HYDRO- ECOLOGY OF BHITARKANIKA MANGROVES, ODISHA

AN ASSESSMENT FOR INTEGRATED MANAGEMENT

INTERNATIONAL CLIMATE INITIATIVE

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

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New Delhi, 2023

HYDRO- ECOLOGY OF BHITARKANIKA MANGROVES, ODISHA

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Chilika
Development Authority

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Photo credit: WISA (Harsh)

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1. BACKGROUND

Executive Summary

Bhitarkanika Mangroves lies in Kendrapara District of Odisha, situated in the deltaic region of the Brahmani and Baitarani rivers. They are the second largest mangrove forests of mainland India.

This assessment was primarily conducted as a hydrological study to support the preparation of an integrated management plan for this Ramsar Site. Chilika Development Authority (CDA) conducted a detailed hydroecological characterisation of the site through field surveys and of secondary data analysis and presented the physicochemical status of the water and sediment quality of Bhitarkanika.

The report is an extensive collation of the core information from secondary data sources and highlights knowledge gaps that need to be addressed in a hydroecological assessment of this Ramsar Site. The status, trends, patterns and projected changes in the water regime and their impacts on the hydroecology of the sanctuary were examined. The long-term LULC changes in the basin and in Bhitarkanika Mangroves, pollution, threats and recommendations emerging from present assessments and secondary data sources have been discussed. The status and trends in the ecological components, processes and services have been evaluated for the management of this site.

The study has recommended management measures, monitoring parameters and a protocol for ecosystem based management of Ramsar site

1.1 Major findings

- Bhitarkanika Mangroves receives freshwater from two river basins i.e., the Brahmani and Baitarani basins. These basins and their sub-basins were delineated using the Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM), of 90 m resolution. The area of its direct catchment is 6258 km^2 which represents only 11.68% area of total basin of Brahmani and Baitarani rivers
- The land use land cover analysis suggests asgriculture to be the predominant land use type in the sanctuary. The LULC change detection analysis reveals transformation of agriculture land to aquaculture farms for the purpose of shrimp culture resulting in significant increase in area under aquaculture. The area under agriculture declined declined from 338.2 km^2 (50.3% of total area) in 1990 to 311.4 km^2 in 2020 (46.3%). Similarly there is decline in dense mangroves from 118.2 km^2 to 101.41km^2. However the area under open mangroves increased from 37.2km^2 to 49.5 km^2 due to afforestation programmes of the Willdife Divison, natural germination and programmes such as plantation in fringe areas of national park after super cyclone struck the Odisha coast in 1999.
- The Central Water Commission (CWC) has estimated that the annual renewable water resources of the Brahmani basin are 21,920 million cubic metres, which includes both surface water and groundwater resources (CWC, 1988). It is estimated that 16,618 MCM of this water (about 75%) will continue to flow to the sea, indicating that the basin would not have any water shortage (CPSP, 2005).

1.2 Policy-related recommendations

- The management of Bhitarkanika Mangroves must consider a landscape approach to include forests, pastures, and barren lands, people, and industries as it has large impact on availability of waters in rivers and eventually into the wetlands.
- The maintenance of water accounts, in terms of withdrawals, consumption and returns, separately for individual sectors (water for agriculture, people and nature) needs to be assessed and integrated in order to understand the real impacts of land and water use and management policies.
- The first priority of the National Water Policy is drinking water. Industrial, environmental and navigational uses are given lower priorities compared to irrigation. The core water demands for drinking and the water required for maintaining the rich biodiversity of the Brahmani delta and the Bhitarkanika estuarine region may require to be given higher priorities.
- EFRs (environment flow requirements) need to be be defined following further investigation to ensure optimal ranges for riverine ecosystems in water-rich basins. Better methods based on the water regimes required by different species and on the trade-offs between the environmental flow and uses (as preferred by society) need to be evolved.
- The correlations among various issues such as aquaculture, loss of mangroves, coastal erosion, salt water ingress and loss of productivity of paddy fields should be recognised. Conservation of biodiversity and the consequent restriction of livelihood options open to the resource-dependent population and development of ports and loss of tourism beaches need to be realised. Adverse impacts need to be addressed and resolved.
- Involving more researchers to identify suitable mangrove restoration sites may give an impetus to the work being done by Forest Department. Potential mangrove plantation sites should ideally be selected close to cyclone-prone areas. Recognition of traditional rights (using socio-economic surveys) in mangrove growing areas is important when planning regulations to avoid conflicts. Active community participation in plantation activity and providing post-plantation care must be ensured.

1.3 Recommendations and policies for environmental management at the basin

- Waste generation due to mining and industrial activity in Angul-Talcher and any expansion of this activity will have an adverse effect on the water resources. Industrial effluents, mine drainage water, untreated sewage from urban settlements, runoff from agricultural fields and mining areas and open defecation on the riverbanks have contributed to the pollution load of the river water. There is need for developing a monitoring & action plan for the same to ensure that water quality remains in desirable limtis.
- Four tributaries of the Brahmani, namely the Tikra, the largest tributary in Odisha (3536 km^2), Singhdajhor (436 km^2), Banguru (131 km^2) and Nandira (595 km^2), have different industrial and mining activities in their lower basins. A master plan needs to be drawn up for the integrated development of these basins for the long-term resilience of ecosystem services. It is recommended that the SPCB investigate the distal impacts of these grossly polluting industries in consultation with the Mangrove Forest Division, Rajnagar.
- Tourism in the sanctuary needs to be regulated in order to reduce pressure on certain areas, such as Dangamal and Gupti, which are easily accessible by roads. Increased tourist footfall can create disturbances to the wetland habitat. All arrangements to accommodate tourists should be located away from the sanctuary, and a proper eco-tourism plan needs to be developed for the park.

1.4 Key highlights of water and sediment quality assessment

- The health status of Bhitarkanika Mangroves was found to be “good” (82% score, grade B-) during the monsoon and “excellent” in winter (92% score, grade A-) with respect to water quality indicators. The overall status was “good”, with 87% of the parameters within the desired ranges.

- The status of most of the water quality indicators (such as pH, DO, BOD, Chl-a and DIP) was “excellent” (score > 90%).
- The water turbidity of the rivers was higher than the threshold prescribed by CPCB, New Delhi (not suitable for wildlife propagation and fisheries) during the monsoon. Still, it was within the range during the winter months. Although the high turbidity indicated a ‘very poor health status (32%), it is not alarming due to the seasonal monsoonal flow and subsides in the dry season, when there is no freshwater inflow.
- The organic load (in terms of BOD) in Bhitarkanika Mangroves was within the limits during the monsoon and in winter.
- The FC concentrations of both the sanctuary and rivers were higher than the limits allowed by CPCB (100 MPN/100 ml) during the monsoon but were within the range in winter.

1.5 Recommended parameters for hydrological monitoring and health report card, periodicity and methodology

The present study recommends having long-term wetland monitoring of the river input points, sea mouths and core areas of the sanctuary. A total of 17 sampling locations covering the entire Bhitarkanika Mangroves, including the proposed Mahanadi mangrove area and major rivers, have been recommended (Figure 67). Sampling may be carried out per the recommended periodicity in these locations. A total of 14 parameters are recommended for continuous monitoring, as mentioned later sections. Selected parameters can be used to prepare the annual health report cards.

1.6 Recommendation for hydrological monitoring

Long-term observation of discharge upstream of Bhitarkanika Sanctuary (Pattamundai, Aul and Chandbali) could give a more realistic view of the freshwater supply to the sanctuary. Similarly, long-term observation of the discharges to the sea (tidal prism) at the Hansua, Maipura and Dhamra estuaries could substantiate the water balance at Bhitarkanika Mangroves.

- Long-term observation of the tides near Dhamra Port, Dangamala and Gupti could help understand the tidal hydrodynamics of the sanctuary.
- Seasonal simultaneous longitudinal observation of the salinity (through each river from the estuary upstream) could help know the extent of saline water propagation.
- Long-term observation of meteorological parameters at Dangamal through a permanent weather station.
- Periodic pathymetric survey of entire lengths of the rivers in Bhitarkanika Mangroves to measure the rate of sedimentation.

2 GEOMORPHIC SETTINGS OF BHITARKANIKA RAMSAR SITE

Bhitarkanika Mangroves are located in the state of Odisha and are the second largest mangrove forests of mainland India. The sanctuary is located in Kendrapara district, between longitudes 86° 45′ E and 87° 17′ E and latitudes 20° 17′ N and 20° 47′ N. It spreads across the estuaries of the Brahmani, Baitarani, Dhamra and Mahanadi (Figure 1). It is covered by Survey of India in topo sheets (73 L/13, L/14, P/1 and P/2).

An extent of 672 km^2 was declared Bhitarkanika Mangroves in 1975, and an extent of 145 km^2 inside the sanctuary was declared Bhitarkanika National Park in 1998. The sanctuary boundary has been rationalised recently by Mangrove Forest Division, Rajnagar, Kendrapara, Odisha and the new extent of Bhitarkanika Sanctuary is 673 km^2, including the protected forests, rivers, creeks and waste lands of Rajnagar, Rajkanika, Aul, Pattamundai, Talchua Marine, Tantiapal Marine, Jambu Marine and Mahakalpada.

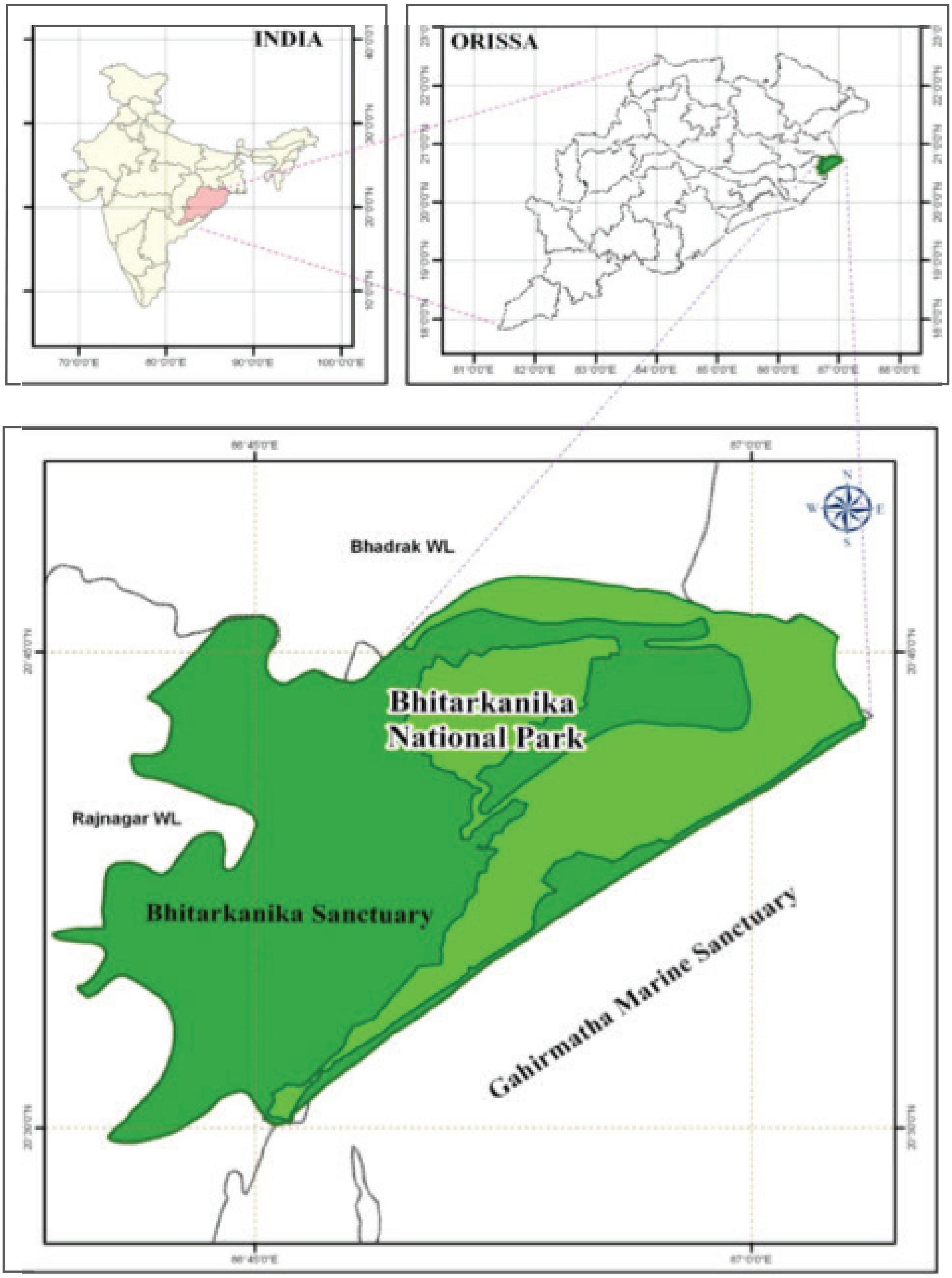


Figure 1 *Location map of Bhitarkanika Sanctuary*
(Source: CDA, 2020)

The floral and faunal diversity of the area include more than 300 mangrove and non-mangrove plant species, 31 species of mammal, representing 25 genera and 14 families, 29 species of reptile, with four species of turtle, and 174 species of bird. It is a critical habitat of the endangered Saltwater Crocodile *(Crocodylus porosus*, >1700 in number) and the nesting ground of the Olive Ridley sea turtles *(Lepidochelys olivacea).*

Considering its ecological and social values, the sanctuary has been designated a Ramsar Site under criteria no. 2 (largest nesting beach of Olive Ridley sea turtles in the world and highest density of the endangered Saltwater Crocodile), no. 4 (mangrove diversity), no. 5 (bird diversity) and no. 8 (estuarine and brackish fishes).

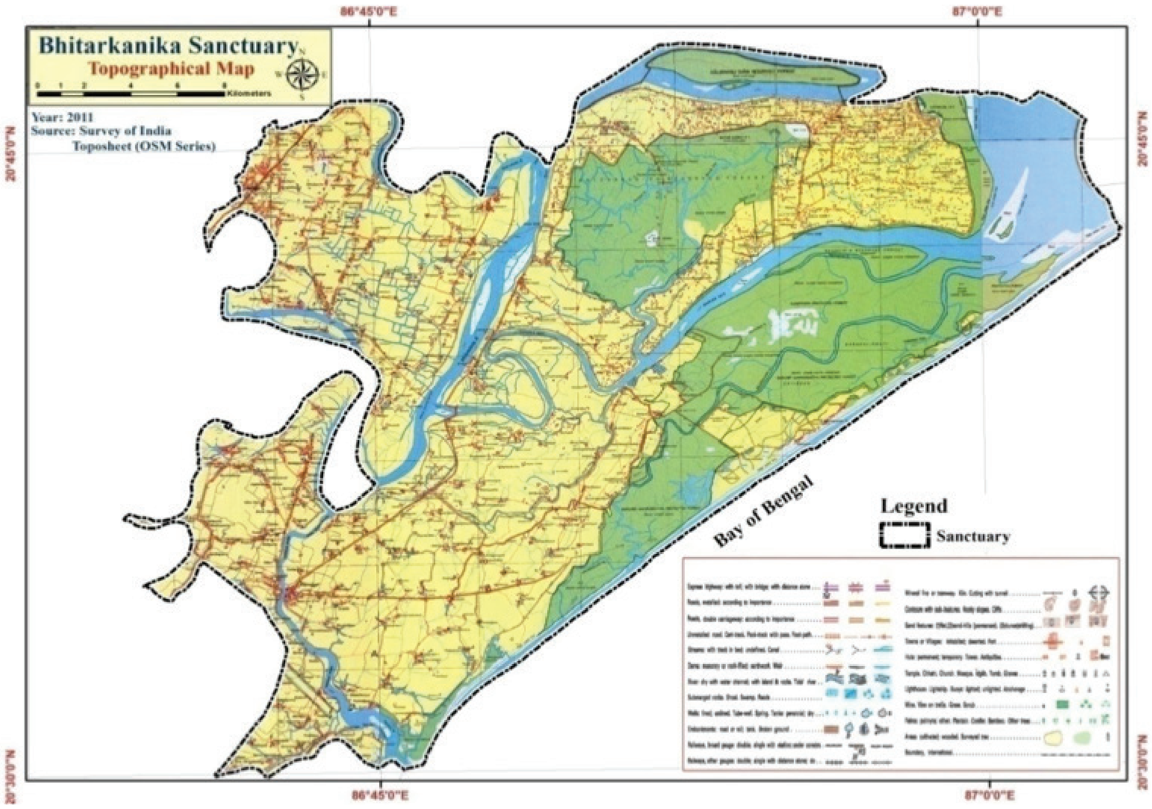


Figure 2 *Topographical map of Bhitarkanika Sanctuary*
(Source: Survey of India (SOI) Topographic sheet, OSM series. Year: 2011)

Table 1 *Chronology of events*

Year	Key Events
1975	Bhitarkanika declared a sanctuary (672 km^2)
1980	Creation of Chandbali Wildlife Division
1990	Renamed Mangrove Forest Division, with headquarters at Rajnagar, with the Mahanadi delta in its jurisdiction
1998	Declaration of National Park (145 km^2)
2002	Declaration of Ramsar site (650 km^2)
2020	The sanctuary area has been rationalised and the new area of the sanctuary is 673 km^2.

2.1 Bhitarkanika Sanctuary Drainage Network

For all practical purposes, the boundary of the sanctuary is considered to be the external boundary and that of the national park is treated as the internal boundary of the protected area. The natural boundaries of the sanctuary are rivers and the Bay of Bengal. The sanctuary is bounded by the river Dhamra to the north, the river Maipura to the south, the river Brahmani to the west and the Bay of Bengal in the east. The 35 km coast line from the mouth of the river Maipura to Barunei forms the eastern boundary of the sanctuary. The rivers Baitarani and Brahmani, after meeting near Dangamal, flow into the Bay of Bengal at Palmyra Point at the Dhamra Estuary, as shown in Figure 3.

The sanctuary is interspersed with numerous rivers, creeks and creeklets as shown in Figure 3, which allow a tidal influx of seawater inside the sanctuary. The area is influenced by heavy alluvial silt brought down by the rivers and deposited in the deltaic areas due to regular tidal inundation. The entire area is further influenced by the high detritus content resulting from fallen mangrove litter. The soil is clayey loam with sand, overlaid by a rich humus layer. The mosaic of rivers and creeks is influenced twice daily by the high and low tides at approximately 6 hour interval. The tidal level varies from the outer estuarine part towards the inland areas according to the lunar cycle.

Figure 3 *Drainage map of Bhitarkanika Sanctuary*
(Source: CDA, Bhubaneswar, Odisha, 2020, SOI topographic sheet. Year: 2011)

2.2 Infrastructure and settlements in Bhitarkanika Sanctuary

2.2.1 Administrative infrastructure

Bhitarkanika Sanctuary has physical infrastructure at different sites for the administration and management of the sanctuary as well as the national park (Figure 4).

