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

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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.

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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 2nd 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.

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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, Jajpur, 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.

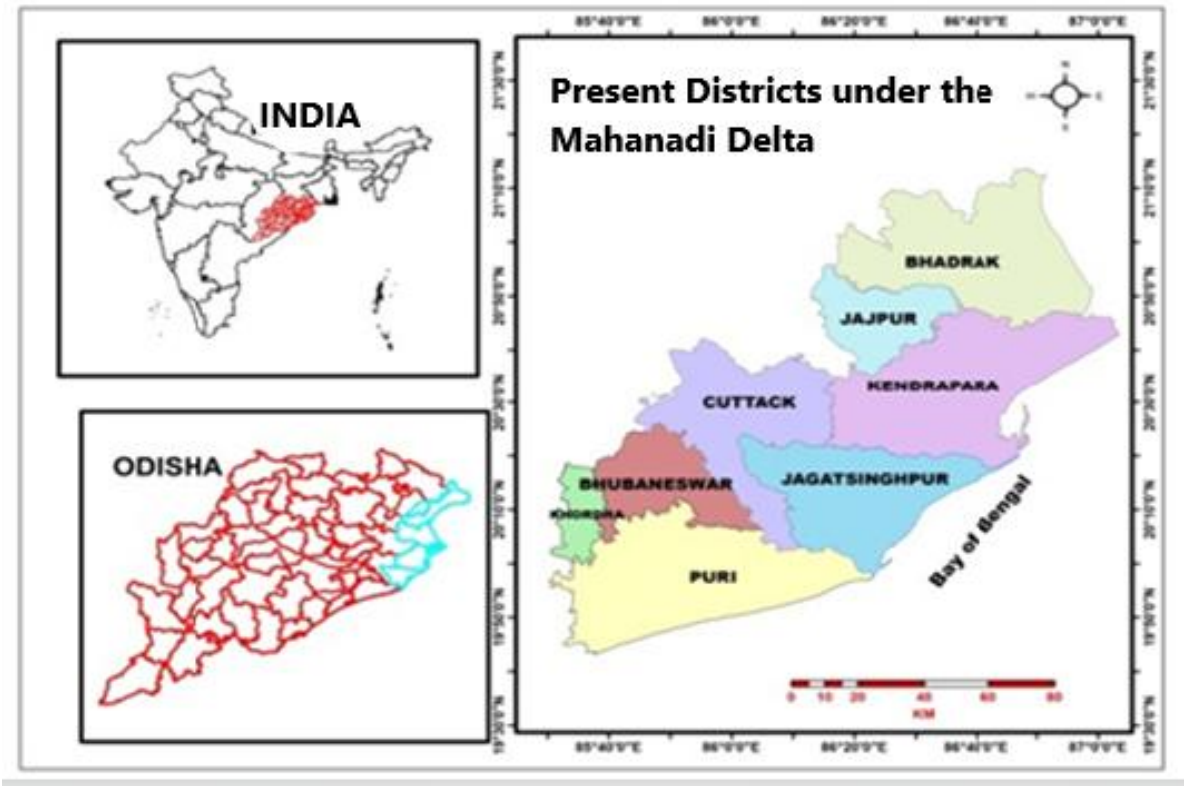


Fig. 1. The index map of the study area of the Mahanadi Tri-delta and the Chilika lagoon

