinghpur district (CMD)

| Jagatsinghpur District | The year 2007 Ha | % of total area | The year 2017 Ha | % of total area | % of increase/decrease | Major Causes |
|------------------------|-----------------|----------------|-----------------|----------------|-----------------------|--------------|
| Agricultural Land      | 115845          | 69.39662051    | 112872          | 65.20625       | -4.19037              | Agriculture land is reduced due to reformations in Hukitola bay as sandy area & water bodies |
| Built up & Transportation | 33267          | 19.92850252    | 34535.9         | 19.95142       | 0.022915              | Forest |
| Forest                 | 3058.6          | 1.832245703    | 3223.56         | 1.862253       | 0.030008              | Waste/ SANDY AREA |
| Waste/ SANDY AREA      | 1026.2          | 0.61474216     | 4256.79         | 2.459151       | 1.844409              | Water bodies |
| Water bodies           | 7071.1          | 4.235922511    | 11285           | 6.519354       | 2.283431              | Water bodies |
| Wetland                | 5554.86         | 3.327623216    | 5018.23         | 2.899036       | -0.42859              | Wetland |
| Others                 | 1109            | 1.2723         | 1908.5          | 1.102542       | -0.16976              | Others |
| Agricultural Land      | 166932          | 100            | 173100          | 100            |                       |                           |

There is constant accretion and erosion along the coasts of the district since two decades. There are changes in the Ekakula spit and formation of parallel channels at the out falls of drainage channels and rivers and extension of Paradeep port and waste disposed due to rise in population.

3.6 Kendrapada District

Kendrapada district (between 86°14’ to 87°3’ E long, and 20°21’ to 20°47’N Lat) is delimited by the Bhadrak, Jagatsinghpur, Cuttack and Bay of Bengal in North, South, west and east respectively covering area of 2644 Km². The Coastal areas of Mahanadi delta is influenced (clarified) by variation of LU/LC features (changes in towns, forests, agricultural land etc) are vigorously structured due to marine and terrestrial processes and controlling by natural and anthropogenic activities.

The district covers one national park and wild life sanctuary at Bhitar Kanika encompassed by Mangroves and a nesting area for sea turtles (Olive Ridley) and salt water crocodiles. The Paradeep port and few land marks Jambu dwipa, APJ Kalam Island are along the coast. High marine erosion and transigration has been observed in last decade at places Satabhaya, and Pentho villages submerged under sea.
The LU/LC of the area is little changed between year 2007 and year 2017. The LU/LC coverage exhibits various classes such as water body, vegetation; agricultural land settlement and roads, Waste and wet lands, scrub, mangroves and sand have little changes.

3.7 Jajpur District

Jajpur district (20°35'N to 21°10'N Lat and 85°41'E to 86°38'E long) of area 2899 Km² is bounded by Keonjhar and Bhadrak districts in north, Cuttack in south, Dhenkanal in west and Kendrapada and Bhadrak districts in east. Jaipur district depicts countryside area with high mining activities with industries.

Geographically the district is a fusion of river plains of Bramhani system, mountainous ridges and high lands. The steel pivoted district is occupied by agriculture, mining and steel industry. It is a cyclone and flood vulnerable district. The huge mining activities are plummeting vegetation which is restored by afforestation. The changes inferred from the LU/LC decadal data of the district narrates agricultural lands are increased with increase in population and search for food grains. The built up areas has increased by 3% between 2007 and 2017 as the demographic and industrial activities in the area has increased.

3.8 Bhadrak District

The district is positioned (21°0′ N to 20°59′ N & 86°17′ E to 86°53′ E) of area 2505 km², population of 1506522 in 2011 census with population density (601 per /km²). Recently constructed Dhamara port on the Baitarani estuary has changed the LU/LC pattern of the district. The coastal length of the district is 52.61 km which is included in Bramhani- Baitarani delta. The inland at 10 km distance there lies buffer zone which is lagging forest cover but during last 2 to 3 decades, plantations with settlement has increased [41].

4. DISCUSSION

From the beginning of Sindhu civilization to date, deltas are tempting places for settlement due to abundance in fertile land (alluvial and flat terrain), food, water and favourable climate (clarified). During British era; land was used as tools for earning revenue whereas post-independence philosophy was poverty mitigation, augmenting of yield and fare distribution of land among its stake holders through land reforms and industrialization and infrastructural development.