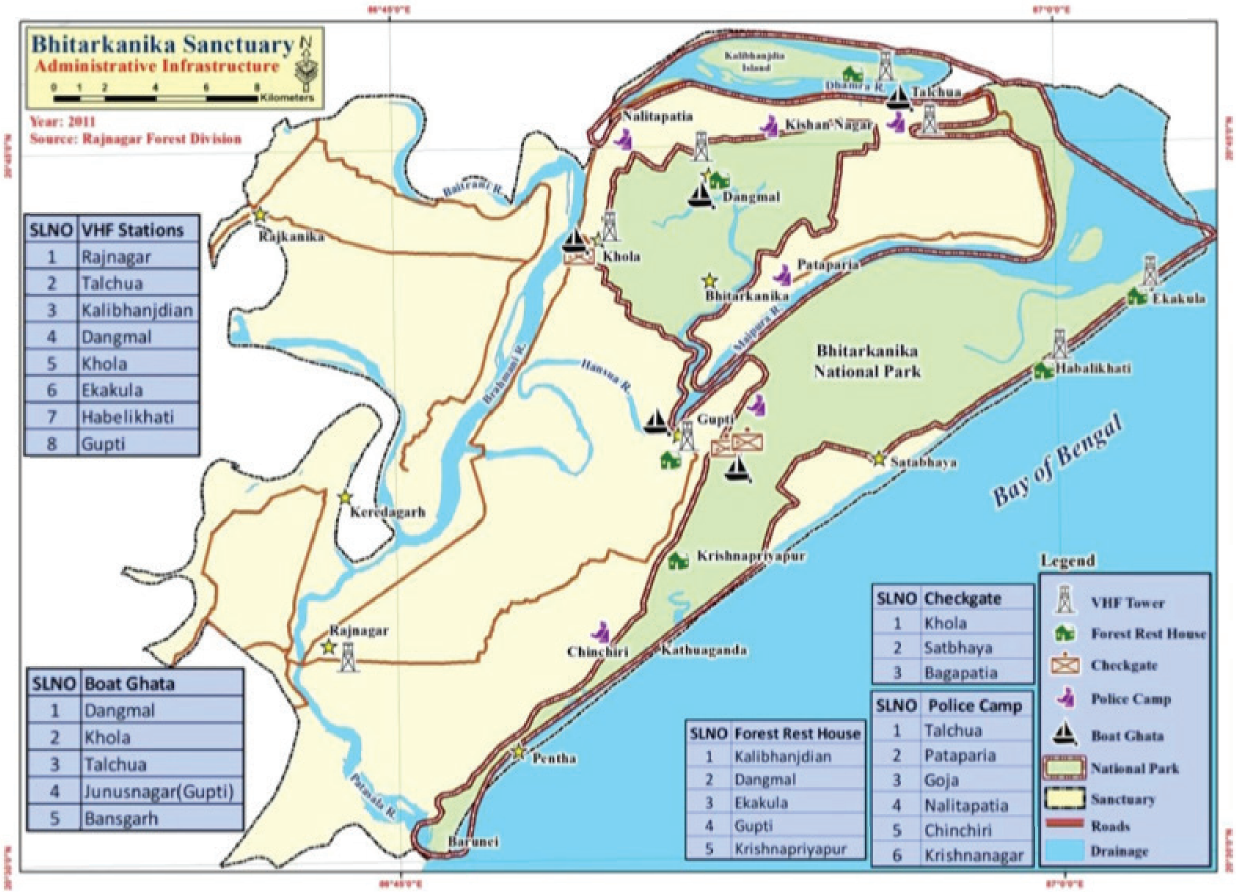


Figure 4 *Map showing administrative infrastructure in Bhitarkanika Sanctuary (Source: CDA, Bhubaneswar, Odisha, 2020, SOI Topographic sheet. Year: 2011)*

2.2.2 Villages and Settlements

Bhitarkanika is surrounded by thickly populated villages and has dense mangrove forests surrounded by rivers and criss-crossing creeks. The sanctuary includes 410 villages with about 2 lakh people and 75,000 cattle, which puts a heavy pressure on the sanctuary (Figure 5). As per information received from Mangrove Forest Division, Rajnagar (February 2021), there is a proposal to include new area of 1 km^2 in the sanctuary which would result in total sanctuary area of 673 km^2. There is proposal to include Sasanpeta protected reserve forest (PRF), Suniti PRF, Kantilo Reserve Forest, Kandarapatia PRF, Jambo Protected Forest, Sanatubi PRF, Kansaridiha PRF, and Hetamundia PRF. This proposal would exclude 49 villages from sanctuary area leading to 361 villages to be included in sanctuary area.

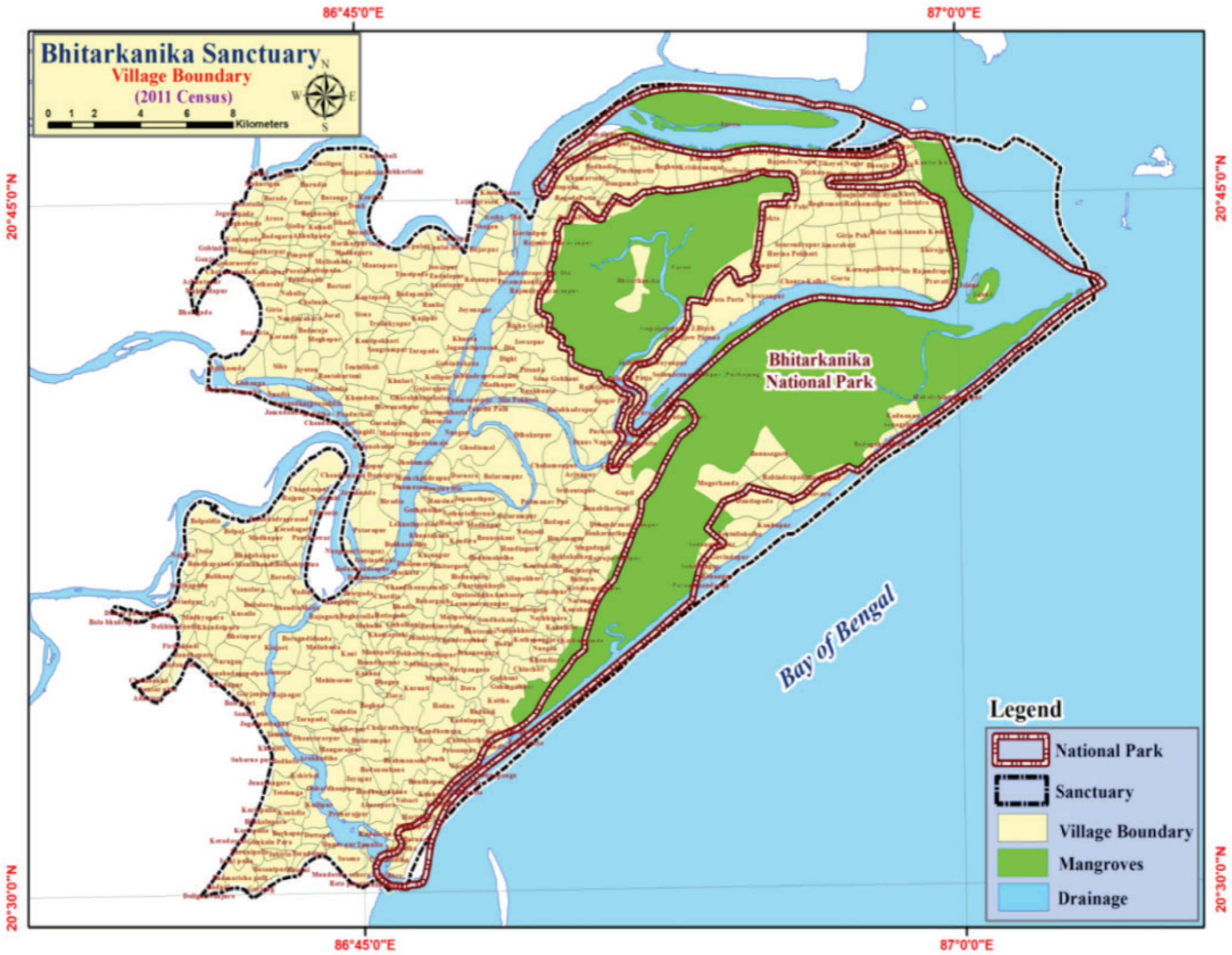


Figure 5 *Map showing the village boundary of Bhitarkanika Sanctuary*
(Source: CDA, Bhubaneswar, Odisha, 2020.SOI Topographic sheet Year 2011, 2011 census)

Photo credit: Shambhavi

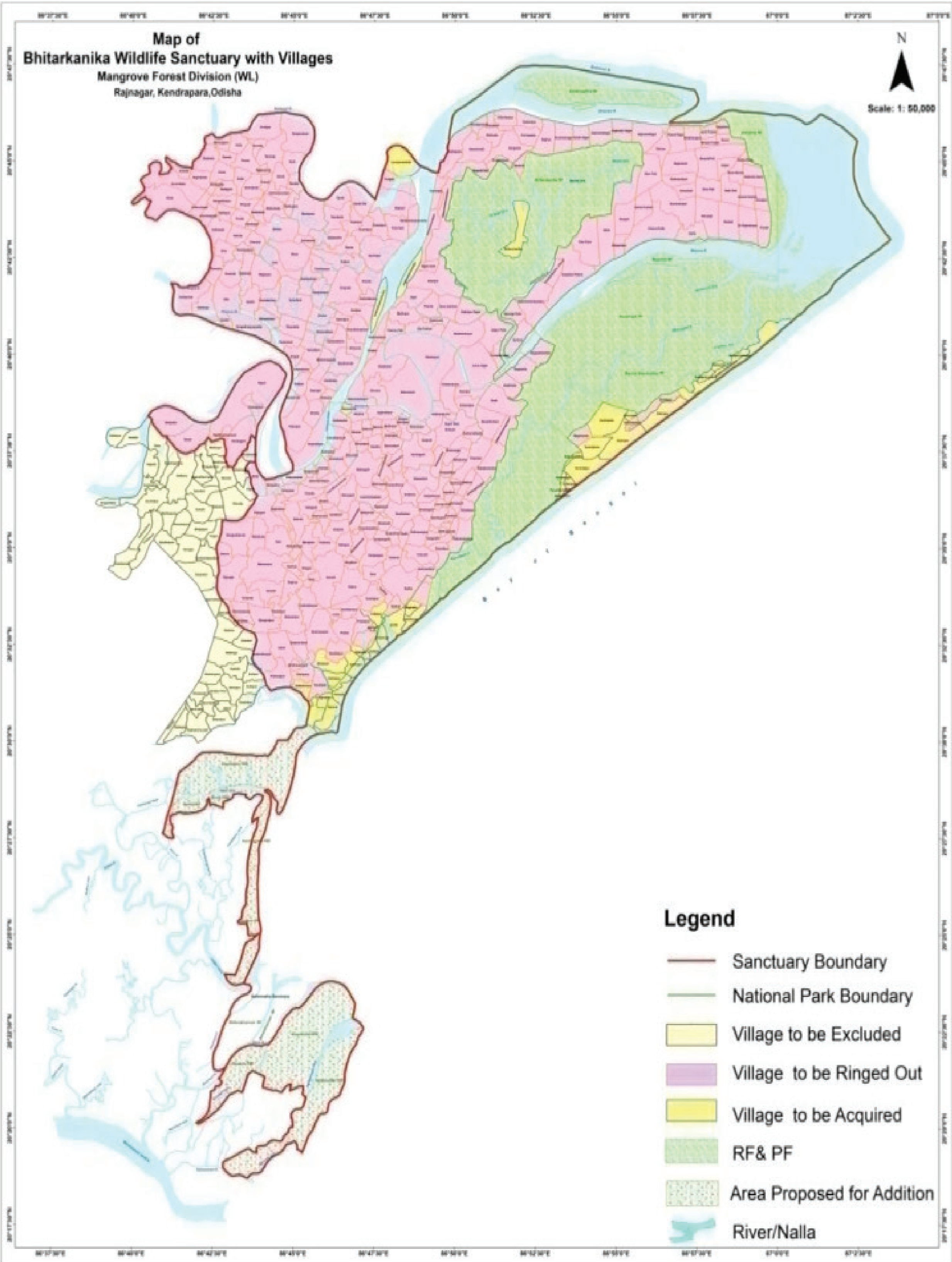


Figure 6 *Map showing new boundary of the Bhitarkanika Ramsar site with villages (Source: Mangrove Forest Division, Rajnagar, Kendrapara, Odisha. February 2021)*

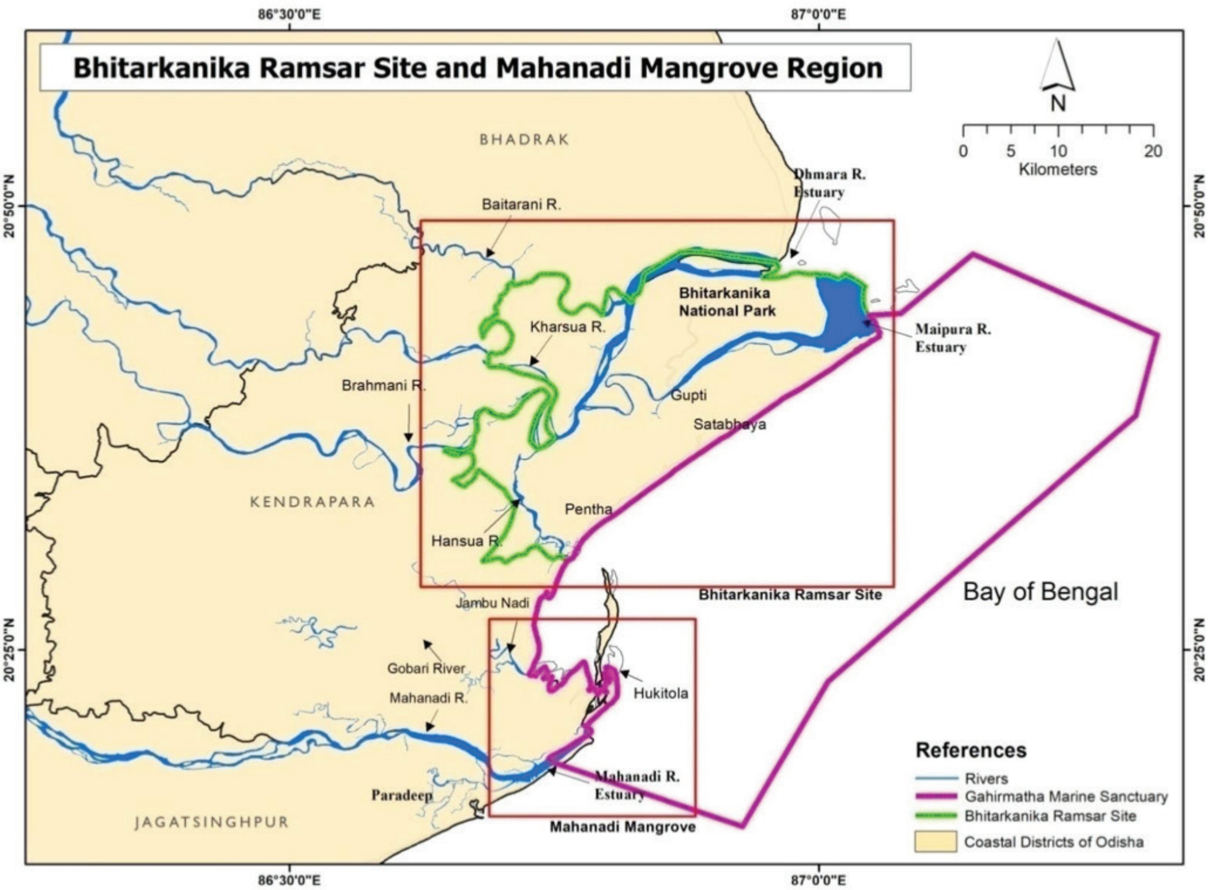


Figure 7 *Boundary map showing the proposed inclusion of the Mahanadi mangrove region in Bhitarkanika Sanctuary. The sources of the rivers associated with the Mahanadi mangrove include distributaries from the Mahanadi and Brahmani rivers and are marked with arrow (Source: CDA, Bhubaneswar, Odisha, 2020)*

2.2.3 Jetties

Nine government jetties have been constructed in Bhitarkanika Sanctuary for navigation to destinations within and outside the sanctuary (Figure 8).

The jetties inside the protected Bhitarkanika National Park are maintained by the Forest Department. Odisha State Disaster Management Authority and the district administration are also involved in the construction and maintenance of jetties in Bhitarkanika Sanctuary. Local village communities use these jetties heavily for daily commutation and for their livelihoods, such as tourism and fishing.

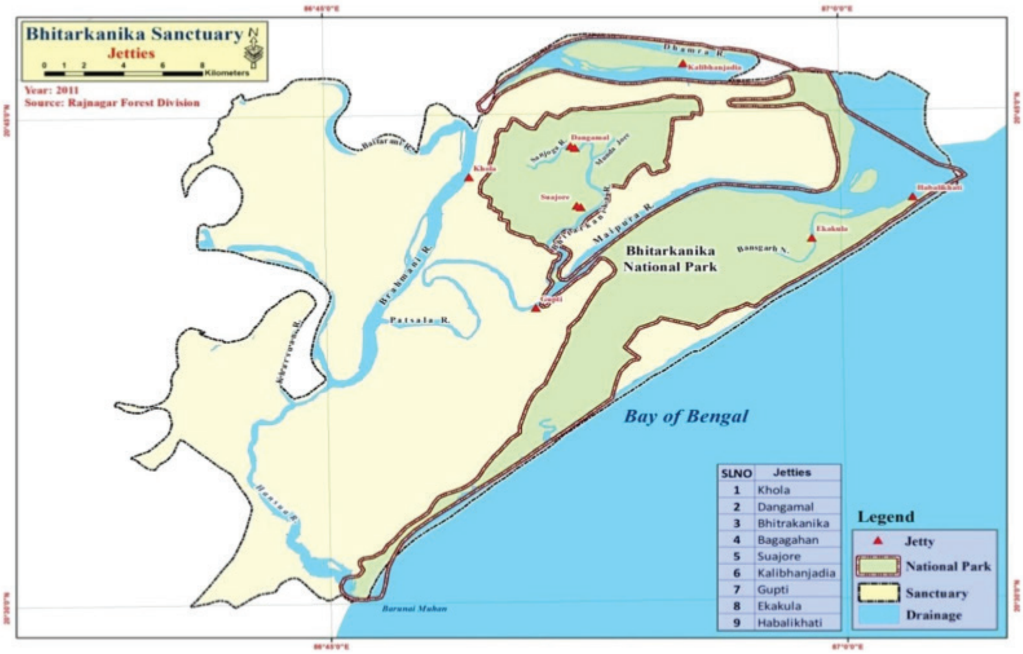


Figure 8 *Map showing jetties situated in Bhitarkanika Sanctuary (Source: Mangrove Forest Division, Rajnagar Data period : 2018-19. SOI topographic sheet. Year: 2011)*

2.2.4 Tourism sites

Bhitarkanika Sanctuary has some important tourist sites at Pentha, Keredagarh, Gupti, Bhitarkanika and Khola. There is a king's palace called Kanika Raj Prasad in Rajkanika, which is famous for its architecture (Figure 9). Eco-tourism sites (camping and Rest houses) have been developed in Dangamal, Gupti and Kathuaganda, which promote sustainable development while protecting nature and ensuring the livelihoods of local communities.