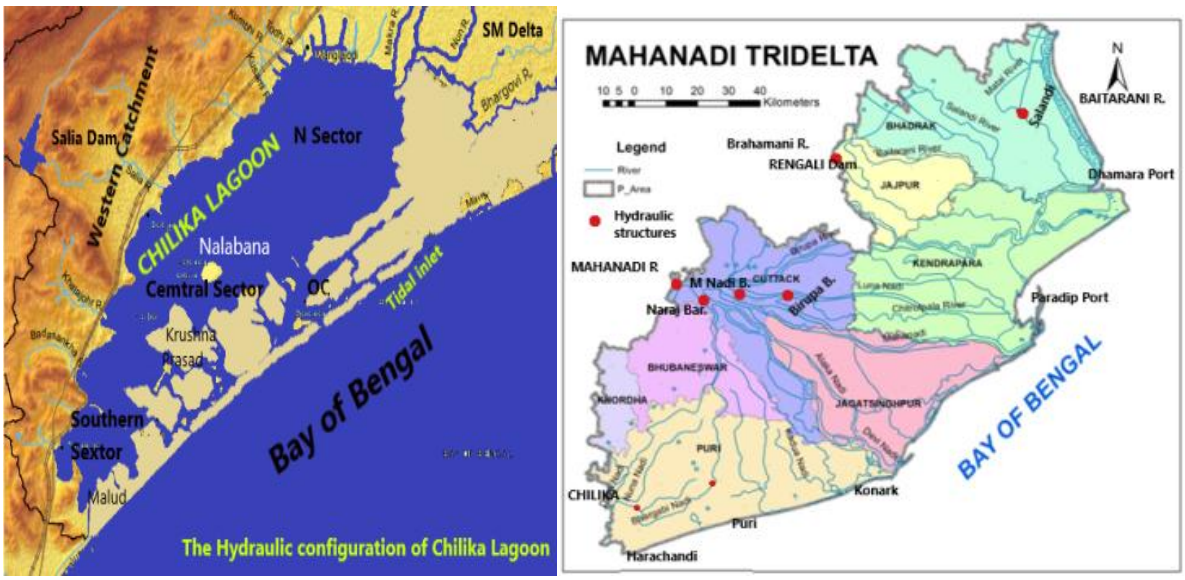


Fig. 2(A) & (B). The Chilika lagoon (A) and Mahanadi tri-delta (B) The rivers/drainage system: GIS imagery

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 deltares) 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 Km^2 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, Jajpur, Kendrapada, Cuttack, Jagatsinghpur, Khurdha 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 Brahmani, 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), Khurdha 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/Km^2 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 fring lies the Chilika estuarine Lagoon covering about 1500 Km^2 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 -Jurrasic period [31,32,33] (SOURCE given). The basins along EC of India is having NE-SW trend and the rivers formed are Subarnarekha, Baitarani, Bramhani 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 Gandwana land of Antartica. 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 Maikela range, Brahmani and Baitarani from east Maikela 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	Stormsurge area	Recent area flooding	Sediment drop (%)	20th/ 21st century deposit rate	RSLR	Dams/ barrages built	Deltaic erosion or shoreline recession, Average Sediment
	(km^2)	(km^2)	(km^2)	(km^2)	mm/yr	m		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 Km^2: 336 Km coast 1965-2008),1983-2012 Sed.Flux45.57MMT
Mahanadi	150	1480	2060	74%	2/0.3	13	Hirakud, Hasdeo-Bango, Ravishankar Sagar, Tandula and Dudhawa 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, Naga rjuna 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	Coast length /delta apex	Populace density	Populace 1991	Populace 2001	Populace 2011	Decadal Increase	All forest/ area rise 21st Cent.
	(Km^2)	Km	(Per/Km^2)	Persons	Persons	Persons	%	Km^2(2015)
Bhadrak	2,505	52.61	601	1105834	1333749	1506337	12.94	75/2
Jajpur	2899	Bramhani	630	1386177	1624341	1827192	12.49	303/3
Kendrapada	2644	83.55	545	1149501	1302005	1440361	10.63	305/14
Cuttack	2505	Mahanadi	667	2053000	2340832	2624470	12.10	796/11
J S Pur	1668	58.95	682	934000	1057891	1136971	07.50	136/6
Khurdha	2813	Chilika	800	1502014	1877,395	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, https://archive.india.gov.in/know india/ districts/ andhra1 .php?, https://www.census2011.co.in/census/state/districtlist/orissa.html, http://fsi.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 bay disturbances, Phailin 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. 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/Km^2 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.

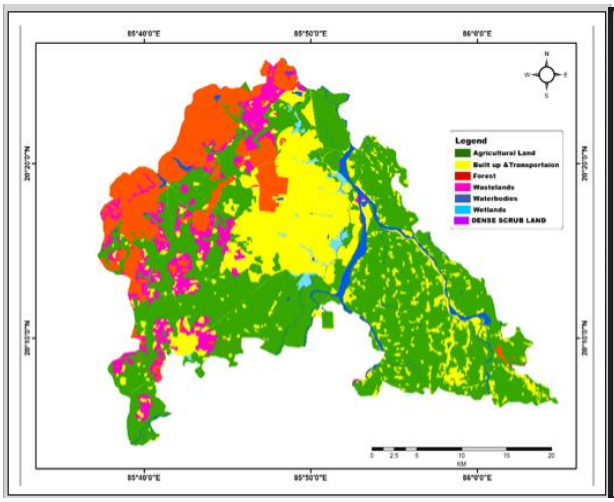


Fig. 3(a). Geomorphologic map BBSR 2007

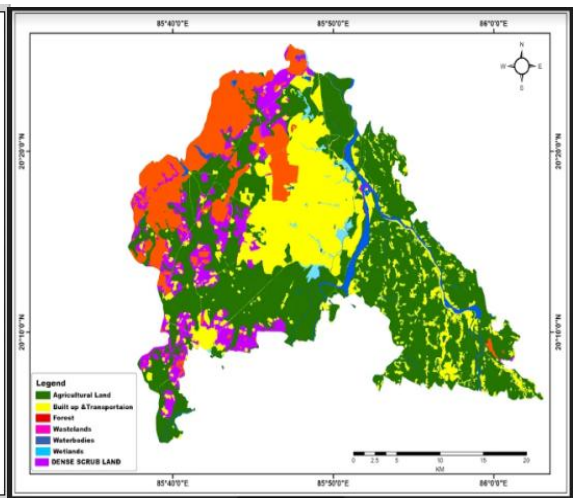


Fig. 3(b). Geomorphologic map BBSR 2017

Table 3. The LU/LC changes in the Mahanadi tri-delta (2007 and 2017) of Bhubaneswar (SMD)