Geospatial changes in geomorphology and river courses were prominent and coastal land mark which was up to 10-20 m contour extension from MSL. People migrate from inland to deltatic topography, fertile alluvial land, flat terrain, and ample water). It is studied by different authors and reported that the deltas are transitory and long scale migration is common in deltas [42,39] (evidence provided). However in the beginning of 21st century the Mahanadi tri-delta has become prey to meteorological extremes, high tidal waves, heat waves resulting in regional sea level rise in Bay of Benga, It is predicted that future sea level shall rise, sink shrink and subside coupled with other disasters triggered by environmental changes [43] (cleared). The study has the result of coastal inundation which shall affect large numbers of people and shall cause mass migration. There is urge for LU/LC of the tri-delta immediately through regular intervals to convey information for strategic planning to combat coastal flooding due to deltatic retrogression (cleared).

Table 8. The LU/LC changes in the Mahanadi tri-delta during 2007 and 2017 of Kendrapada district (CMD +BBD)

| Jagatsinghpur District | FY 2007 | % of total | FY 2017 | % of total | Major Causes |
|------------------------|---------|------------|---------|------------|--------------|
|                        | Ha      | %          | Ha      | %          |              |
| Agricultural Land      | 182518  | 71.26852731| 182078  | 71.09639  | -0.17214     |
| Built up & transport   | 24631.9 | 9.6181158  | 25163.7 | 9.825724  | 0.207609     |
| Forest                 | 20286.3 | 7.921272014| 20216.5 | 7.893981  | -0.02729     |
| Wasteland              | 1578.52 | 0.616370965| 3109.5  | 1.214173  | 0.597802     |
| Water bodies           | 17617   | 6.878979857| 17548.9 | 6.852357  | -0.02662     |
| Wetland                | 2812.8  | 1.098325171| 2383.8  | 0.930808  | -0.16752     |
| SAND                   | 854.5   | 0.333660004| 591.2   | 0.230847  | 0.10281      |
| Others                 | 5800    | 2.264749002| 5008.6  | 1.955719  | -0.30903     |
|                        | 256099  | 100        | 256100.2| 100       |              |
It is necessary to conduct research and find out the impacts of deficient fluxes to deltas due to sediment retention by hydraulic structures and effect on thickly populated deltaic population and ecosystems and the changes in respective LU/LC of the areas by the Federal institutions like MoEF, MOWR MRD and UD department in India Government through environmental impact assessment studies.

The possible LU/LC changes may take place in the area such as forest cover, canopy density, settlement area, flora and fauna; water logged, waste land, coastal erosions and accretions and wetland areas by proper planning by the state (clarified). The dimensional changes of the parameters can only be ascertained through geospatial studies of the tri-delta.

Satabhaya a victim of coastal erosion in Kendrapara district was under submergence by 65% in 21st century and about 7villages consisting of more than 550 families were oustees as declared by the state government and were partly resettled in a nearby village in the study period [39].

Examples of coastal inundation are submergence up to Ramchandi temple by formation of a lateral channel of 6 Km parallel to coast. Similarly the lateral channels near Devi river mouth and Jahania beach have changed the local morphology. The continuous changes in Ekakula shift and transformations in the Hukitola bay have some impact on the territorial ecosystem. (made clear)
The alluvial western boundary of the tri-delta has shifted landward due to provision irrigation system and has vegetative agricultural covers (clarified). Since there is no space for shift of delta it is extending to southern direction where the southernmost river shall be replaced by the Makara river in near future [28].

The erosion and land inundation areas must be attended on war footing basis by constructing sea walls, regular dredging of the river estuaries. That can avoid lateral channel formation. As soft measures to fight coastal erosion it is pertinent to have Cashew/mangrove plantation in coastal areas. (clarified)

The entire Mahanadi tri-delta is considered as a single entity due to its nearness and similar tropical forests, township and agriculture. From the individual study it is observed that all the transformations are coherent in all the sub-deltas so need a unanimous developmental plan to protect it from deterioration from coastal direction, climatic and Anthropocene changes.