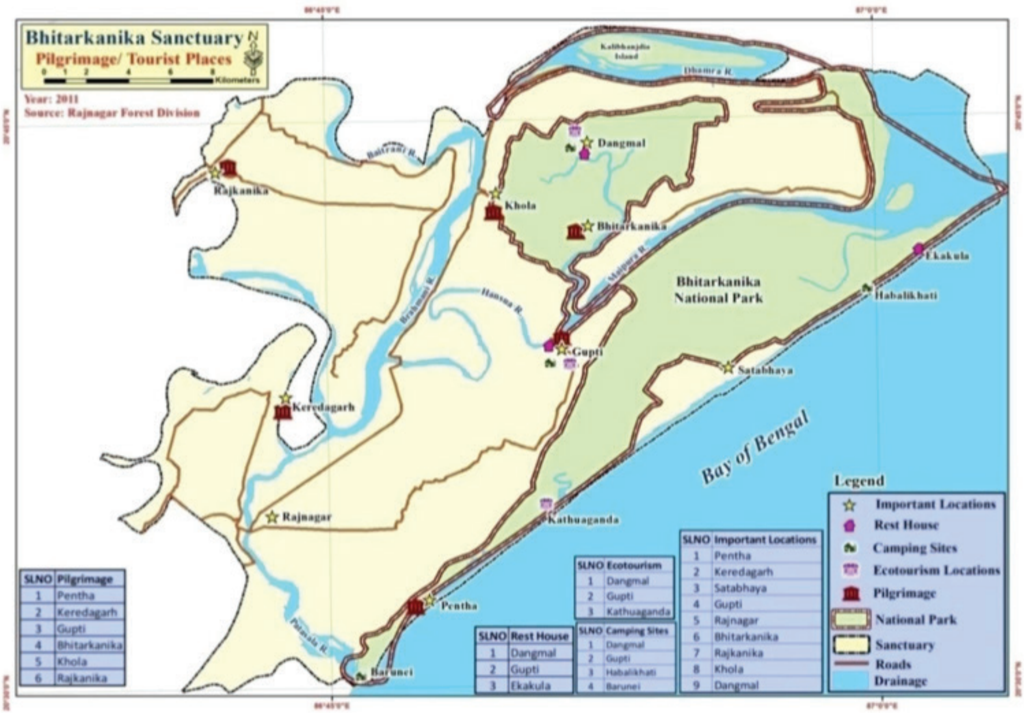


Figure 9 *Map showing tourism sites in Bhitarkanika Sanctuary. (Data source: Mangrove Forest Division, Rajnagar. Data period: 2018-2019. SOI topographic sheet. Year: 2011)*

3. MANGROVE SPECIES DIVERSITY AND DISTRIBUTION

The mangrove diversity and distribution in Bhitarkanika National Park were studied during field surveys conducted in October and December in 2020 (Table 2). The Bhitarkanika mangroves differ substantially from those of other patches in India because of the dominance of *Sonneratia apetala, Heritiera fomes, H. littoralis* and several other *Avicennia* species. A total of 38 species (26 true mangrove species and 12 mangrove associates) were recorded during these field surveys. The species diversity recorded in 2020 agreed well the results of surveys carried out earlier by (i) Space Application Centre and Chilika Development Authority under the project “Biophysical Characterisation and Site Suitability Analysis for Indian Mangrove” during the period 2014—16 and (ii) NCSCM during 2018—19. All the species recorded by these two earlier surveys were also recorded during the 2020 field survey. The Ramsar Information Sheet (2002) refers to the Bannerjee and Rao (1990) study which found the presence of 55 of the 58 recorded Indian mangrove species in Bhitarkanika.

Table 2 *Mangrove species diversity recorded from Bhitarkanika National Park during the surveys conducted in 2020. The major species at a particular site have been highlighted in bold; their abundance is given in parentheses*

Site	Species (abundance %)	Site	Species (abundance %)	Site	Species (abundance %)
Dangamal	***Heritiera fomes (50%)*** ***Sonneratia apetala (20%)*** ***Acanthus ilicifolius (10%)*** *Acrostichum aureum* *Avicennia marina* *Brownlowia tersa* *Ceriops decandra* *Excoecaria agallocha* *Heritiera littoralis* *Kandelia candel* *Myriostachya wighitiana* *Porteresia coarctata* *Xylocarpus moluccensis*	Satabhaya	***Tamarix troupii (30%) Avicennia officinalis (20%)*** ***Excoecaria agallocha (20%)*** ***Acanthus ilicifolius (10%)*** ***Rhizophora stylosa (5%)*** *Brownlowia tersa* *Bruguiera cylindrica* *Cynometra iripa* *Heritiera fomes* *Merope angulate* *Myriostachya wighitiana Phoenix paludosa* *Rhizophora mucronate* *Sonneratia apetala* *Suaeda monoica*	Khola	***Acanthus ilicifolius (20%)*** ***Sonneratia apetala (15%)*** ***Excoecaria agallocha (10%)*** *Ceriops decandra* *Excoecaria indica* *Phoenix paludosa* *Rhizophora apiculata* *Rhizophora mucronate* *Sonneratia alba* *Sonneratia caseolaris*
Bhitarkanika	***Excoecaria agallocha (40%)*** ***Avicennia marina (20%)*** ***Kandelia candel (15%)*** *Acanthus ilicifolius* *Acrostichum aureum* *Bruguiera gymnorrhiza* *Bruguiera sexangular* *Fimbristylis ferruginea* *Heritiera fomes* *Heritiera littoralis* *Intsia bijuga* *Myriostachya wighitiana* *Nypa fructicans* *Phoenix paludosa* *Rhizophora mucronate* *Sonneratia apetala* *Tamarix troupii* *Xylocarpus granatum* *Xylocarpus moluccensis*	Habelikhati	***Excoecaria agallocha (40%)*** ***Heritiera fomes (30%)*** ***Avicennia alba (10%)*** *Acanthus ebracteatus* *Avicennia marina* *Ceriops tagal* *Fimbristylis ferruginea* *Heritiera littoralis* *Kandelia candel* *Lumnitzera racemose* *Myriostachya wighitiana* *Rhizophora apiculata*	Gahirmatha	***Excoecaria agallocha (30%)*** ***Suaeda monoica (25%)*** *Aegiceras corniculatum* *Bruguiera cylindrica* *Flagillaria indica* *Rhizophora mucronate* *Tamarix troupii*
		Gupti	***Excoecaria agallocha (50%)*** ***Myriostachya wighitiana (20%)*** ***Acanthus ilicifolius (15%)*** ***Avicennia alba (10%)*** *Phoenix paludosa*		

4. BHITARKANIKA CATCHMENT BASIN

4.1 Brahmani basin

The Brahmani basin lies between latitudes 20° 28′ N and 23° 35′ N and longitudes 83° 52′ E and 87° 30′ E. It is an inter-state basin falling in districts in Chhattisgarh, Jharkhand and Odisha. The Brahmani basin is situated between the Mahanadi and Baitarani Basin. The total area of the Brahmani basin is 39,033 km^2 (Odisha, 22364 km^2; Jharkhand, 15,769 km^2 ; Chhattisgarh, 900 km^2) (CWC, 2021). The Brahmani river is the second largest river in the state of Odisha. The river is 799 km long and about 450 km is in Odisha.

4.2 Baitarani basin

The Baitarani river originates in Keonjhar district, of Odisha, about 2 km from Gonasika village, at an elevation of 900 m at latitude 21° 31′ N and longitude 85° 33′ E. A major portion of the river basin lies in Odisha, while a smaller part of the upper reach lies in Jharkhand. The total area of the Baitarani basin is 10,982 km^2 (Odisha, 10,246 km^2; Jharkhand, 736 km^2) (CWC, 2021). In Odisha, the major portion of the basin area is in Keonjhar district.

4.3 Delineation of direct catchment (zone of influence) of Bhitarkanika Sanctuary

Bhitarkanika receives freshwater from two river basins, i.e., the Brahmani and Baitarani basins. The Brahmani and Baitarani basins and their sub-basins were entirely delineated on the basis of the Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) of 90 m resolution by CDA. The lower sub-basin was considered as the direct catchment, which directly influences the hydrological regime of Bhitarkanika Sanctuary (Figure 10). This direct catchment was defined in accordance with the sub-basin delineation done by the ICID (International Commission on Irrigation and Drainage, New Delhi) for the Brahmani basin (CPSP, 2005). Downstream of Jenapur, the Brahmani river heads towards sea and enters the deltaic region. Hence, the lowest sub-basin was considered as the direct catchment (CPSP, 2005). The area of the direct catchment of Bhitarkanika was 6258 km^2, which represented only 11.68% area of the total basin of Brahmani and Baitarani rivers.

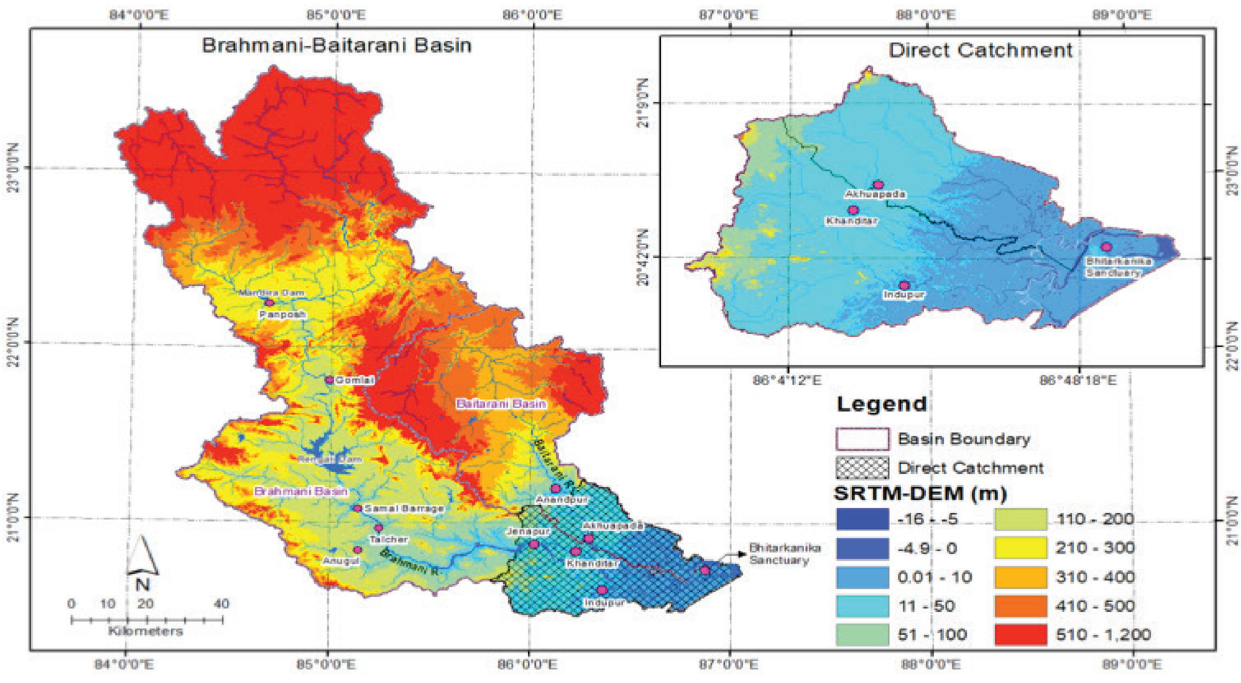


Figure 10 (a) *Total basin of Brahmani & Baitarani & direct Bhitarkanika catchment*

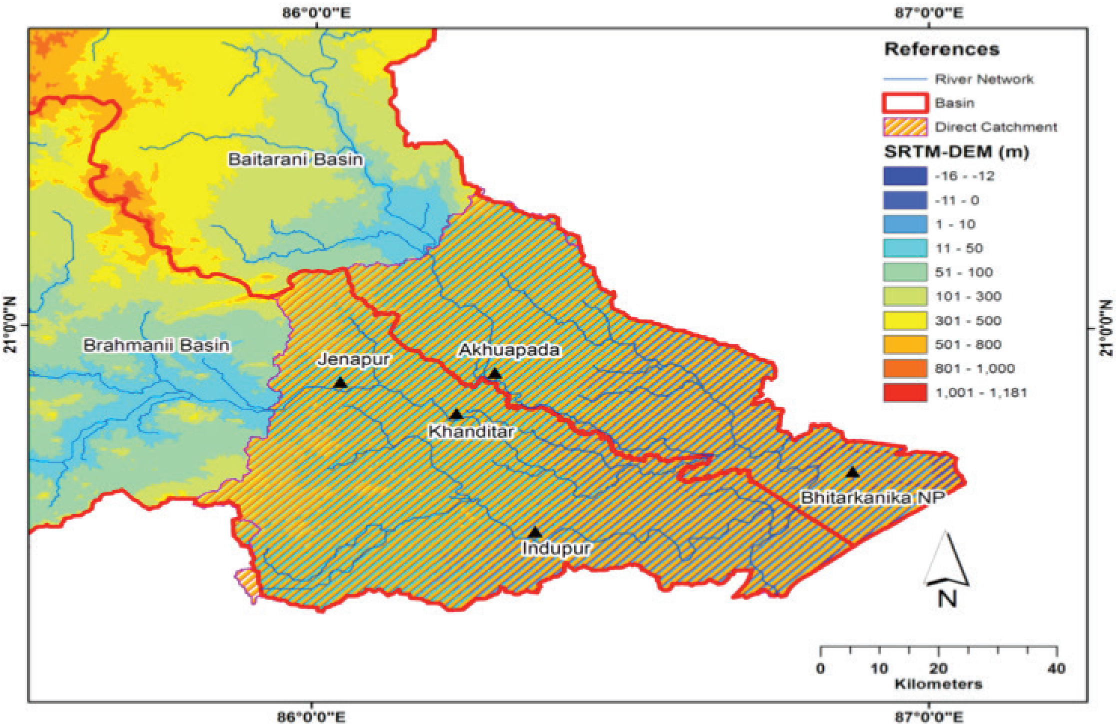


Figure 10 (b) *Total basin of Brahmani & Baitarani & direct Bhitarkanika catchment*

4.4 Basin agriculture and cropping intensity

The cropping seasons in the basin are Kharif, Rabi and Zaid, with Kharif and Rabi being the main cropping seasons (NRSC and CWC, 2011). Kharif is dominated by rice, Rabi by safflower and Zaid by groundnut. Mainuddin et al. (2016) undertook an analysis of the basin districts' cropping intensity (defined as the number of times a crop is planted per year in a given area). The average cropping intensity was around 160% during 2007–2008, and the cropping intensity was lower in the northern part of the basin, relative to the south, as shown in Figure 11.

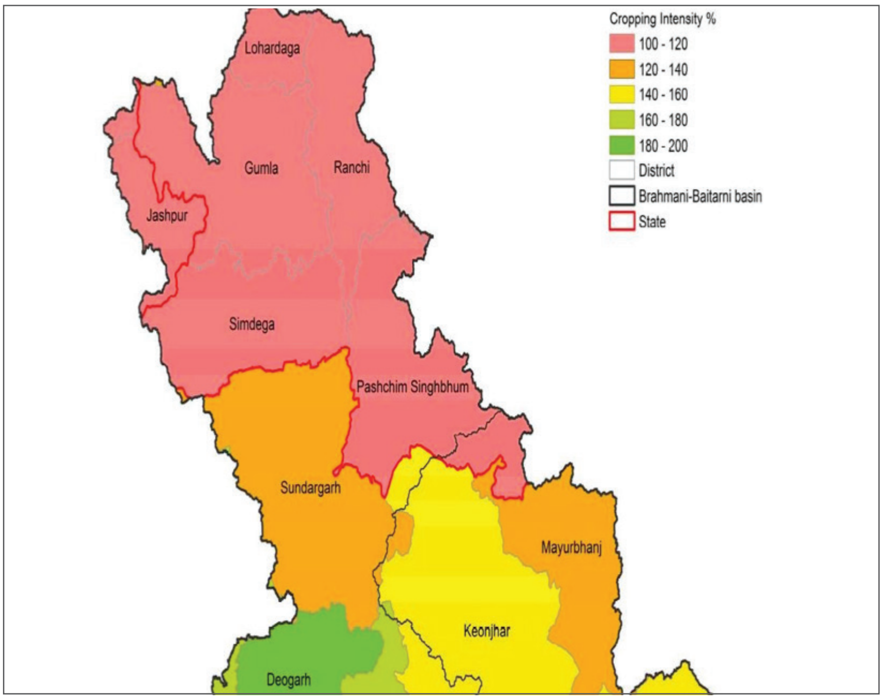


Figure 11 *Cropping intensity at district level (2007–2008) in Brahmani - Baitarani Basin (Source: Pollino et al., 2016)*

The cropping intensity in the south has been increasing over time. The main reason for the lower cropping intensity and lower rice yields in the northern part of the basin is due to a historical lack of supplementary irrigation, where additional water from irrigation is used to extend crop periods. Other constraints that are also likely to contribute to lower cropping intensity include low-yielding crop varieties, a lack of nutrients and farming practices. The paddy production trend (1988-2020) in Rajnagar block showed a declining trend, as shown in Figure 12. The cropping intensity of all the blocks of Kendrapara that comes under the direct catchment is shown in Figure 13. The average cropping intensity is 194% in the district.

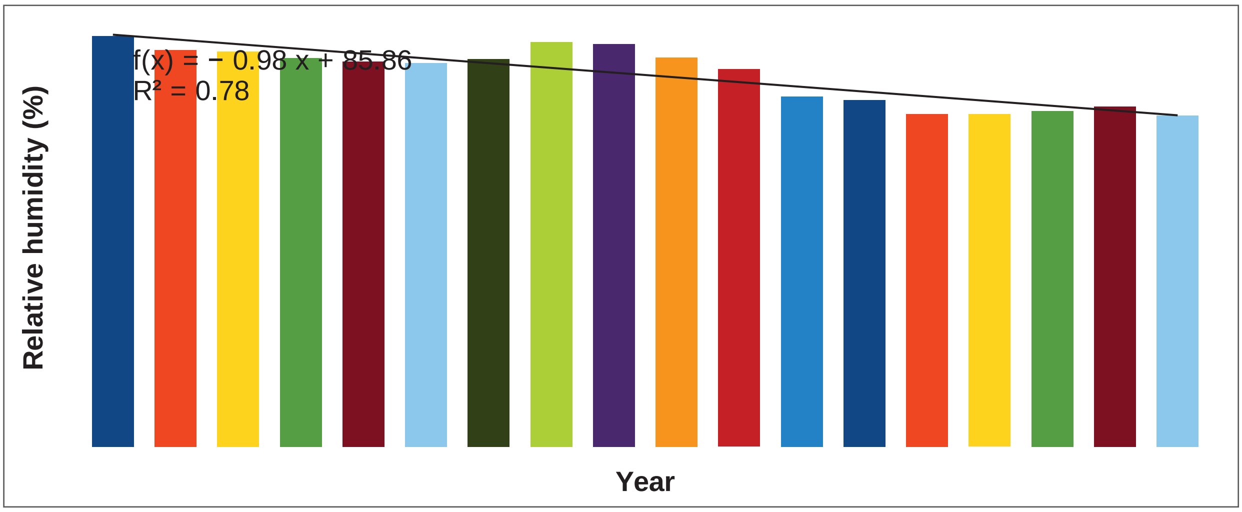


Figure 12 *Year-wise production of paddy in Rajnagar Block from 1987 to 2020 (Data source: Directorate of Economics and Statistics, Odisha)*

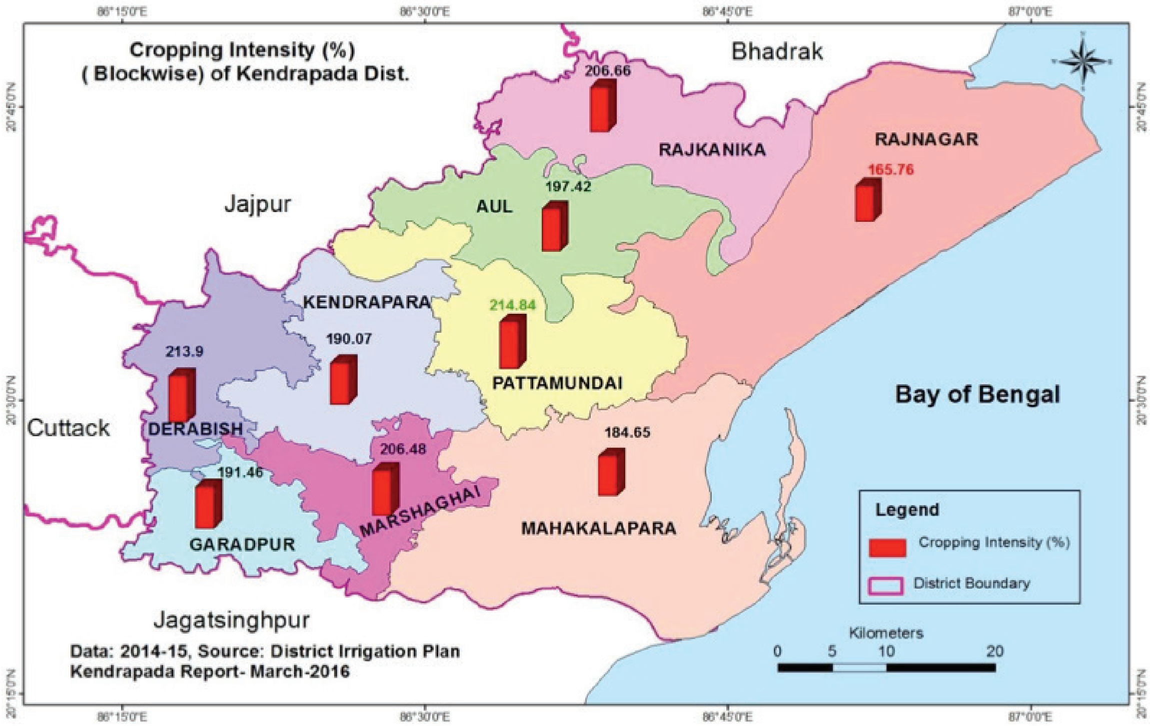


Figure 13 *Block-wise cropping intensity in Kendrapara district Data period: 2014-2015 (Source: District Irrigation Plan, Kendrapara)*

4.5 Rainfall pattern

The mean rainfall data over the last 30 years (1989–2019) of each district of the Brahmani and Baitarani basin were sourced from IMD. The spatial distribution map of the mean rainfall over the basin was interpolated on the basis of the inverse distance weighting (IDW) method on the GIS platform.