BBSR City	FY 2007	% of total area	FY 2017	total area	Increase (+)/ decrease (-)	Major Causes
	Ha	%	Ha	%	%	
Agricultural Land	4973.4	5.202301255	4570.2	5.017011	-0.18529	The reserved forest to south of the city converted to settlement, more area for built up &transportation
Built up & Roads	21002.9	21.96956067	19627.62	21.54654	-0.42302	
Forest	13295.5	13.90742678	25442.7	27.93014	14.02271	
Westland	7287.98	7.623410042	19.12	0.020989	-7.60242	
Waterbodies	2674.31	2.797395397	2571.82	2.823257	0.025862	
Wetland	929.49	0.972269874	860.72	0.944869	-0.0274	
Others	45436.4	47.5276	38001.9	41.7172	-5.8104	
Total	95600	99.99996402	91094.08	100		

3.2 Khurdha District

Khurdha District (19°55' to 200 25' Lat. N and 84° 55' to 860 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 42.20C 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.

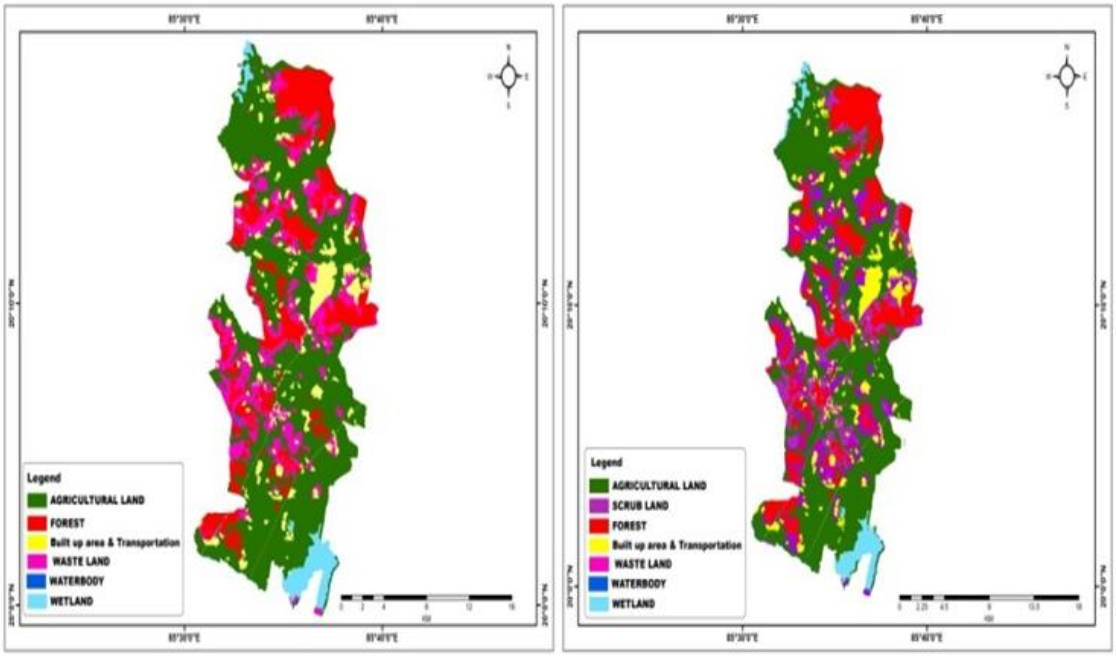


Fig. 4(a). LU/LC map Khurdha except BBSR 2007 Fig. 4(b). LU/LC map Khurdha except BBSR 2017

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 was noticed in the last decade. Most of the city waste of BBSR is dumped in Khurdha area so major change is seen
Built/ transport	2658.5	8.031722	3677.05	11.10891	3.07719033	
Forest	6223.5	18.80211	6261.2	18.91601	0.11389728	
Waste Land	5200.65	15.71193	6913.3	20.8861	5.17416918	
Water bodies	68.33	0.206435	213.8	0.645921	0.4394864	
Wet land	1176.04	3.552991	1097.5	3.31571	-0.237281	
Others	95.48	0.288459	349.25	1.055136	0.76667674	
Total Area	33100	100	33100	100	33100	

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.