During working in the field for 30 years; it is that mining activities changes the natural topography and a positive threat to flora and fauna with the vegetative cover of the area which is explained in the Bramhani and the South Mahanadi deltaic areas in Jajpur and Khurda districts in last 10-20 years (clarified).

The increase in wet lands is noticed in coastal areas in the land sat imagery of the delta which is due to formation of aquaculture ponds in Puri, Jagatsinghpur, Kendrapada and Bhadrak districts. Lateral channels in river estuaries in Puri, Jagatsinghpur and Kendrapada districts which has diverted sands to water channels and inundation.
As per the in situ observations there is constant people’s shift from Jagatsinghpur area in search of livelihood, and migration from rural to urban has become a constant phenomenon in the delta. The industrial and modernization processes have brought in adaptations in the tri-delta which is shown that 10000 deaths in 1999 in super cyclone to only 64 deaths during Fani.

5. CONCLUSION

In the present Anthropocene epoch, the major challenge for the rural areas of the Mahanadi Delta is to restore or maintain the natural delta dynamics as far as possible, to combat the cumulative threat of sea-level rise and coastal erosion, salinity ingress, flooding and frequent cyclones and drought. The riverine system, land deterioration due to excess use of ground water must be addressed.

The LU/LC cover of the six districts has the common problem of increase in home stead land, decrease in agricultural and coastal lands. The coastline is under erosion and reduction in surface water bodies. The change in land cover may challenge the delta residents with pollution, paucity of drinking water, sedimentation of rivers, and deterioration of the present ecosystem and bring changes in biodiversity which must be attended within the tri-delta.

The industrialization, urbanization, shift of rural to urban shall be a challenge within the tri-delta which shall challenge the availability of food, water, vegetation and clean air for future generation, (clarified). The revolution shall incur in the socio-political-economic front which can be only attended if the three river deltas are considered as on delta and integrated planning must be chalked out to save the delta and its people in future.

ACKNOWLEDGEMENTS

We are obliged to Mr. K. C. Sethi who has helped during the preparation of the script. We are also thankful to the people, Water Resources Dept, Odisha for cooperation.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Bianchi TS, Allison MA. Large-river delta-front estuaries as natural “recorders” of global environmental change; 2009.
2. Syvitski JPM, Kettner AJ, Correggiari A, Nelson BW. Distributary channels and their impact on sediment dispersal. Marine Geo. 2005;222&223:75-9.
3. Syvitski JPM, Kettner AJ, Overeem I, Hutton EWH, Hannon MT, Brakenridge GR, et al. Sinking deltas due to human activities, Nature Geoscience. Nature Geoscience Advance Online Publication. 2009;1-6. Available: www.nature.com/naturegeoscience

4. Sterling Andrew Orissa: Its geography, statistics, history, religion and antiquities, late personal secretary to Bengal Government, Burton-on-Trent, Staffordshire; 1846.

5. Harrish JC, Young CB. Captain harrish report on mahanadi flood protection survey works, correspondences between the chief engineer and superintending engineer and executive engineer, lower provinces 1858 to 1860. Source Water Resources Dept. Library Odisha. (Not Published); 1860.

6. Niyogyi D. Geology of the coastal plain in West Bengal and Orissa. Indian Journal of Earth Sciences. 1991;2:51-61.

7. Rao SM, Rao KN, Vaidyanadhan R. Morphology and evolution of Mahanadi and, Brahmani Baitarani deltas, symposium on morphology and evolution of landforms. Dept. of Geology, University of Delhi, New Delhi. 1978;241-249.

8. Bharali B, Rath S, Sarma R. A Brief review of Mahanadi delta and the deltaic sediments in Mahanadi basin. Memoirs Geol. Soc. Ind. 1991;22:31-49.

9. Mahalik NK, Das C, Maejima Wataru, Geomorphology and evolution of Mahanadi Delta, India. Journal of Geosciences, Osaka University. 1996;39:6:111–122.

10. Mishra N. Macroscale hydrological modelling and impact of land cover change on streamflows of the Mahanadi River Basin; M. Tech. dissertation, Indian Institute of Remote Sensing (ISRO); 2008.