The lower reaches of the basin gets an annual rainfall of around 1500–1700 mm (Figure 14, data source : IMD). The inter-annual variation of rainfall over the basin was acquired from Pollino et al. (2016), which indicated that the mean annual rainfall was 1427 mm, and a decreasing trend, i.e., − 3.4 mm per year in the basin was noted (Figure 15, Data Source : IMD). Monsoon was the season that contributed the highest percentage (73.4%) of rainfall, followed by the post-monsoon (16.2%) (Figure 16).

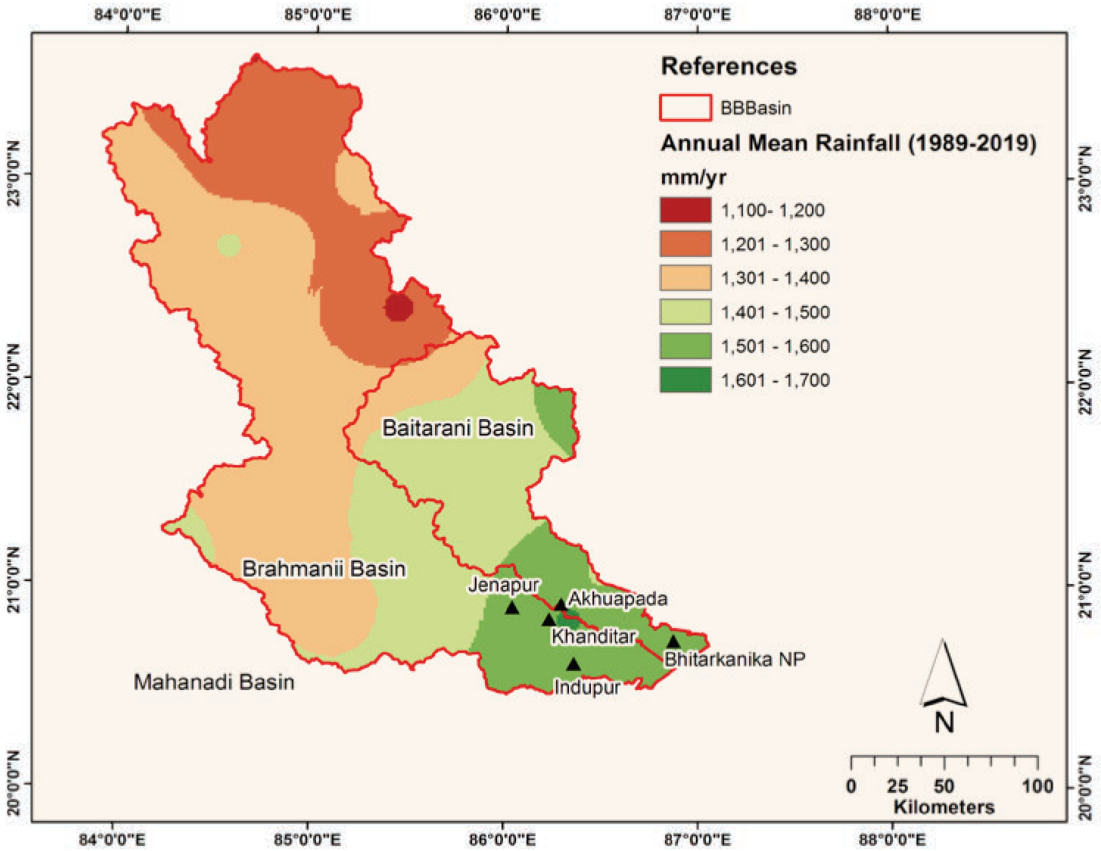


Figure 14 Spatial distribution of annual mean rainfall (1989–2019) in Brahmani and Baitarani basins

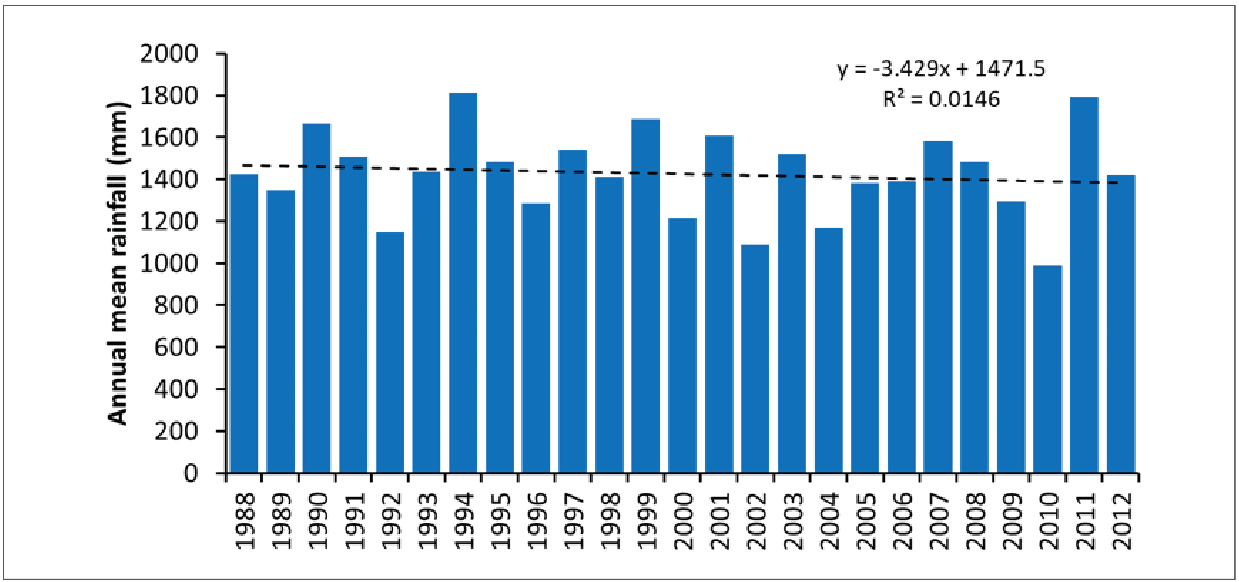


Figure 15 *Inter-annual variation in rainfall over the Brahmani and Baitarani basin*

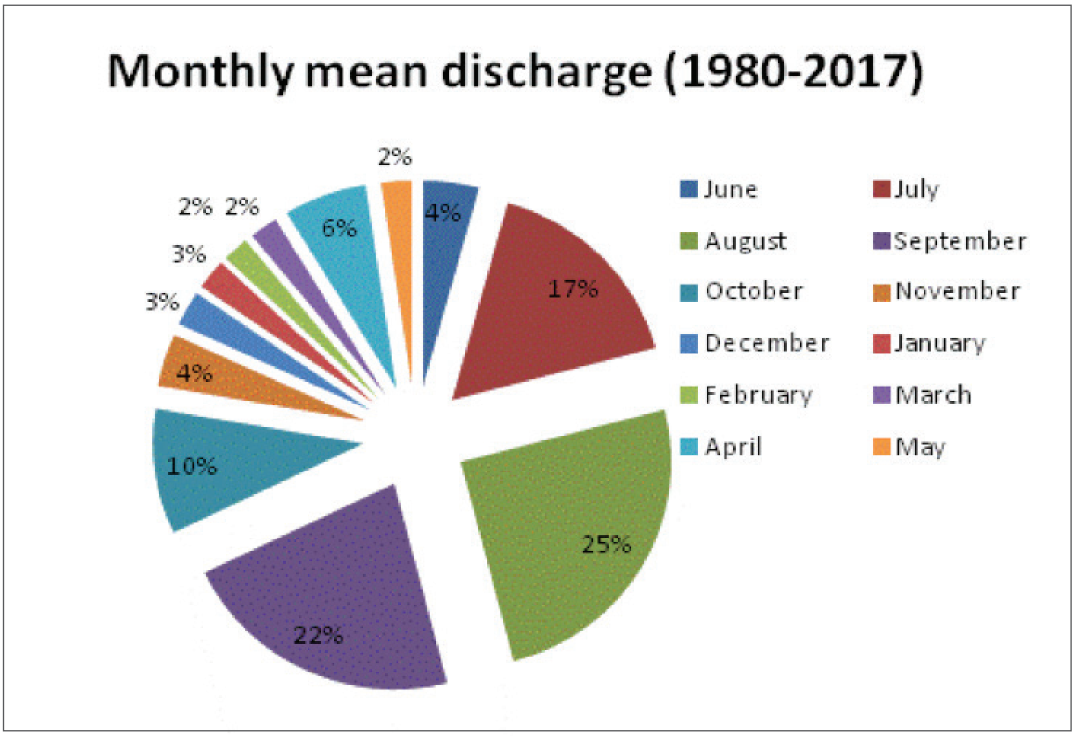


Figure 16 *Monthly mean discharge at Jenapur gauge station in the Brahmani Basin (1980-2017)*

Monsoon contributed the highest freshwater discharge in the sanctuary. The daily rainfall data from 1988 to 2019 were collected from nine IMD rain gauge stations from each block of Kendrapara district. The regression line showed that the annual mean rainfall over Kendrapara is decreasing at - 3.26 mm/year, as shown in Figure 17. The mean annual rainfall of Kendrapara was 1558.9 mm. The minimum and maximum rainfalls recorded in a year were 873.9 mm (in 2000, the driest year) and 2121.1 mm (in 1990, the wettest year), respectively (Figure 17).

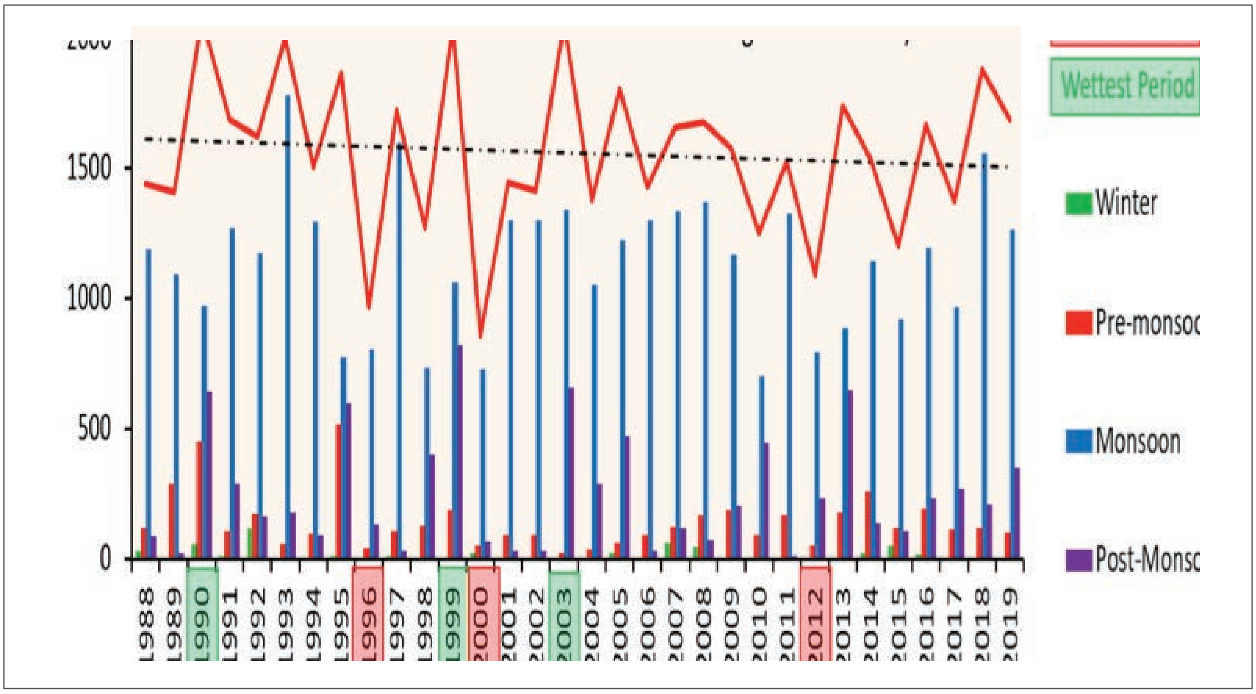


***Figure 17** Inter-annual and seasonal variability of rainfall in Kendrapara District*

With continued global warming and anticipated reductions in anthropogenic aerosol emissions in the future, CMIP5 models for rainfall prediction over entire India project an increase in the mean and variability of the monsoon precipitation by the end of the 21st century, together with substantial increases in daily precipitation extremes (Krishnan et al., 2020).

The rainfall projection for the Brahmani–Baitarani basin, based on an ensemble of three climate models (HadGEM2, GFDL and MIROC), reported by CWC in 2015 suggests that the monsoon rainfall could increase by 230 mm by the end of this century (400 mm in the HadGEM2 model). However, a 40% rise in the total monsoon rainfall by the middle of this century is expected. The multi-model ensemble rainfall is marginally lower than the rainfall inferred from HadGEM2; however, both the analyses suggest that the Brahmani-Baitarani basin is likely to experience an increase in rainfall by the mid-21st century and beyond. This will impact the salinity regime of the sanctuary, which will influence the entire coastal food web and mangrove composition.

Bhitarkanika experiences a dynamic freshwater-to-marine gradient from the upper reaches towards the mouth, where it meets Bay of Bengal. The projected increase in rainfall and thus freshwater flow from the rivers can affect the Bhitarkanika Sanctuary by lowering the salinity level.

The changing salinity levels can affect the biodiversity of the mangroves as they require an optimum salinity range for their growth. The reduction in salinity will also impact other trophic levels of the food web such as the phytoplankton and zooplankton. The large runoff can also lead to increased sedimentation, coastal erosion and loss of mangrove patches located on the shoreline. The flow of the Brahmani is regulated through the Rangali Dam, while the Baitarani flow is not regulated. From a management perspective, a strategic plan to divert surplus water through an irrigational project or barrage will be required by the DoWR during extreme rainfall events.

4.6 Temperature trend in Baitarani basin

The annual average temperature data form IMD for Chandbali station in Baitarani basin for the past 18 years (2001–2018) were analysed and is shown in Figure 18.

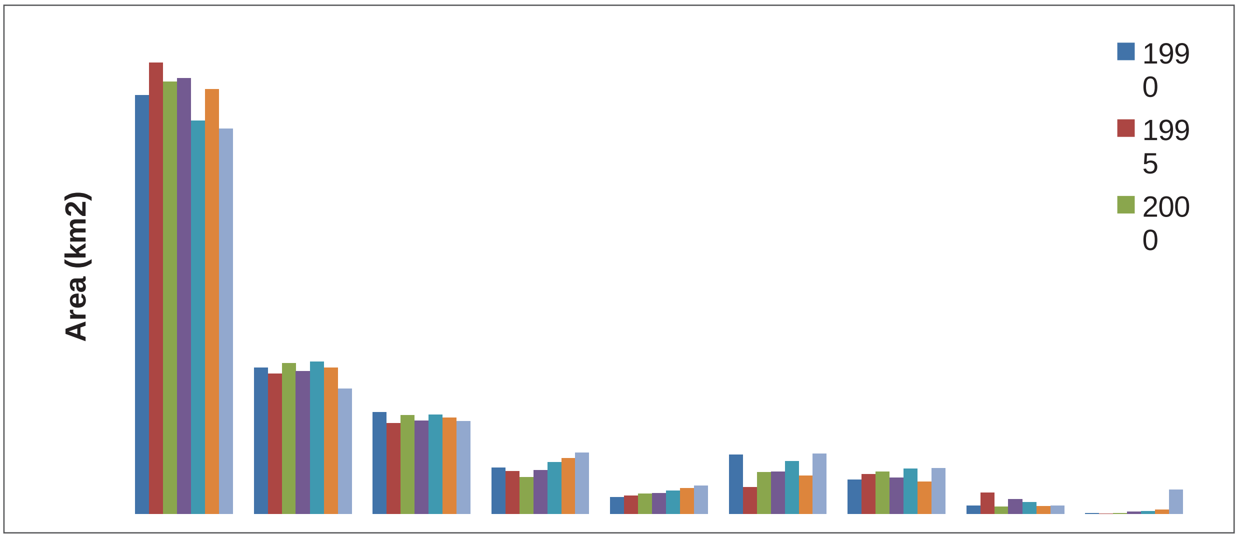


Figure 18 Mean annual temperature at Chandbali station, in Baitarani Basin

The mean annual temperature of the station during the study period was 27.7°C. The annual mean temperature displayed a non-significant increasing trend. The average annual maximum temperature of the Chandbali station was 29.3°C, while the average annual minimum was 26.7°C.

4.7 Relative humidity in Baitarani basin

The inter-annual variation of the relative humidity from 2001 to 2018 Chandbali station indicated that the mean annual relative humidity was 76.6%, with a significant decreasing trend as shown in Figure 19 (Data source : IMD).