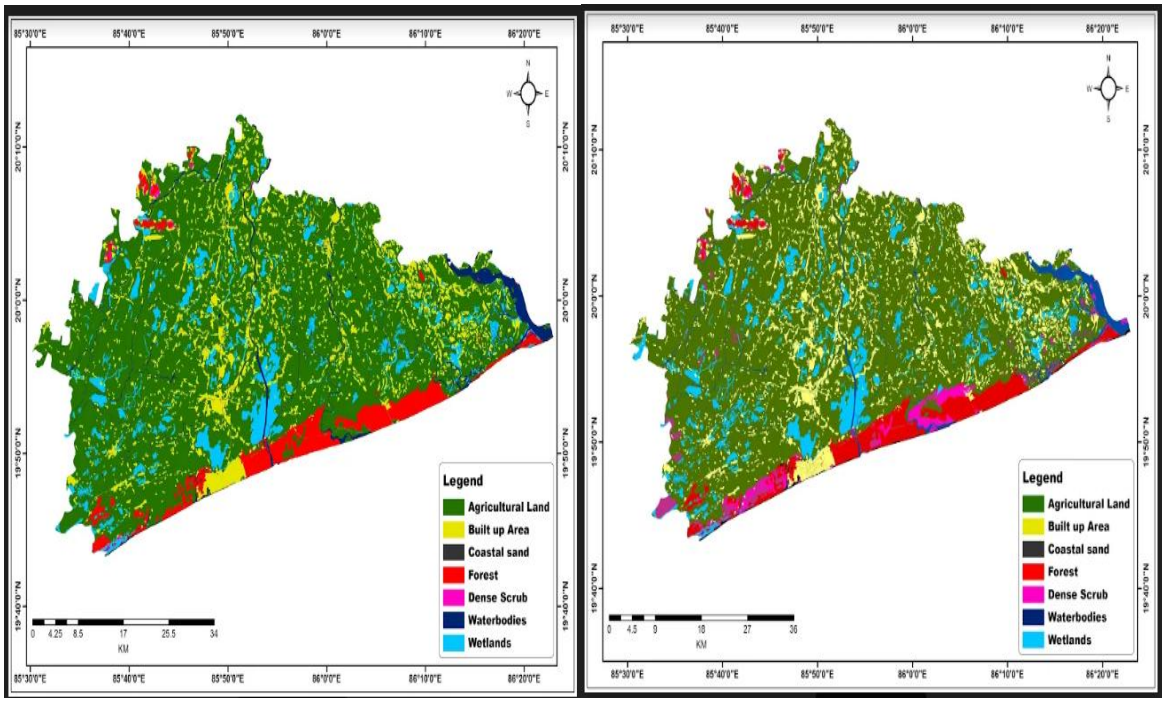


Fig. 5(a). LU/LC map Puri district 2007

Fig. 5(b). LU/LC map Puri 2017

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 Land	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 Km^2 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 Km^2 [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.