11. Somanna K, Reddy TS, Rao TS, Geomorphology and evolution of the modern Mahanadi Delta Using Remote Sensing Data, Int. JR. of Science and Research (IJSR). 2016;5(2)-7.

12. Mishra SP, Sethi B Ku., Barik K. Ku., Delta Partitioning, Geospatial changes, anastomosis of Mahanadi Tri-delta, India, International Journal of Earth Sc. and Eng. Caffetinnova org. 2019;12(01):21-40. DOI:10.21276/ijee.2019.12.0103

13. Dandekar P. Shrinking and sinking deltas: Major role of dams in delta subsidence and effective sea level rise. Delhi, India: South Asia Network on Dams Rivers and People (SANDRP); 2014. Available: http://www.indiaenvironmentportal.org.in/files/file/Shrinking_and_sinking_deltas_major_role_of_Dams_May_2014.pdf

14. Gupta H, Kao SJ, Dai M. The role of mega dams in reducing sediment fluxes: A case study of large Asian rivers. Journal of Hydrology. 2012;464-465,447-458. Available: https://doi.org/10.1016/j.jhydrol.2012.07.038.

15. Mishra SP. Management of the sediment transported by the south Mahanadi deltaic rivers to the Chilika lagoon. Int., Jour. Adv. Research. 2017;5(6):1005-1020.

16. Rao SM, Rao KN, Vaidyanadhan R. Morphology and evolution of Mahanadi and Brahmani Baitaran delta. Symposium on Morphology and Evolution of Landforms, Dept; 1978.

17. Hema Malini B, Rao KN, Coastal erosion and habitat loss along the Godavari Delta Front: A fallout of dam construction (?), Current Science; 2004.

18. Gamage N, Smakhtin V. Do river deltas in east India retreat? A case study of the Krishna delta. Geomorphology. 2009;103:533–540.

19. Pramanik MK, Biswas SS, Mukherjee T, Roy AK, Pal R, et al. Sea level rise and coastal vulnerability along the eastern coast of India through geo-spatial technologies. J Geophys Remote Sensing. 2015;4:145. DOI: 10.4172/2469-4134.1000145

20. Ericsson JP, Vörösmarty CJS Dingmanb L, Ward LG, Effective sea-level rise and deltas: Causes of change and human dimension implications, Glob. Planet. Change. 2006;50:63–82. DOI: 10.1016/j.gloplacha.2005.07.004-2006

21. IPCC (Intergovernmental Panel on Climate Change) AR-4, Climate change, impacts, adaptation and vulnerability, contribution of working group ii to the fourth assessment report of the Intergovernmental Panel on Climate Change, Geneva, Switzerland. 2007:976.

22. IPCC, (Intergovernmental Panel on Climate Change) AR-5., Climate Change 2014: Synthesis Report. Contribution of working groups I, II and III to the Fifth Assessment Report of the IPCC [Core Writing Team, R.K. Pachauri and L.A. Stern, Andrew Orissa: Its geography, statistics, history, religion and antiquities, late personal secretary to Bengal Government, Burton-on-Trent, Staffordshire; 1846.
23. Mukhopadhyay A, Ghosh P, Chanda A, Ghosh S, Das S et al. Threats to coastal communities of Mahanadi Delta due to imminent consequences of erosion—Present and near future. Science of the Total Environment. 2018;637–638, 717–729. Available:https://doi.org/10.1016/j.scitotenv.2018.05.076

24. Sharma BS, Ramesh R, Ramchandran S, Coastal landuse and land cover mapping of Puri to Konark coastal stretch of Odisha, Indian geographical Journal. 2007;82(1): 37-42.

25. Sharma PK, Lahkar BP, Ghosh S, Rabha A, Das J, Nath NK, Dey S, Brahma NLand-use and land-cover change and future implication analysis in Manas National Park, India using multi-temporal satellite data, Current Science. 2008; 95(2):223-227.

26. Panwar S, Sinha R Ku, Singh G. Time sequential surface change analysis of Talcher-Angul region of Orissa using remote sensing and GIS, Inte. Jr. of Geomatics and Geosciences, Resources, Working-papers. 2011;1(4):828-838.