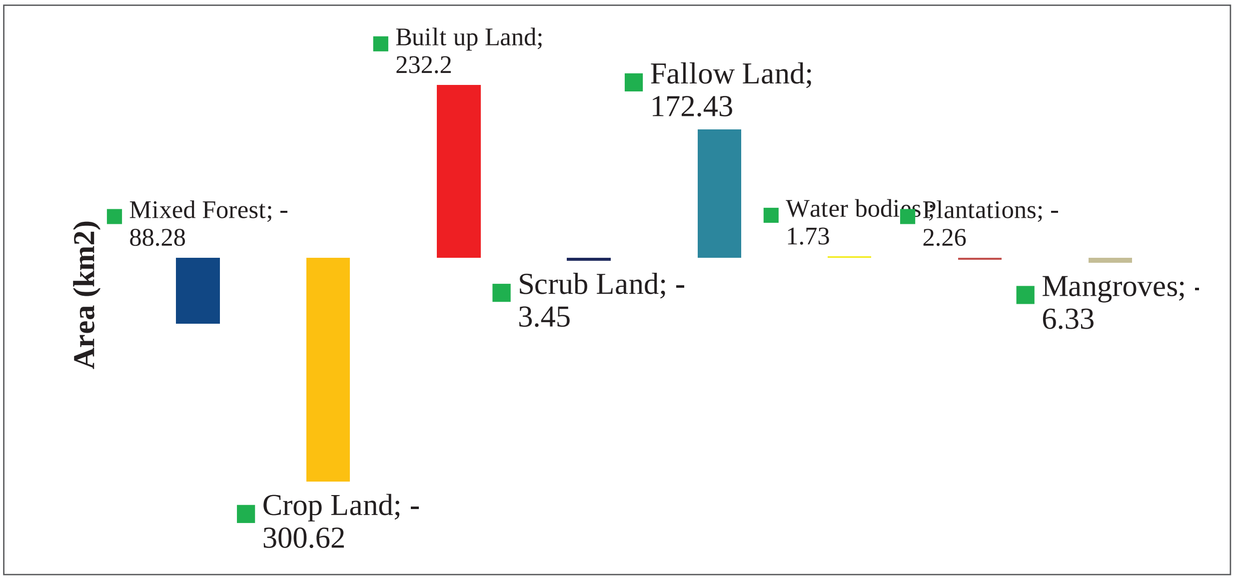


Figure 19 Inter-annual variability of relative humidity of Chandbali station, in the Baitarani Basin

4.8. Freshwater abstraction and impact on the hydro-ecology of the sanctuary

Freshwater is one of the natural resources that are vital not only for agriculture but also for industries, hydro-power and domestic uses. Consequently, there is a conflict when meeting the requirement of water for the conservation of wetlands. Bhitarkanika Sanctuary is located at the confluence of the Brahmani and Baitarani rivers and gets enriched by the perennial flow of the freshwater of these rivers. The Bhitarkanika mangrove forest needs freshwater for survival and growth, but due to the distal position of Bhitarkanika Sanctuary, it gets residual river water after all the upstream societal and industrial water demands are fulfilled.

Many anthropogenic activities such as irrigation projects have directly or indirectly impacted the natural flow of river channels in the Brahmani–Baitarani basin and eventually resulted in changes in the freshwater flow to Bhitarkanika Sanctuary. The intensification of economic activities upstream, especially the mining and industrial activities in the Brahmani basin and the number of multi-purpose hydro-power irrigation dams and upcoming water projects along the rivers are likely to impact the biodiversity of the area. The biggest threat seems to be coming from the mining and industrial activities of Talcher, Angul area, but the reduced freshwater flow due to diversion for irrigation projects may further amplify the threat manifold. Poor water quality, with pollutants (e.g., heavy metals) and a low water flow, with a reduced sediment load, had already been noted in the freshwater inflow of Bhitarkanika. These will impact the growth of mangroves through changes in the salinity and nutrient load (CPSP Report, 2005). After the construction of Rengali Dam and the Rengali Irrigation Project, the water flow to Bhitarkanika changed, but as of now the Bhitarkanika mangrove forest appears to be resilient to changes in the freshwater flow to the sanctuary. *Heritiera fomes,* locally known as Sundari, is known to require low soil and water salinities. The dominance of this species in Bhitarkanika indicated a low salinity and an optimal freshwater inflow to the sanctuary.

The sustainability of the mangroves is crucially dependent on a delicate mix of abundant freshwater (riverine flow) and saline water, which the tides provide. Salinity at an adequate level is the most desirable condition, as in the absence of the optimum salinity range, mangroves will not survive. The optimal salinity is 5–15 ppt (low salinity) for luxuriant growth and sustenance of mangroves. Mangroves can tolerate higher salinity (>25 ppt) compared with non-mangrove plants. Some species are more tolerant than others. For example, *Rhizophora mucronata* seedlings thrive in salinity values of 30 ppt, whereas *R. apiculata* cannot live in salinity levels above 15 ppt (Kathiresan & Thangam, 1990; Kathiresan et al., 1996). *Sonneratia alba* grows in water salinity values between 2 ppt and 18 ppt, but *S. lanceolata* can only tolerate salinity values up to 2 ppt (Ball & Pidsley, 1995). In general, mangrove vegetation is more lush in lower salinities (Kathiresan et al., 1996). Experimental evidence indicates that at high salinity values, mangroves use more energy to maintain the water balance and ion concentration rather than for primary production and growth (Clough, 1984). Mangroves are poor competitors under non-saline conditions, under which freshwater marsh plants easily out-compete them.

The dominant species of Bhitarkanika Sanctuary according to the Space Application Center Report (2019) were *Excoecaria agallocha, Heritiera fomes, Avicennia officinalis, Avicennia marina, Avicennia alba, Rhizophora mucronata, Sonneratia apetala, Sonneratia caseolaris, Acanthus ilicifolius, Aegiceras corniculatum, Phoenix paludosa* and *Kandelia candel.* Species such as *Heritiera fomes* (locally known as Sundari), *Nypa fruticans* (locally known as Golpata) and *Sonneratia apetala* are freshwater loving, whereas *Phoenix paludosa* (locally known as Hental), *Ceriops decandra* (locally known as Chanti Goran), *Avicennia* sp. and *Excoecaria agallocha* prefer high salinity levels. Further detailed studies should be carried out on these mangroves species to examine their spatial distribution in Bhitarkanika Sanctuary with respect to the salinity range to identify the indicator species of different salinity regimes. Thus identification of mangrove indicator species is important for the assessment of the changes in salinity of the sanctuary.

The mangrove areas of Bhitarkanika support a range of inter-connected food webs, which directly sustain shrimps and provide a food source for fishes. Some of the commercially important fishes are Ilisha *(Hilsha illisha),* Khainga (mullet species), Bhekti *(Lates calcifer),* Kantia *(Mystus gulio)* and Kokili *(Anchovella sp.).* Prawns such as *Penaeus indicus, Penaeus monodon* and *Metapenaeus affinis* and crabs, mainly the Mud Crab *(Scylla serrata)* and Fiddler Crab *(Uca sp.),* are seen in large numbers in commercial catches. Many of these fishes and shellfishes are directly harboured by the mangroves during a part of their life cycle, and they remain dependent on the mangrove food web throughout their life cycle. Therefore any disturbance to the mangrove ecosystem, either due to reduction in salinity level or through cutting down trees for fish pond development, will result in smaller catches in the off-site fisheries. In addition to indirect influence through loss of mangroves, water salinity has also been shown to impact directly the fish development and growth. At intermediate salinities (8–20 PSU), better fish growth is often linked to a lower standard metabolic rate (Boeuf & Payan 2001). Thus, an optimum freshwater flow and salinity value are key elements in sustaining the near-shore fisheries of Bhitarkanika.

4.9. Sources of pollution and potential impacts on Bhitarkanika Sanctuary

Bhitarkanika Ramsar site has been facing increasing threats from different industrial developmental activities in the river basin and on the shoreline (e.g., ports, water diversion projects, jetty projects). The anthropogenic pressure includes livelihood-related exploitation of both water (e.g., aquaculture) and forest resources from the sanctuary.

The natural calamities, i.e., cyclones, floods, etc. also directly impact the sanctuary. The Dhamra port is located at a distance of 5 km from Bhitarkanika Sanctuary and 15 km from the mass nesting beaches of Gahirmatha Marine Wildlife Sanctuary (Figure 20). The port and its accompanying industrial and residential development, dredging, artificial lighting, shipping traffic, pollution, accidental oil and chemical spills, invasive species transported in bilge water, etc. are some of the potential problems posed to the turtles and the wider environment (Dhamra Port Project Backgrounder Report, 2009). Therefore, the management plan for the sanctuary should consider all such stressors that directly or indirectly affect the hydrology and ecology.

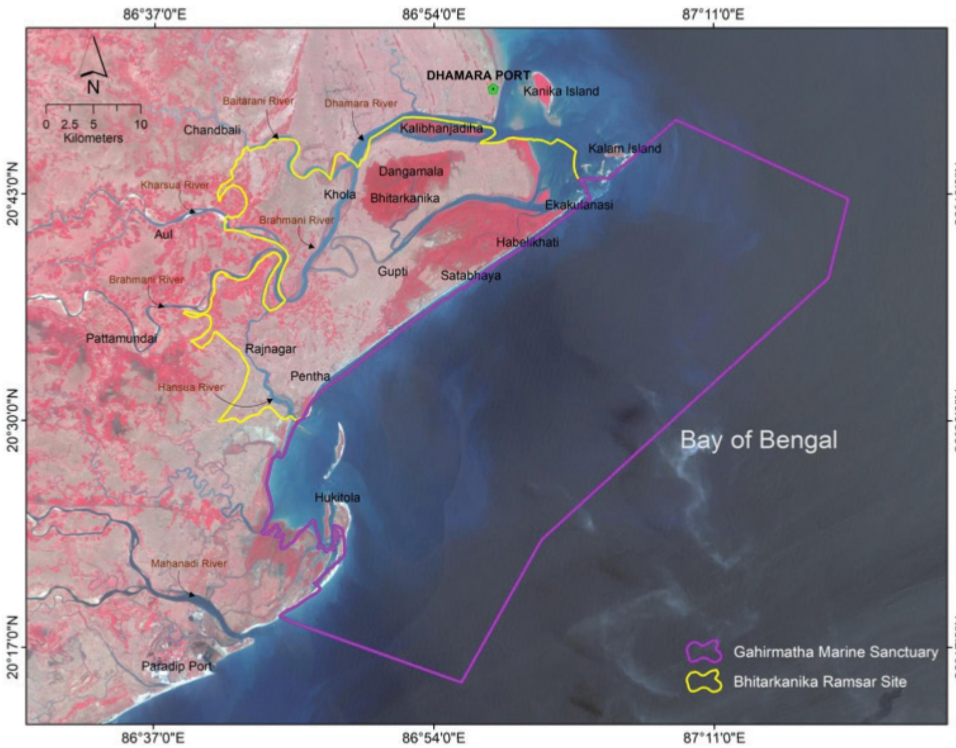


Figure 20 *Map showing the location of Dhamra port along with Bhitarkanika and Gahirmatha Marine Wildlife Sanctuary*

The Bhitarkanika Sanctuary outer boundary is about 25 km from the Paradeep port. However, the new proposed boundary of the sanctuary, which includes a 1 km^2 area of the Mahanadi mangroves, is only 5–6 km away from Paradeep port. The port town of Paradeep has a population of 1,15,000, which has a major contribution of sewage to the coastal waters. Paradeep Phosphates Ltd. (PPL) and Oswal Chemicals and Fertilizers Ltd (OCFL), producing nitrogenous and phosphate fertilisers, are the major industries in Paradeep (Figure 21 and Table 3). These industries are likely to add to the phosphate pollution load in the estuarine and coastal waters and pose additional challenges to the conservation of the Mahanadi mangroves. The major sources of oil spills are collisions between ships, grounding of ships and oil tankers and accidents involving vessels visiting the major port of Paradeep and vessels cruising off the coast of Odisha to the ports of Haldia and Kolkata (ICZMP Report).

The Odisha Government has planned for massive industrial growth in the region by way of establishing a large number of thermal power plants, steel plants and other coal-based industries. The mining industry has provided numerous developmental benefits, but it has also caused substantial environmental pollution and degradation by clearing vast forested areas, destroying natural habitats, making heavy use water resources and polluting them and producing harmful dust. According to Survey of India toposheets, 1972, the noticeable forest cover of the Angul Talcher-Meramundali region was 2315.04 km^2 (46.04%). The satellite imagery of December 2007 showed the forest cover to be 1770.32 km^2 (35.20%). This reveals a decrease of 23.54% in the forest cover since 1972 (Technical Report: Carrying Capacity Study of Angul Talcher Area, OSPCB, 2018).

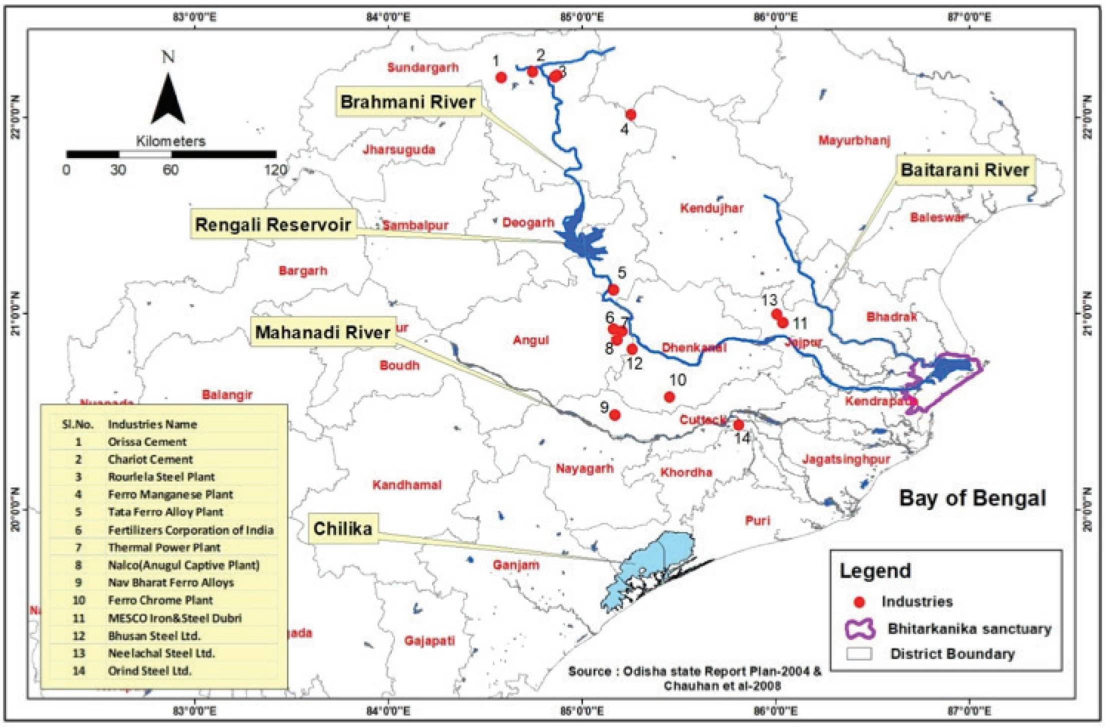


Figure 21 *Industries in the Brahmani and Baitarani river basins*

Surface mining pollutes groundwater and surface water via both direct degradation and indirect degradation. Direct degradation happens when groundwater bodies are located down a gradient or downhill from a mine area. Coal mines and related industries are spread over the Talcher region of the Brahmani river basin.

Since, coal is the major resource of coal based-industries, i.e., thermal power plants, steel plants, etc., industrial exoansion is envisaged. The addition of these activities will stress all the components of the prevailing environment.

Industries such as the coal mines of MCL, the aluminium plant of National Aluminium Company Limited (NALCO) and its Captive Power Plant (CPP), Talcher Super Thermal Power Station and Talcher Thermal Power Station of NTPC are situated along the river stretches (Figure 21 and Table 3).

Table 3 *Major polluting Industries and the rivers concerned in the Angul-Talcher industrial area, Brahmani river basin*

Name of industry	Public/ private sector	Category	Effluent recipient	Concerned River
NALCO, CPP, Angul (industrial effluent and ash pond overflow, ash pond water is completely reused)	Public sector	Thermal power	Nandira river	Brahmani
NTPC, Kaniha (industrial effluent)	Public sector	Thermal power	Tikira river	Brahmani
NTPC, Kaniha (ash pond overflow, effluent)	Public sector	Thermal power	Tikira river	Brahmani
TTPS (NTPC), Talcher, Angul (industrial effluent)	Public sector	Thermal power	Nandira Jhor	Brahmani
TTPS (NTPC), Talcher (ash pond overflow, effluent)	Public sector	Thermal power	Nandira Jhor	Brahmani

Source: Environmental Statement (Form-V), (2006–07), Mahanadi Coal Limited, Odisha.

Raw water to the extent of about 86 million cubic metres/annum is drawn from the river for industry/ mining activity, apart from other surface and ground withdrawals (36 million cubic metres/annum) (Technical Report: Carrying Capacity Study of Angul Talcher Area, OSPCB, 2018). The water consumption and waste water generation by the major existing industrial users and some of the proposed industries are as given in the following. Rivers and streams are not far from the industries, and effluents from point as well as non-point sources contaminate them continuously.

Table 4 *Production of coal, water consumption and waste water discharge from the various coal mines in the Angul-Talcher industrial area in the Brahmani river basin*

Mines	Area (ha)	Production (MTY)	Water consumption (kl/day)	Waste water discharge (kl/day)	Concerned river
Jagannath OC	590.853	5.57	1168.71	701.23	Brahmani
Ananta OC	242.810	12.0	1648.84	989.30	Brahmani
Kalinga OC	117.350	NA	NA	NA	Brahmani
Chendipada OC	24.300	0.28	34.3	20.58	Brahmani
Bharatpur OC	1237.180	9.23	4090.43	2454.26	Brahmani
Lingaraj OC	1248.510	10.82	2263	1357.8	Brahmani
Hingula OC	1063.560	7.88	1290	774.0	Brahmani
BalaramPrsad OC	NA	4.12	1135	681.0	Brahmani
Talcher UG	1140.000	0.20	2420	1452.0	Brahmani
Nandira UG	1785.750	0.22	1751	1050.6	Brahmani
Total	**7450.30**	**50.33**	**15801.28**	**9480.78**	

Source: Environmental Statement (Form-V) (2006–07), Mahanadi Coal Limited, Odisha.

Table 5 Existing and proposed industries in Angul-Talcher industrial area, Brahmani river basin

Name of the industry	Products	Water consumption (thousand litres/day)	Waste water generation (thousands litres/day)
A) Existing industries			
National Aluminum Company - smelter unit	Aluminum	5066	4900
National Aluminum Company - captive power plant	Electric Power	1,35,000	90,000
ORICHEM Ltd.	Chemicals	170	10
Talcher Thermal Power	Electric Power	13,227	6,483
Talcher Super Thermal Power Plant NTPC, Kaniha	Electric Power	1,37,099	52,080
Miscellaneous	---	45,883	16,608
Total		**3,36,445**	**1,70,081**
Proposed industries			
MESCO Iron Steel Ltd. Duburi	1.0 MT, iron	84,840	40,078
MESCO Kalinga Steel Ltd. Duburi	4.5 MT, steel	1,93,200	91,268
Bhusan Steel Ltd.	3.0 MT, iron and Steel	2,29,200	1,08,274
Neelachal Steel Ltd.	2.5 MT, iron and steel	1,75,200	82,764
Brahmani Steel, Duburi	1.0 MT, Iron and steel	84,840	40,078
ORIND Steel Ltd.	1.0 MT, Iron and steel	16,800	7,936
Other steel plants	3.0 MT, iron and steel	2,88,000	1,36,051
Ancillary industries		45,840	21,655
Kalinga Power	4 × 250 MW	3,36,000	1,58,726
Total		**14,53,920**	**6,86,832**

(Source: Technical Report: Carrying Capacity Study of Angul Talcher Area, OSPCB, 2018)

Due to industrial development and the dense human population settled along the Brahmani river and faecal contamination (open defecation) is also one of the issues. The release of untreated domestic or industrial wastes into rivers results in high Biological Oxygen Demand values and deterioration of the water quality. In Bhitarkanika mangroves, sediment-associated trace element concentrations are also increasing as a result of anthropogenic inputs and will influence the biota and biogeochemistry of this ecosystem. Furthermore, the decreasing water quality due to heavy metal pollution will further put a stress on mangrove species as mangroves have a natural ability to act as a sink of toxic pollutants.