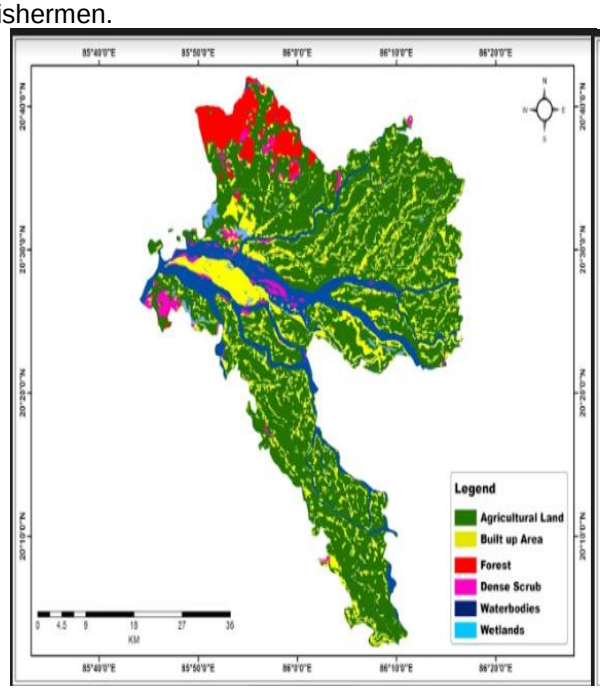


Fig. 6(a). LU/LC map Cuttack 2007

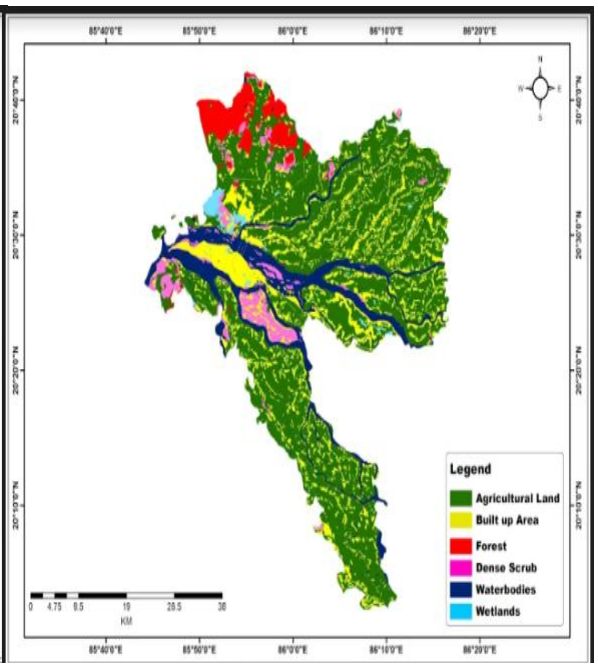


Fig. 6(b). LU/LC map Cuttack 2017

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
	Ha	%	Ha	%	%	
Agricultural Land	110970	61.85619	105634	58.69045	-3.1657409	Deforestation
Built& Transportation	31252.5	17.42057	36438.5	20.2453	2.82472966	and new settlement
Forest	8733.06	4.867926	8771.5	4.873462	0.00553526	area, new
Waste land	4260.36	2.374783	8323.7	4.624663	2.24988056	wetland
Water bodies	21659.2	12.07313	17136.1	9.520849	-2.5522837	Scrub rise in
Wetland	1752.2	0.9767	2205.5	1.22538	0.24867978	Surua –
Others	772.68	0.430702	1475.7	0.819902	0.38919932	Kathajodi doab
	179400	100	179985	100		

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 860 3‟ E to 860 45‟ E. and between lat. 190 58‟ N to 200 23‟ N) carved out of Cuttack district in 1993 from Cuttack district. It is coastally 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.

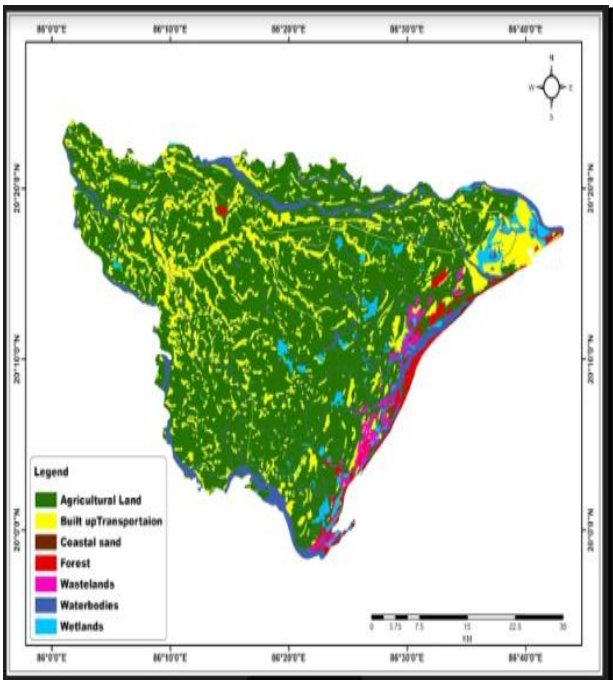


Fig. 7(a). LU/LC map J. S. Pur district 2007

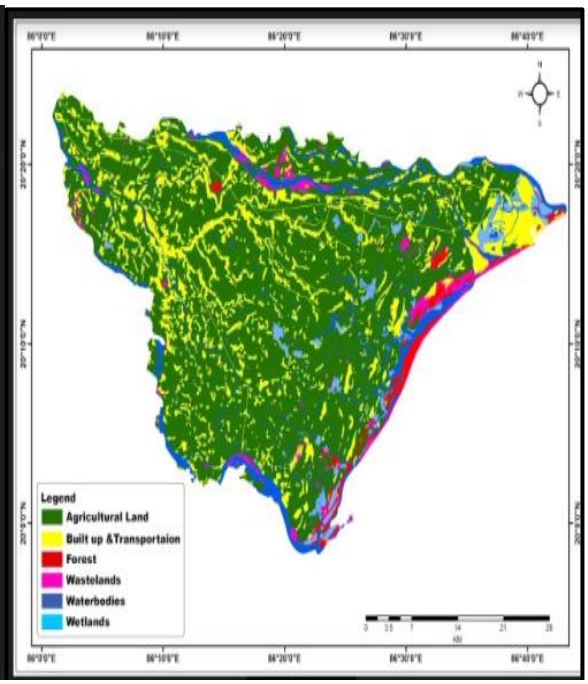


Fig. 7(b). LU/LC map J. S. Pur district 2017

Table 7. The LU/LC changes in the Mahanadi tri-delta during 2007 and 2017 of Jagatsinghpur district (CMD)