27. Guru B, Neha SVM, Anubhooti Y. Study the land use and land cover changes and CRZ in the coastal area of Ganjam district, Odisha, Conf.: Inter. Soc. of Photo grammar and Remote Sensing (ISPRS), Mid-Term Symp of the Tech Commission VIII -At: Hyd, India, Proceedings, 2014;1-5. Available:http://www. planningcommission. nic.in/plans/stateplan/sdr_pdf/shdr_ori04.pdf

28. Mishra SP, Das K. Management of soil losses in South Mahanadi Delta, India, International Journal of Earth Sciences and Engineering. 2017;10(02):222-232. DOI: 10.21276/ijeet.2017.10.0213

29. Rout SP, Palanivel K, Kathiravan R, Delineation of Subsurface features of Geological importance using GPR along Coastal Tract of Puri-Balasore Districts of Odisha, India. JASC; Journal of Applied Science and Computation. 2018;5(11): 1081-1087.

30. Mishra SP. Rejuvenation of lagoons along the east coast of India, management: Anthropocene approach, Int. Jr. of advanced Research. 2019;7(1):688-714. DOI:http://dx.doi.org/10.21474/IJAR01/8378

31. Sastri VV, Venkatachalam BS, Narayanan V, The evolution of the east coast of India, Elsevier, Palaeogeography, Palaeoclimatology, Palaeoecology. 1981;36(1-2):23-54. Available:https://doi.org/10.1016/0031-0182(81)90047-X(too old citation BUT RELEVANT)

32. Lal NK, Siwal A, Kaul AK. Evolution of East Coast of India – a plate tectonic reconstruction”. Journal Geological Society of India. 2009;73:249-260.

33. Mishra SP, Jena JG. Morphological reconstruction of southern Mahanadi delta and Chilika lagoon, India – a critical study” Int. Journal of Advanced Research. 2015; 3(5):691-702.

34. Nayak S, Das S, Bastia R, Kar B. Lava delta below 85 0 ridge, Mahanadi offshore basin, identification characterization and implication of hydrocarbon prospectively, Petroleum Business (E&P), Reliance Industries limited, India; 2012.

35. Ramachandran R, Purvaja R, Ahana laxmi, Deltas, Coastal vulnerability and management, Inst. for Ocean Management, Anna University Chennai, Chennai - 600025. INDIA. 2009;26.

36. Ramesh R, Purvaja R, Senthil Vel A, National assessment of shoreline changes, Odisha coast, NCSCM/ MoEF Report. 2011;1:1-57

37. Mishra SP, Ojha AC, Fani, an Outlier among pre-monsoon intra-seasonal cyclones over Bay of Bengal, International Journal on Emerging Technologies 2020;11(2): 271-282(2020). ISSN No. (Online): 2249-3255; 11(2); 271-282.

38. Hazra S, Dey S, Ghosh AK. Review of Odisha State adaptation policies, Mahanadi Delta (Deltas, Vulnerability and Climate Change: Migration and Adaptation [DECCMA] Working Paper). Southampton, UK: DECCMA Consortium; 2016. https://generic.wordpressoton.ac.uk/deccma/

39. Hazra S, Das S, Ghosh A, Raju PV, Patel A, Deltas in the Anthropocene, The Mahanadi Delta: A rapidly developing delta in India, Chapter 3, R. J. Nicholls et al. (eds.), Deltas in the Anthropocene. 2020;53-77. Available:https://doi.org/10.1007/978-3-030-23517-8_3

40. Pattanaik S. Conservation of environment and protection of marginalized fishing communities of Lake Chilika in Orissa,
Barik KK, Annaduari R, Mohanty PC, Mahendra RS, Tripathy JK, Mitra D. Statistical assessment of long-term shoreline changes along the Odisha Coast; Indian Journal of Geo Marine Sciences. 2019;48(12):1990-1998.

Mohanty MM. Coastal processes and management of the Mahanadi river deltaic processes, east coast of India, from “Holocene evolution of deltas on the east coast of India”; In book: Deltas of the World, Publisher: American Society of Civil Engineers, New York; 1993.

Unnikrishnan A, Gangan N, Lengaigne M, Sea-level-rise trends off the Indian coasts during the last two decades. Current Science. 2015;108(5):966-971.