The deterioration of river water quality eventually will impact the ecological health of Bhitarkanika Sanctuary as the Brahmani river is one of the major sources of freshwater. A study by Chauhan and Ramanathan (2008) found that the Brahmani and Baitarani rivers have extremely variable trace element concentrations, which are consistently higher than the world river average. The study also reported high concentrations of heavy metals (Fe, Mn, Zn, Ni, Cr, Co, Cd and Pb) at the estuarine sites of the national park. The authors have correlated the heavy metal pollution to the industrial activities in the upstream stretches of Brahmani river and concluded that this mangrove system is facing severe threats due to this.

Another study by Panda et al. (2013) showed that the heavy metal concentration in Bhitarkanika sediment samples was in the range of 5.99–92 ug/g, which was much higher than the bioaccumulation potential of the mangrove species of Bhitarkanika. Therefore the sanctuary management plan should keep a constant watch on the river water quality, and if the situation goes beyond the permissible limits, the CPCB or SPCB should be informed to look at the possible sources and deploy mitigation techniques.

OSPCB has prepared a 5-year action plan (2010–11 to 2014–15) for the Angul-Talcher area (OSPCB, 2016). According to an Odisha SPCB report (2016) that gives a detailed account of the actions taken by different industries for abatement of pollution, several corrective measures were employed by the concerned industries for managing the mine drainage and water quality of effluents, solid/hazardous waste disposal and for water and air pollution control.

Environmental monitoring showed that the BOD level in the Brahmani river exhibits an increasing trend from downstream of Talcher, near Rajbati, till Mangalpur and that from the Mangalpur BOD value starts dropping; nevertheless, it remains within the Class-C criteria of 3.0 mg/l. The trend thus indicates excess an BOD load from Talcher town. Similarly the value of the total coliform (TC) count also shows an increasing trend. The concentrations of specific pollutants such as fluoride, nitrate and chromium (hexavalent) in the river Brahmani, flowing adjacent to the critically polluted area (CPA), remained within the norm during the 5-year period The fluoride concentration, though within limits, shows an increasing trend in downstream of Talcher. The monitoring results (SPCB) of groundwater around the coalfield area suggest that the Pb, Hg, Cd and Zn levels in most of the locations remain within the acceptable limit. The results of the groundwater quality monitoring being carried out by MCL also corroborate these results.

Central Pollution Control Board independently monitors various parameters for evaluating the Comprehensive Environmental Pollution Index (CEPI) score and has published the CEPI scores of 43 industrial clusters, including those of Angul-Talcher for the periods 2009, 2011 and 2013. It can be seen that the implementation of the abatement of action plan is quite effective in bringing down the CEPI score from 82.09 in 2009 to 72.86 in 2013. Thus, the action plan should be continued with additional points for bringing down the CEPI index to safe and acceptable levels.

Panda et al. (2013) compared heavy metal bioaccumulation in 16 species of mangrove in Bhitarkanika. It was found that heavy metal bioaccumulation in *Avicennia alba, Ceriops decandra, Xylocarpus granatum* and *Rhizophora mucronata* was much higher, suggesting greater potential and capacity for the uptake of heavy metals. Hence, plantation of such mangrove species in the polluted coastal areas should be carried out to mitigate the metal pollution for conservation of the mangrove ecosystem. The management plan should assess the feasibility of planting these species in upstream river areas so that the pollutants, especially heavy metals, are sequestered before they reach downstream parts of the sanctuary.

Agriculture is the most abundant land use in both the Brahmani and Baitarani basins. Nitrogen (N), phosphorous (P) and potash (K) consumption during 1993–2013 were analysed. The year-wise fertiliser consumptions (in terms of N, P and K) in the two districts (close to Bhitarkanika Sanctuary) are shown in Figure 22.

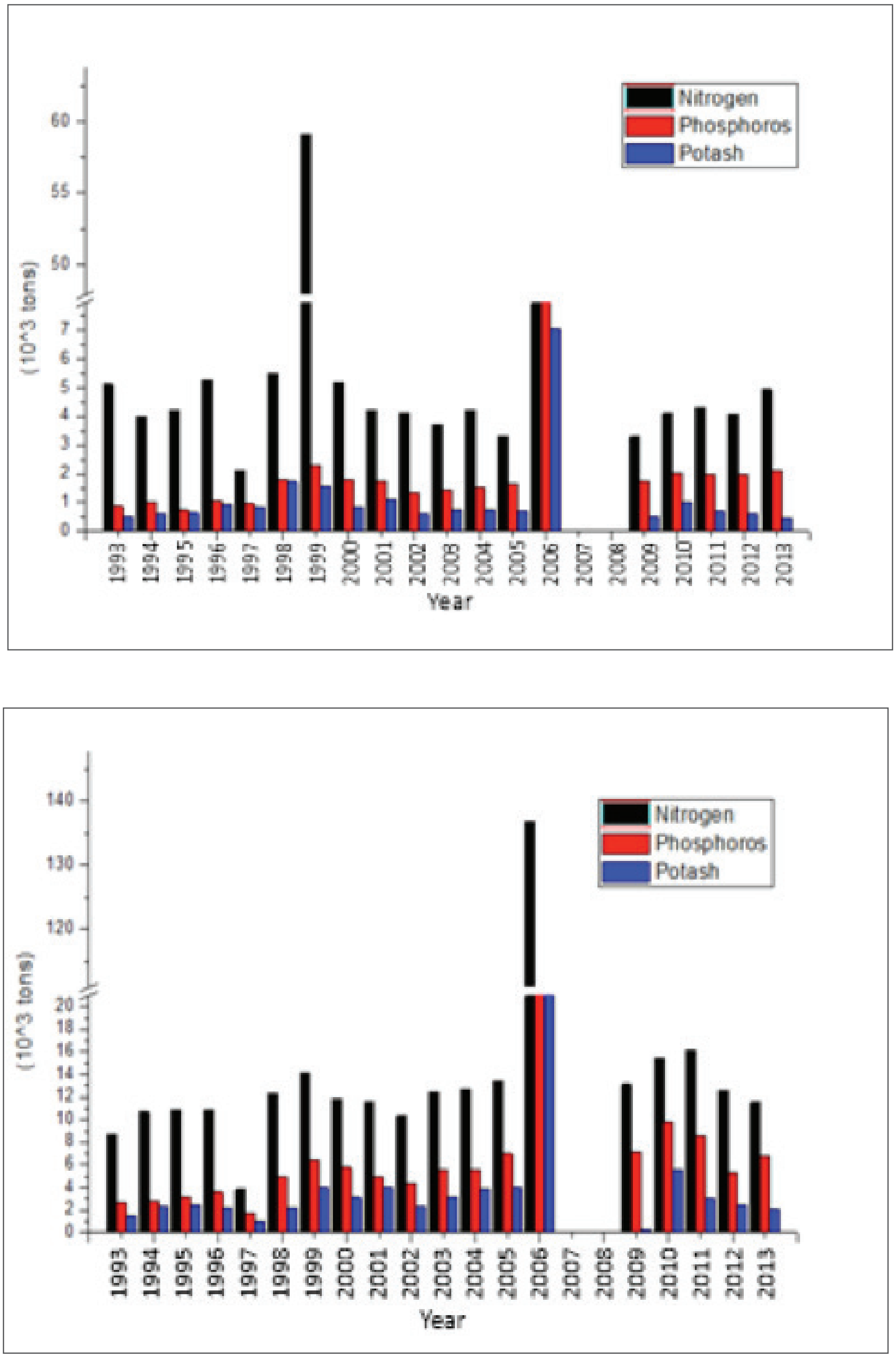


Figure 22 *Fertiliser consumption in (a) Kendrapara and (b) Bhadrak district, Odisha. (Source : Directorate of Agriculture & Food Production, Odisha Agri. Stats., Govt. of Odisha, 2013)*

Statistically, the variations in fertiliser application since 1993 to 2013 were insignificant, which indicated that the fertiliser consumption during this period remained almost the same (except higher consumption during 2006). Compared with Kendrapara, Bhadrak district used higher quantities of fertiliser (~3 times) during the period. The fertiliser application of N, P and K during this period was 8.9, 2.3 and 1.2 (× 103 tons), respectively, for Kendrapara district and 18.4, 8.7 and 4.1 (× 103 tons) for Bhadrak district.

Thus, intensification of agriculture will increase the use of fertilisers which eventually will be transported to the delta region of the Brahmani and Baitarani through land runoff and river discharge, making its way to the sanctuary. The high nutrient loading into the sanctuary will be deleterious to the mangrove forests. Previous studies have shown that increasing nutrient availability introduces instability into mangrove forests and lowers their resilience to environmental variability. The instability arises because nutrients, particularly N, stimulate growth of shoots relative to roots, thereby enhancing productivity during favourable periods but increasing vulnerability to water stress during droughts (Lovelock et al., 2009). The management action plan should include action at both direct basin and sanctuary levels to promote the use of biological fertilisers and organic farming practices and minimise the nutrient loading of the system.

5. LAND USE AND LAND COVER (LULC) CHANGES WITHIN BHITARKANIKA MANGROVES AND ITS DIRECT CATCHMENT

5.1. LULC of Bhitarkanika Ramsar Mangroves

Multi-resolution satellite imagery of Landsat (MSS, TM, ETM+ and OLI) were acquired from https://earthexplorer.usgs.gov/ for the period 1990–2020 (Table 6). All the satellite images have the UTM (Universal Transverse Mercator) Projection system and WGS 84 (World Geodetic Survey 1984) Datum. All the images are ortho-rectified and geo-referenced. The details regarding the satellites and their acquisition dates and times are listed in Table 6.

Table 6 *Details of satellite data used for LULC analysis of Bhitarkanika Sanctuary*

Year	Date of pass	Time (UTC)	Satellite	Resolution	Path/row	Source
1990	23-Dec-1990	04:10	Landsat 4 TM	30m	139/046	Earth Explorer
1995	24-Mar-1995	03:47	Landsat 5 TM	30m	139/046	-do-
2000	29-Mar-2000	04:30	Landsat 7 ETM+	30m	139/046	-do-
2005	15-Feb-2005	04:24	Landsat 5 TM	30m	139/046	-do-
2010	20-Jan-2010	04:29	Landsat 7 ETM+	30m	139/046	-do-
2015	26-Jan-2015	04:38	Landsat 8 OLI	30m	139/046	-do-
2020	28-Mar-2020	04:38	Landsat 8 OLI	30m	139/046	-do-

The extent of Bhitarkanika Sanctuary is 672 km^2 whereas that of the Ramsar site designated area is 650 km^2 (MoEFCC 2020, Ramsar Sites of India, Factsheet). On a broader scale, an LULC analysis of the entire sanctuary area is more meaningful. The LULC of Bhitarkanika Ramsasr site for 1990–2020 was analysed by CDA to reveal the changes in LULC that are the key drivers of the hydrological changes (Wagner et al., 2013; Kaushal et al., 2017). The ground verification of LULC classes was conducted during field surveys in October and December 2020 by the CDA

(Figures 33-38). The LULC change over the period 1990–2020 and net changes are presented in Figures 24 and 25. Also, the LULC changes and their change matrix in time scale are presented in Tables 9 and 10. The percentage distribution of LULC at Bhitarkanika Ramsar Site is depicted in Figure 26 and Figures 27-33, which represent the LULC class map of each selected time period (1990-2020).

5.1.1 Agriculture

Agriculture is the predominated land use type in the area. LULC change analysis showed that there has been a land transformation from agricultural farms to aquaculture farms for the purpose of shrimp culture in recent years. During 1990, an extent of 338.2 km^2 area (50.3% of the total sanctuary area) was under agriculture, which declined to 311.4 km^2 (46.3%) in 2020, according to satellite imagery analysis, as shown in Table 9. The pressure posed by the increasing population of the Bangladeshi refugees by converting agricultural land into shrimp farm is considered a prime reason for the decrease in the agricultural land and a threat to the mangrove ecosystem and its biodiversity.

5.1.2 Dense mangroves

Mangroves with canopy cover density between 40% and 70% are considered as moderately dense mangroves, while canopy cover densities higher than 70% are considered very dense mangroves. In our analysis, both dense and very dense mangrove types were included under "dense category". The sanctuary showed a declining trend in the area under dense mangroves. In 1990, an extent of 118.2 km^2 area (17.6% of the total sanctuary area) was under dense mangroves, which declined to 101.41 km^2 (15.1% of the total sanctuary area) in 2020 (Table 9). The degradation of dense mangroves is mainly due to human encroachment and reclamation of land for aquaculture practices as seen in satellite imagery and ground surveys. Higher tides as a result of the sea level rise have also forced people to migrate towards more inland areas. There is also encroachment and cutting of mangrove forests to make more land available. In addition, the cyclones that strike the Odisha coast also do impact the mangroves (Table 7).

The dependence of the local people on the forests for fuel wood was high among villagers residing within 1.5 km from a forest (Kadaverugu, et al., 2021). More than 14% of the total annual fuel wood consumption of local households comes from nearby mangrove patches. Almost all the households located in the buffers of BNP are involved in making baskets, mats, etc. from mangrove leaves and bark. Fuel wood extraction is one of the major causes of deforestation of the mangroves in the region (Kadaverugu et al., 2021).

Table 7 *List of cyclones that struck Odisha coast since 2010*

Name	Year	Wind speed (km/h)	Brief description
Phailin	2013	215	Phailin intensified rapidly and became a very severe cyclonic storm on October 10. It approached the Indian state of Odisha and made landfall later that day, near Gopalpur, on the Odisha coast, at around 2230 IST on October 12.
Hudhud	2014	185	Hudhud intensified into a cyclonic storm on October 8 and a severe cyclonic storm on October 9. Hudhud underwent rapid deepening in the following days and was classified as a very severe cyclonic storm by the IMD. Shortly before landfall near Visakhapatnam, Andhra Pradesh, on October 12, Hudhud reached its peak strength, with 3-minute wind speeds of 185 km/h (115 mph).

Name	Year	Wind speed (km/h)	Brief description
Titli	2018	110	On October 6, a low-pressure area formed in the Andaman Sea. Over the next two days, this low-pressure system entered the Bay of Bengal and became a depression on October 8. Afterwards, the storm rapidly strengthened, becoming a very severe cyclonic storm on October 9. Titli made landfall near Palasa, Andhra Pradesh, at peak intensity between 4:30 a.m. and 5:30 a.m. IST on October 10-11.
Fani	2019	250	Extremely severe cyclonic storm Fani was the strongest tropical cyclone to strike the Indian state of Odisha since the 1999 Odisha cyclone. Fani rapidly intensified into an extremely severe cyclonic storm and reached its peak intensity on 2 May. Fani weakened before making its landfall and dissipating the next day.
Amphan	2020	115	Cyclonic storm Amphan was a strong tropical cyclone over the Bay of Bengal threatening eastern India as well as Bangladesh. It was the first tropical cyclone of the 2020 North Indian Ocean cyclone season. Amphan was the first cyclonic storm in the Bay of Bengal since the 1999 Odisha cyclone.

We also referred to FSI data to assess changes in the mangrove area (2005–2019) in Kendrapara, Odisha (Table 8 and Figure 23). Combining two types of mangrove (very dense and moderately dense) into one category, i.e., “dense mangrove”, implies that the mangrove area did not change much between 2009 (164 km^2) and 2019 (165 km^2). It should be noted that the FSI does the assessment on a 1:50,000 scale which is desirable for forest cover mapping over all off India. In contrast, our analysis is more refined as the mapping has been done at a 30 m spatial resolution with superimposed classification and manual interpretation using Landsat satellite data.

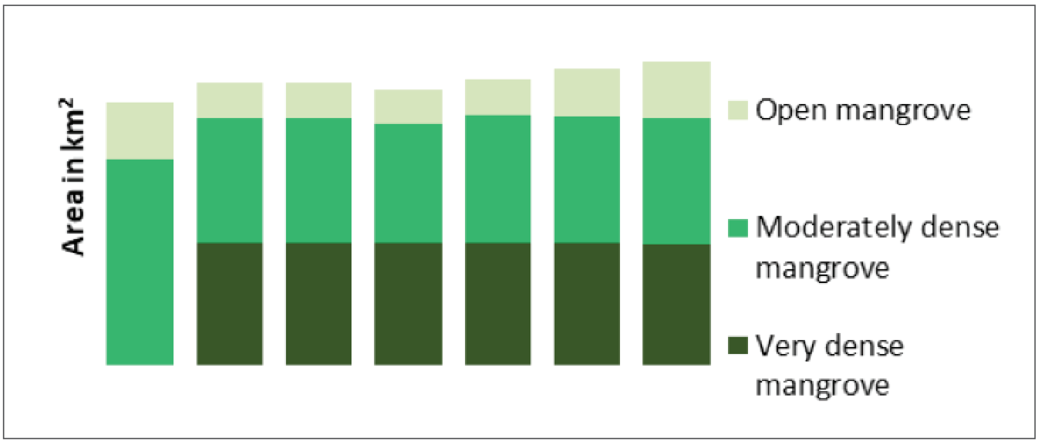


Figure 23 *Mangrove area in Kendrapara, Odisha*
(Source: State of Forest Report (2005-2019), Dehradun, India)

Table 8 *Mangrove coverage in Kendrapara district, Odisha*

Mangrove Category	2005	2009	2011	2013	2015	2017	2019
Very dense mangrove	0	81	81	82	82	82	80.45
Moderately dense mangrove	137	83	83	79	84	83	83.56
Open mangrove	38	23	23	22	24	32	37.48
Total area (km^2)	**175**	**187**	**187**	**183**	**190**	**197**	**201.49**

(Source: State of Forest Report (2005–2019), Dehradun, India)

5.1.3. Open mangrove

Mangrove cover with canopy density between 10% and 40% is considered as open mangroves. The area under open mangrove increased from 37.2 km^2 in 1990 to 49.5 km^2 in 2020 (Table 9). This may be attributed to the intensification of afforestation programmes by the Wildlife Division, natural germination and other programmes such as plantation in the fringe areas of the national park after the super cyclone, which struck the Odisha coast in 1999. A study conducted using satellite data from Bhitarkanika has shown that 70% of the total dense mangroves changed into open mangroves between 2004 and 2017 (Shrestha, 2019). This could also explain the increase in open mangrove area noted in the present analysis. Conversion of dense to open mangroves is an indication of forest degradation, likely due to encroachment and over-exploitation for resources resulting from a lack of strict law enforcement.

5.1.4. Water body

The water body category includes rivers, creeks, channels and ponds. The decline in water body area could also be due to satellite imagery with different tidal conditions. Some of this water also gets in to the feeding channel that supplies water to the aquaculture ponds and contributes to the increase in the extent of the water body category. The LULC change pattern showed that the area covered by water body declined to 75.0 km^2 in 2020, which was 82.1 km^2 in 1990 (Table 9).

5.1.5. Intertidal zone

The intertidal zone is defined as the area between the high tide and low tide marks. The intertidal zone increased over the time, which could be due to shoreline changes and coastal processes. The intertidal area in 1990 was 13.6 km^2, which comprised 2% of the total sanctuary area, and increased up to 22.94% in 2020 (Table 9).