Jagatsinghpur District	The year 2007	% of total area	The year 2017	% of total area	% of increase/ decreas	Major Causes
	Ha	%	Ha	%		
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 and more homestead land
Built up & Transportation	33267	19.92850252	34535.9	19.95142	0.022915	
Forest	3058.6	1.832245703	3223.56	1.862253	0.030008	
Waste/ SANDY AREA	1026.2	0.614742216	4256.79	2.459151	1.844409	
Water bodies	7071.1	4.235922511	11285	6.519354	2.283431	
Wetland	5554.86	3.327623216	5018.23	2.899036	-0.42859	
Others	1109	1.2723	1908.5	1.102542	-0.16976	
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 transgration has been observed in last decade at places Satabhaya, and Pentho villages submerged under sea.

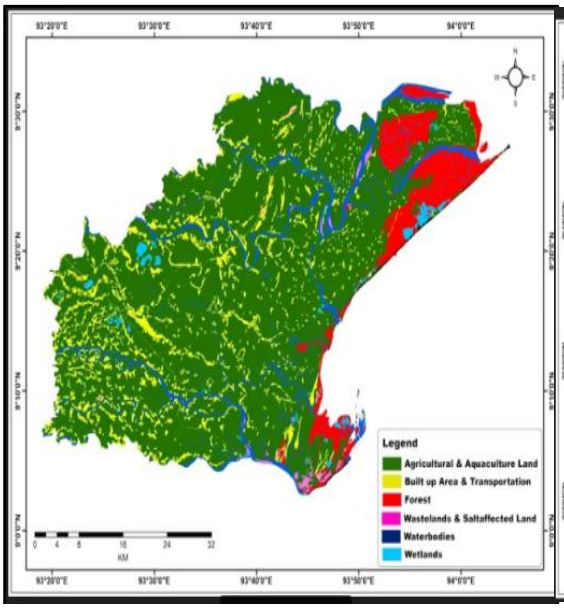


Fig. 8(a). LU/LC map Kendrapada district 2007

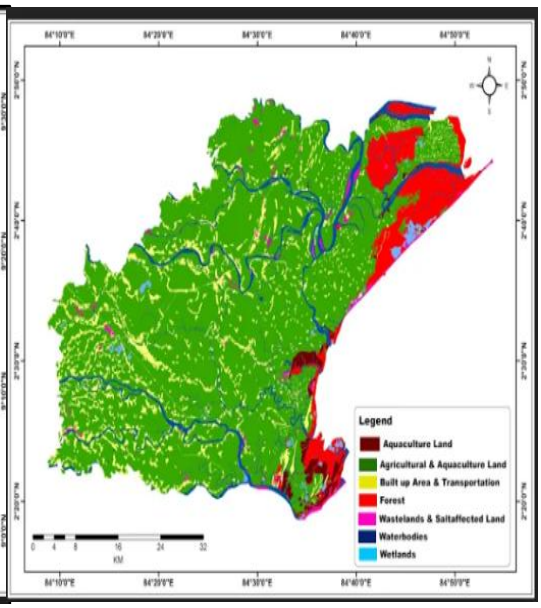


Fig. 8(b). LU/LC map Kendrapada district 2017

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, scrubs, 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 Km^2 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 km^2, population of 1506522 in 2011 census with population density (601 per /km^2). 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 Brhamani- 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 deltaic 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 deltaic 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 area	FY 2017	% of total area		Major Causes
	Ha	%	Ha	%		
Agricultural Land	182518	71.26852731	182078	71.09639	-0.17214	There is
Built up& transport	24631.9	9.61811568	25163.7	9.825724	0.207609	less
Forest	20286.3	7.921272014	20216.5	7.893981	-0.02729	change in
Wasteland	1578.52	0.616370965	3109.5	1.214173	0.597802	area due to
Water bodies	17617	6.878979857	17548.9	6.852357	-0.02662	Govt effort
Wetland	2812.8	1.098325171	2383.8	0.930808	-0.16752	to
SAND	854.5	0.333660004	591.2	0.230847	-0.10281	mangroves
Others	5800	2.264749002	5008.6	1.955719	-0.30903	and forests
	256099	100	256100.2	100		saving

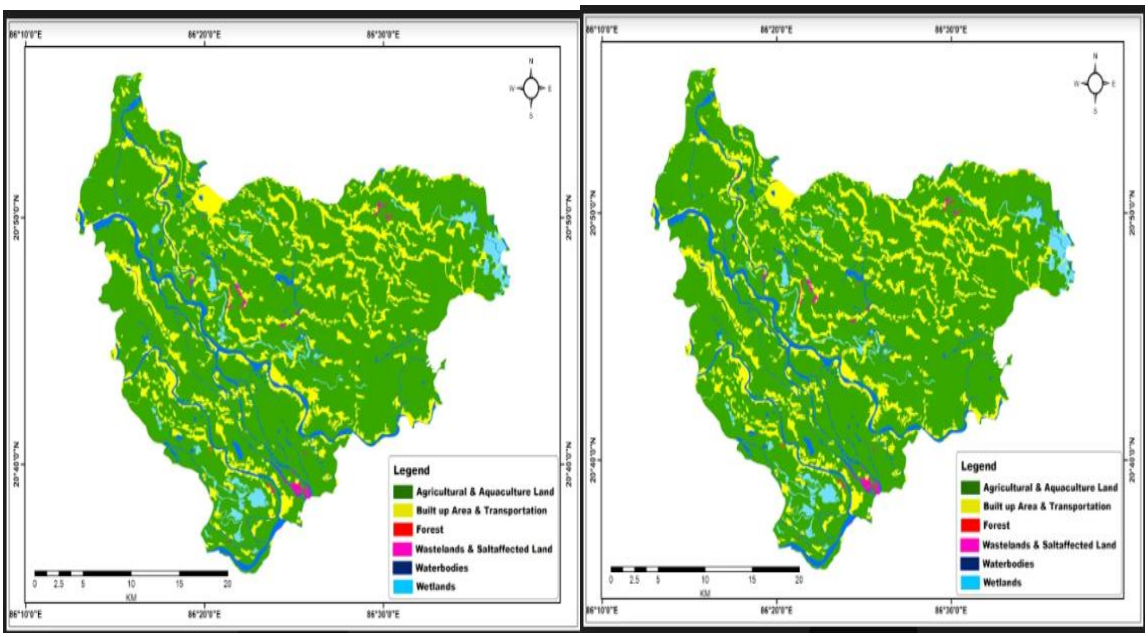


Fig. 9(a). Geomorphologic map Jajpur district 2007 Fig. 9 (b). Geomorphologic map Jajpur, district 2017

Table 9. The LU/LC changes in the Mahanadi tri-delta during 2007 and 2017 of Jajpur district (BBD)

Jajpur District	FY 2007	Total area	FY 2017	Total area	% of total area	Major Causes
	Ha	%	Ha	%	%	There is
Agricultural land	60891.5	74.62194	60202.8	75.2696	0.64766201	0.6%, 1.64%
Built/ Transport	11368.5	13.93199	12452.5	15.56895	1.63696952	and 0.46%
Forest	17.52	0.021471	22.53	0.028169	0.00669794	increase of
Waste Land	295.5	0.362132	656.05	0.820238	0.45810558	agriculture,
Water bodies	4380.87	5.368713	4521.69	5.653322	0.28460837	built and
Wet land	2129.52	2.609706	2127.32	2.659719	0.05001297	waste lands
Others	2516.59	3.084056	2517.11	3.147061	0.06300421	for ports &
Total Area	81600	100	82500	100	82500	human acts.

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)

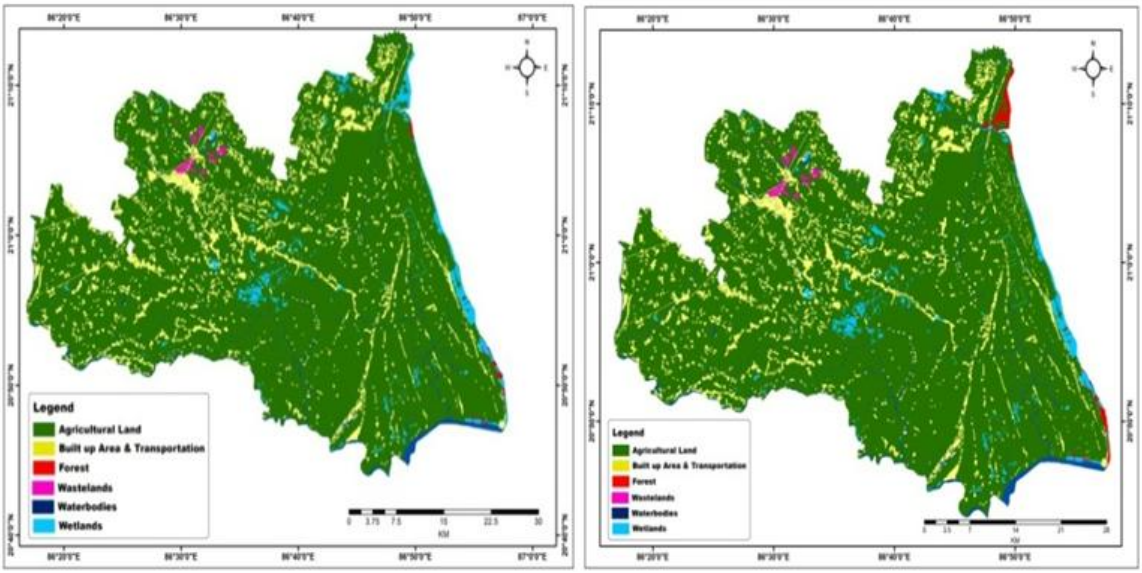


Fig. 10a. LU/LC map Bhadrak district 2007 Fig. 10b. LU/LC map Bhadrak, district 2017