5.1.6. Mudflats/swamps

Mudflats/swamps are areas that are inundated or submerged during the daily high tides and are found mostly in the estuarine areas of the composite delta fronts of the Maipura and Dhamra rivers. The mudflats/swamp area marginally increased from 47.9km^2 in 1990 to 48.7 km^2 in 2020 (Table 9).

5.1.7. Plantation/other vegetation/settlements

This category included all the vegetation and plantations other than mangrove species as well as settlements. The settlements were included in this category as Landsat Satellite data has only a 30 m spatial resolution, making it difficult to differentiate between vegetation and settlements.

5.1.8. Sand

Land in this category is confined to the coastal areas adjacent to the intertidal zone but further inland. The sand category experienced only a marginal increase, by 0.2 km², in 2020 compared with 1990 (Table 9).

5.1.9. Aquaculture

The aquaculture area showed a patchy distribution in the sanctuary in 1990. The area was only 0.4 km², which comprised 0.1% of the total sanctuary area and increased up to 19.5 km² in 2020 (Table 9). Conversion of agricultural land into aquaculture ponds or shrimp culture has caused a significant increase in the area under the aquaculture land use. Aquaculture is lucrative business: it gets very high returns, on minimal investment. An investment of Rs.1 lakh in an acre of land yields a shrimp catch worth Rs.5 lakhs in six months. This is why there is always a race to clear mangroves and convert them into aquaculture ponds. As shrimp culture is a high-profit business, people are converting agricultural land into aquaculture ponds. As the aquaculture farms are in close proximity to the mangrove forests, the impact is direct on the ecology of the mangroves. The untreated effluent from these aquaculture ponds flows back to nearby rivers and creeks thereby affecting the aquatic fauna and the mangroves. The aquaculture ponds require saline water which is siphoned to the aquaculture ponds through inlet channels connected to rivers.

The saline water of the river also adds salt in high concentrations to the adjacent agricultural farms, which will decrease the soil fertility and thus will affect the agro-economy of the dependent communities. Immediate high profit margin lures many outside entrepreneurs and local people to take up shrimp farming unmindful of the damage to the environment. Shrimp farming results in the area becoming permanently unsuitable for the mangrove ecosystem. It causes pollution through addition of chemicals and pesticides and usually makes the land unfit for agriculture or forestry. Many farmers recognise that paddy cultivation is not profitable any more in seaside villages, because of which conversion of agricultural lands into prawn farms is needed for their livelihoods.

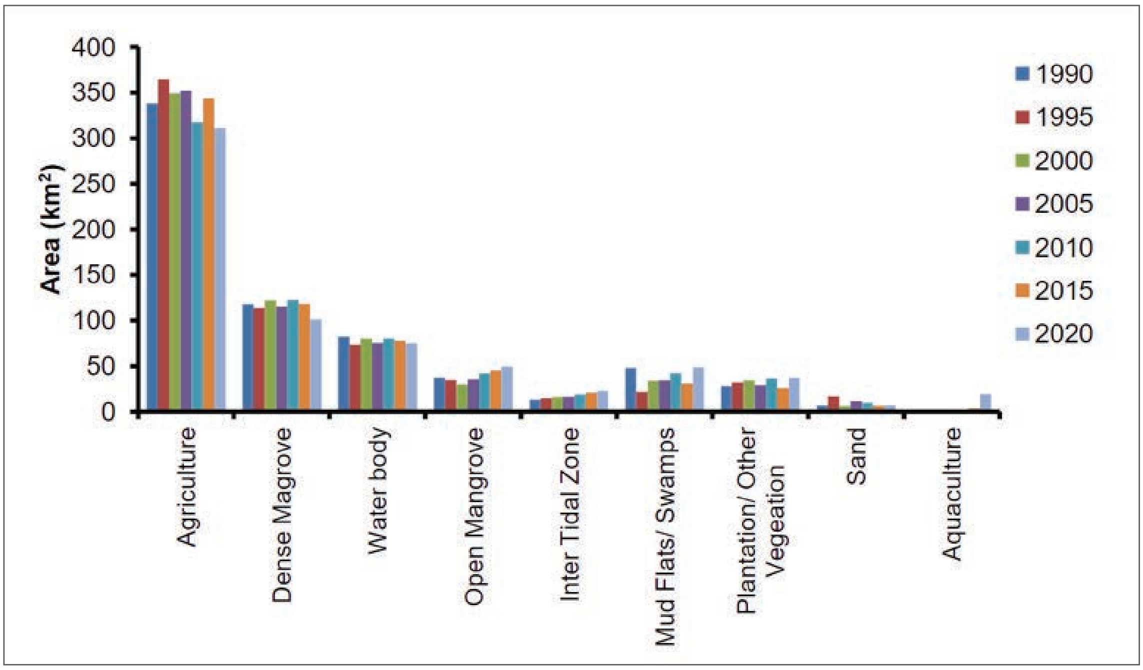


Figure 24 *LULC change patterns in Bhitarkanika Sanctuary (1990-2020)*

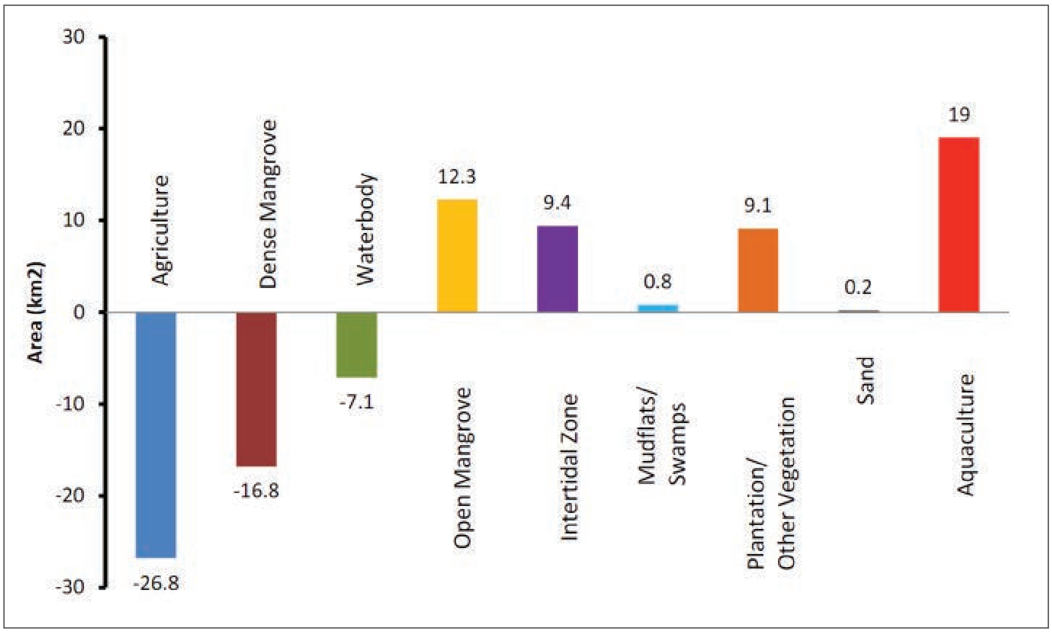


Figure 25 Net changes in LULC in Bhitarkanika Sanctuary (1990 -2020)

Table 9 LULC change patterns (area in km²) in Bhitarkanika Sanctuary (1990–2020)

LULC class	1990	1995	2000	2005	2010	2015	2020	Net change in area (1990–2020)
Agriculture	338.2 (50.3%)	364.7 (54.3%)	349.3 (52.0%)	352.2 (52.4%)	317.6 (47.3%)	343.5 (51.1%)	311.3 (46.3%)	-26.8 (-8%)
Dense mangroves	118.2 (17.6%)	113.5 (16.9%)	122.0 (18.2%)	115.3 (17.2%)	122.9 (18.3%)	118.4 (17.6%)	101.4 (15.1%)	-16.8 (-14.2%)
Water body	82.1 (12.2%)	73.5 (10.9%)	80.0 (11.9%)	75.2 (11.2%)	80.1 (11.9%)	77.9 (11.6%)	75.0 (11.2%)	-7.1 (-8.6%)
Open mangroves	37.2 (5.5 %)	34.6 (5.2%)	29.8 (4.4%)	35.4 (5.3%)	42.0 (6.2%)	45.2 (6.7 %)	49.5 (7.4%)	12.3 (33.1%)
Intertidal zone	13.6 (2.0%)	14.9 (2.2%)	16.2 (2.4%)	16.7 (2.5%)	18.8 (2.8%)	20.9 (3.1%)	22.9 (3.4%)	9.4 (69.1%)
Mudflats/ swamps	47.9 (7.1%)	21.5 (3.2%)	33.9 (5.0%)	34.3 (5.1%)	42.4 (6.3%)	30.7 (4.6%)	48.7 (7.2%)	0.8 (1.7%)
Plantation/ other vegetation	27.8 (4.1%)	32.0 (4.8%)	34.3 (5.1%)	29.3 (4.4%)	36.4 (5.4%)	25.9 (3.9%)	36.9 (5.5%)	9.1 (32.7%)
Sand	6.6 (1.0%)	17.0 (2.5%)	5.9 (0.9%)	11.8 (1.8%)	9.5 (1.4%)	6.2 (0.9%)	6.8 (1%)	0.2 (3%)
Aquaculture	0.4 (0.1%)	0.3 (0.1%)	0.6 (0.1%)	1.9 (0.3%)	2.4 (0.4%)	3.3 (0.5%)	19.5 (2.9%)	19.0 (47.50%)

Table 10 LULC change matrix (area in km²) in Bhitarkanika Sanctuary (1990–2020)

LULC class	1990 – 1995	1995 – 2000	2000 – 2005	2005 – 2010	2010 – 2015	2015 – 2020	1990 – 2020
Agriculture	26.5 7.8%	-15.4 -4.2%	2.9 0.8%	-34.6 -9.8%	25.9 8.2%	-32.2 -9.4%	-26.9 -8.0%
Dense mangrove	-4.7 -4.0%	8.5 7.5%	-6.7 -5.5%	7.6 6.6%	-4.5 -3.7%	-17 -14.4%	-16.8 -14.2%
Water body	-8.6 -10.5%	6.5 8.8%	-4.8 -6.0%	4.9 6.5%	-2.2 -2.7%	-2.9 -3.7%	-7.1 -8.6%
Open mangrove	-2.6 -7.0%	-4.8 -13.9%	5.6 18.8%	6.6 18.6%	3.2 7.6%	4.3 9.5%	12.3 33.1%
Intertidal zone	1.3 9.6%	1.3 8.7%	0.5 3.1%	2.1 12.6%	2.1 11.2%	2 9.6%	9.3 68.4%
Mudflats/ swamps	-26.4 -55.1%	12.4 57.7%	0.4 1.2%	8.1 23.6%	-11.7 -27.6%	18 58.6%	0.8 1.7%
Plantation	4.2 15.1%	2.3 7.2%	-5 -14.6%	7.1 24.2%	-10.5 -28.8%	11 42.5%	9.1 32.7%
Sand	10.4 157.6%	-11.1 -65.3%	5.9 100.0%	-2.3 -19.5%	-3.3 -34.7%	0.6 9.7%	0.2 3.0%
Aquaculture	-0.1 -25.0%	0.3 100.0%	1.3 216.7%	0.5 26.3%	0.9 37.5%	16.2 490.9%	19.1 4775.0%

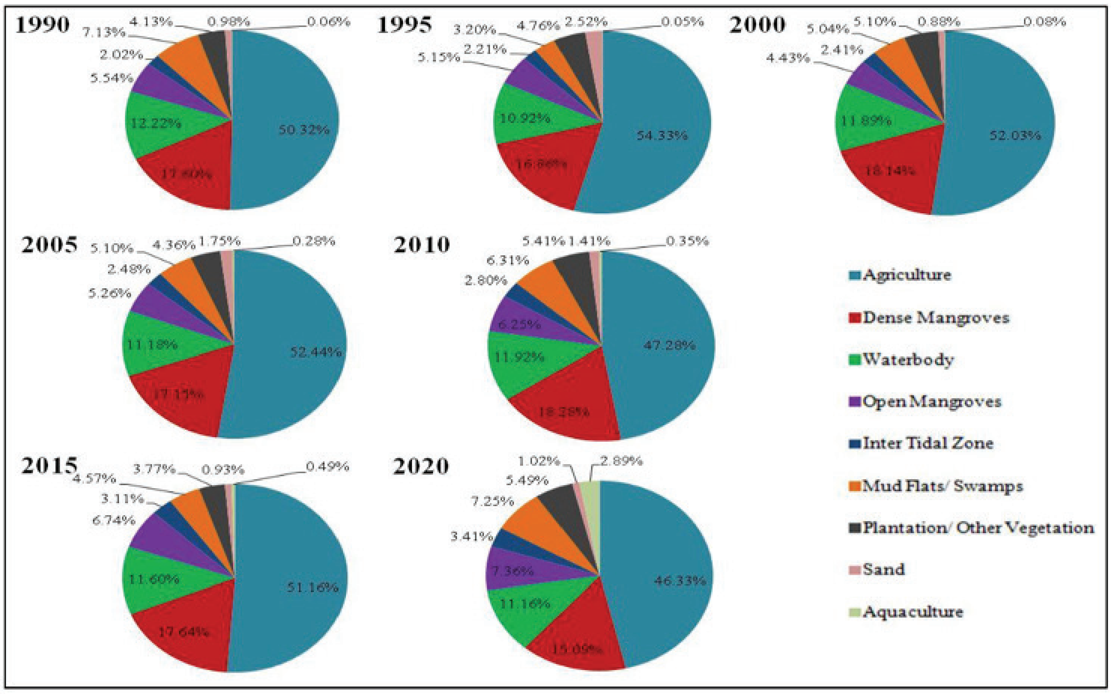


Figure 26 *Changing LULC percent composition from 1990-2020 in Bhitarkanika Sanctuary*