Table 10. The LU/LC changes in the Mahanadi tri-delta during 2007 and 2017 in Bhadrak district (BBD)

Baitarani delta, Bhadrak District	The year 2007	% of total area	The year 2017	% of total area	% of total area	Major Causes
	Ha	%	Ha	%	%	
Agricultural Land	178563	79.43196	178266	79.29982	-0.1321422	Major rise in
Built & Transport	23018	10.23933	23470	10.44039	0.20106443	waste land
Forest	371.36	0.165196	1214.84	0.540409	0.37521347	by 1.94%
Wasteland	648.41	0.288439	5010	2.228648	1.94020898	followed by
Water bodies	4770.12	2.12194	4524.82	2.01282	-0.1091199	forest 0.37%
Wetlands	5321.94	2.367412	5010.17	2.228723	-0.1386885	and built
Others	12107.1	5.385722	7304.17	3.249186	-2.1365364	and roads
Total	224799.9	100	224800	100		by 0.20%

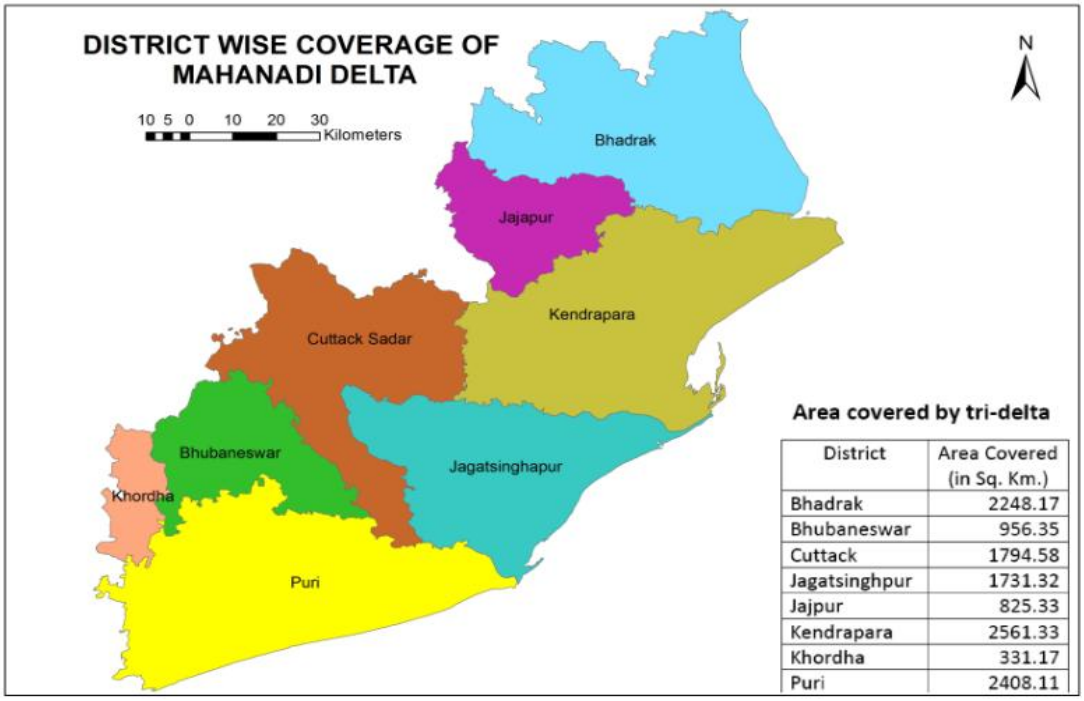
The alluvial western boundary of the tri-delta has shifted landward due to provision irrigation system and has vegetative agricultural covers (clarified). Since there is no space for shift of delta it is extending to southern direction where the southernmost river shall be replaced by the Makara river 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 Khurdha 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.



District	Area Covered (in Sq. Km.)
Bhadrak	2248.17
Bhubaneswar	956.35
Cuttack	1794.58
Jagatsinghpur	1731.32
Jajpur	825.33
Kendrapara	2561.33
Khordha	331.17
Puri	2408.11

Fig. 11. The geomorphological areas of the Mahanadi tri-delta district wise FY 2017

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.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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