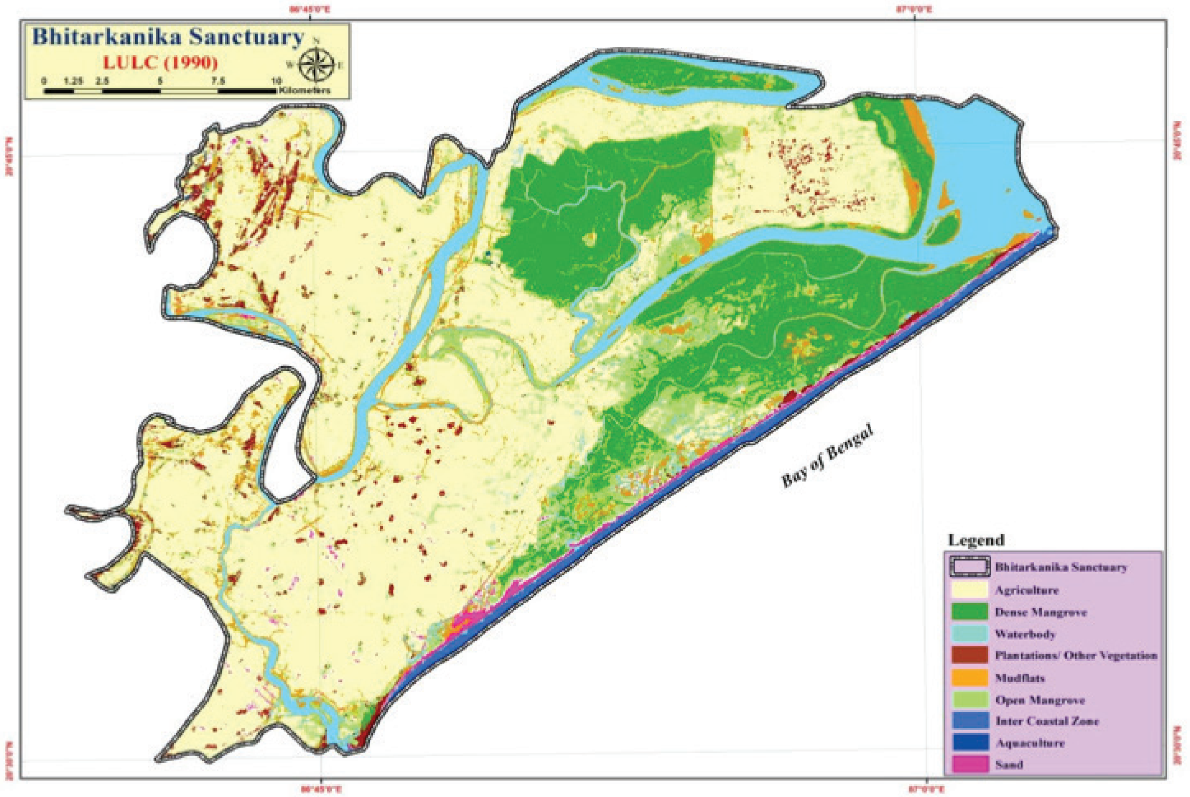


Figure 27 *LULC in Bhitarkanika Sanctuary (1990)*

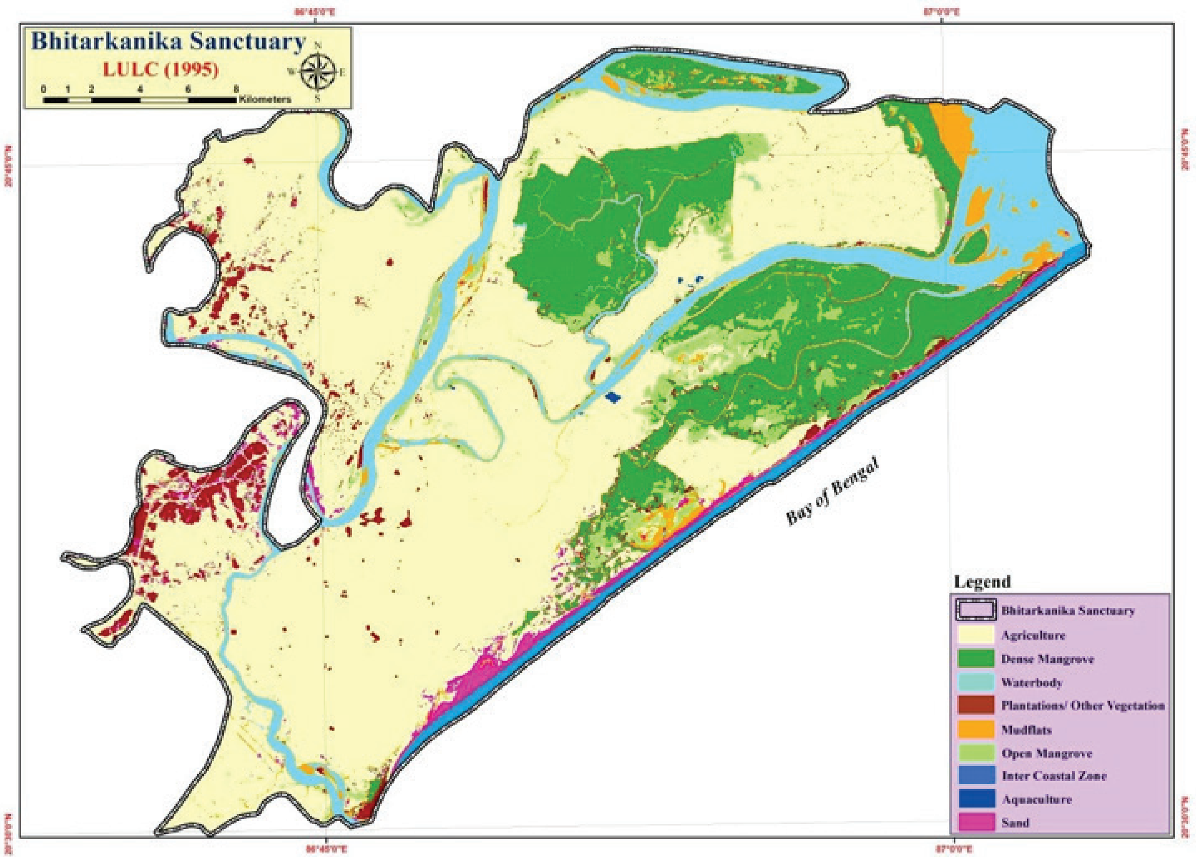


Figure 28 *LULC in Bhitarkanika Sanctuary (1995)*

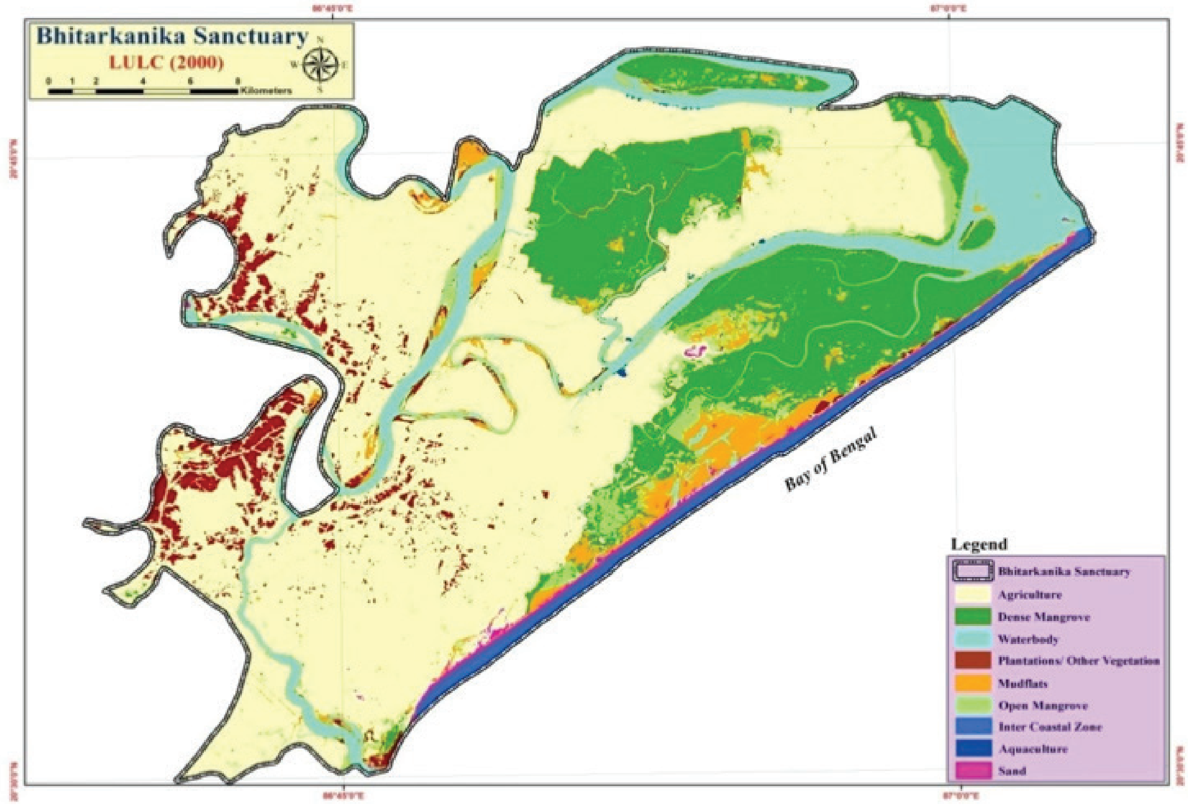


Figure 29 LULC in Bhitarkanika Sanctuary (2000)

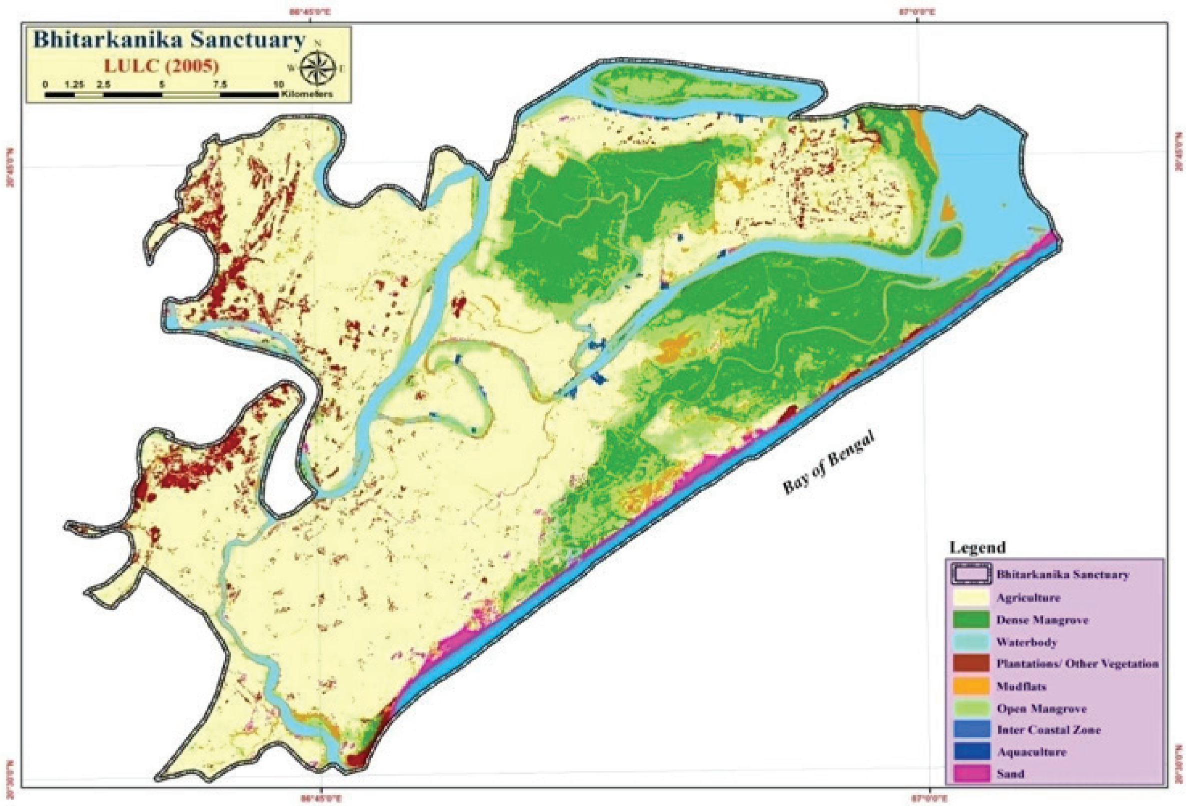


Figure 30 LULC in Bhitarkanika Sanctuary (2005)

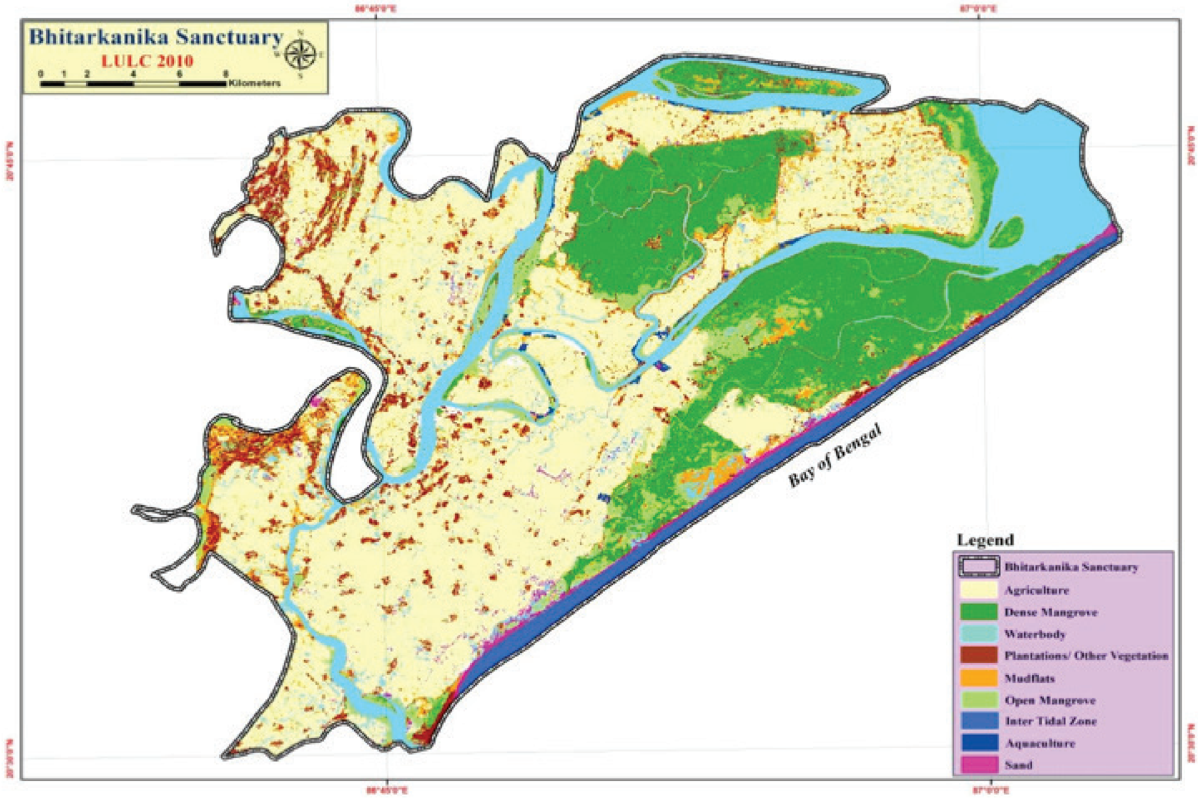


Figure 31 LULC in Bhitarkanika Sanctuary (2010)

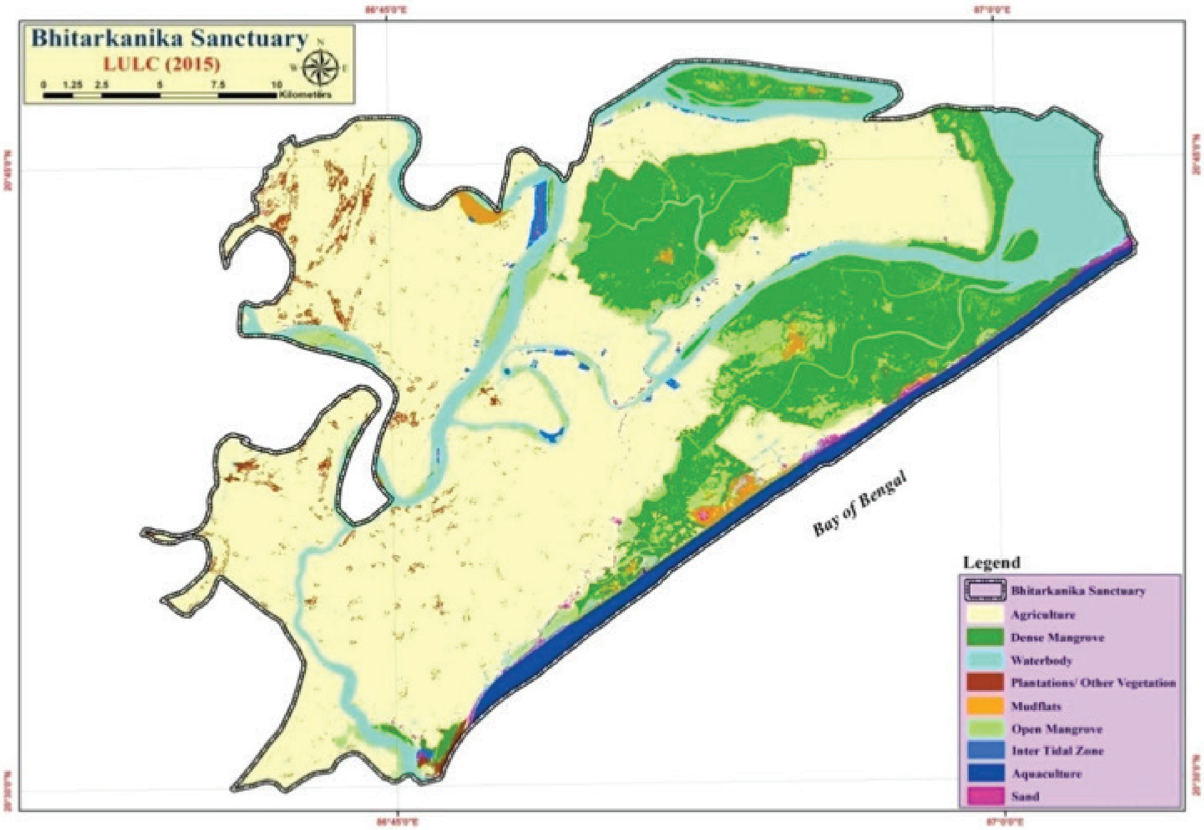


Figure 32 LULC in Bhitarkanika Sanctuary (2015)

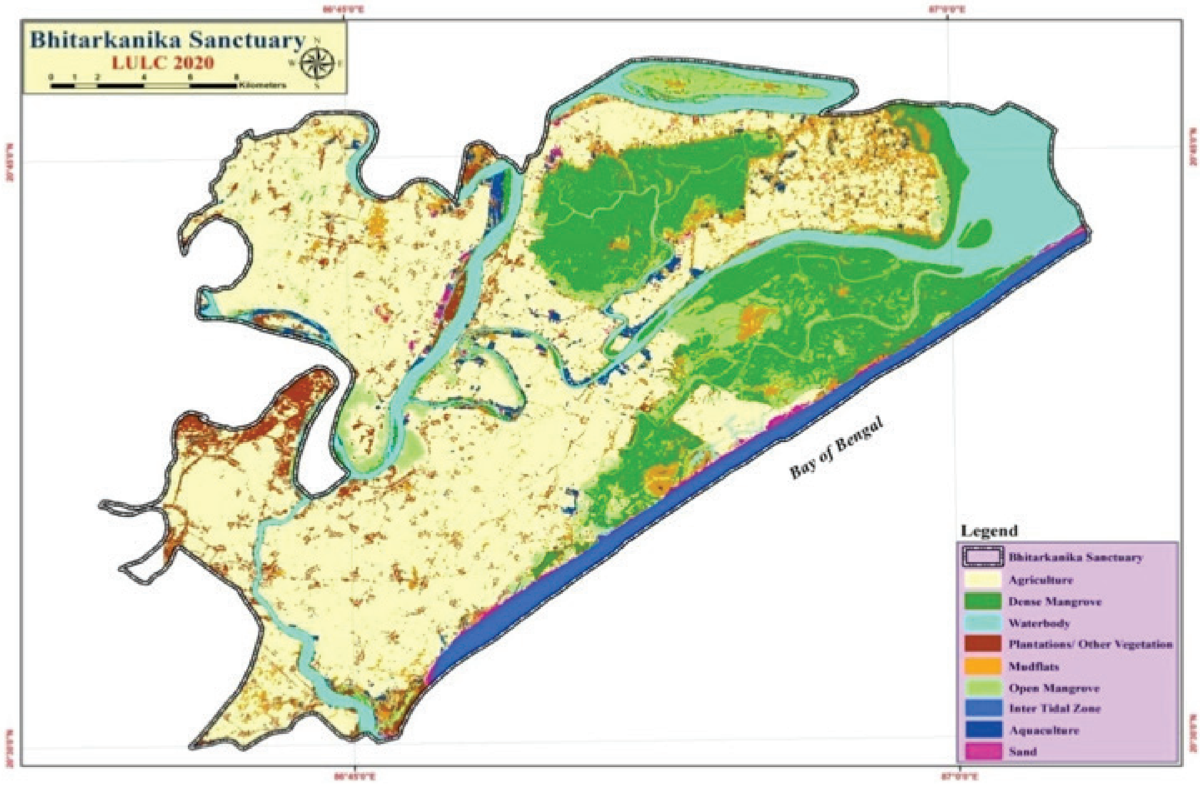


Figure 33 *LULC in Bhitarkanika Sanctuary (2020*

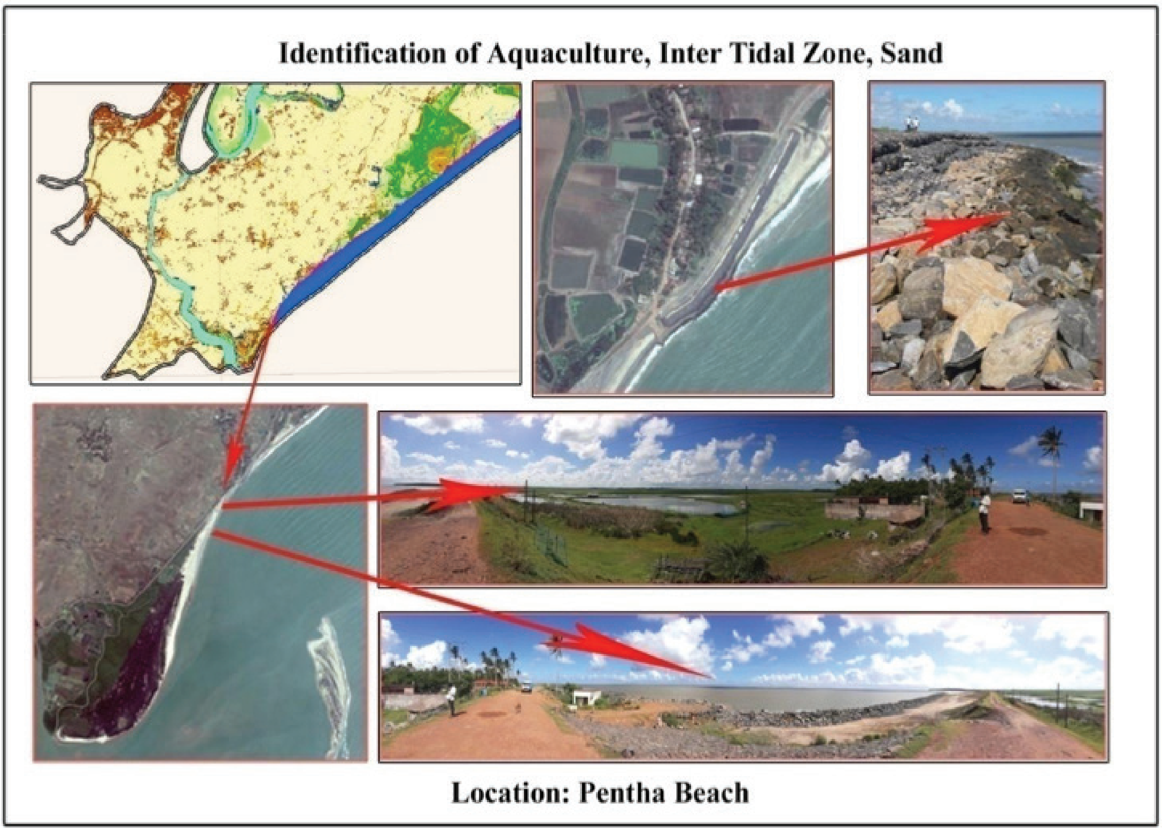


Figure 34 (a) *Ground truthing of LULC features (aquaculture and intertidal zone) inferred from satellite imagery and a field visit to Bhitarkanika Sanctuary in October 2020*

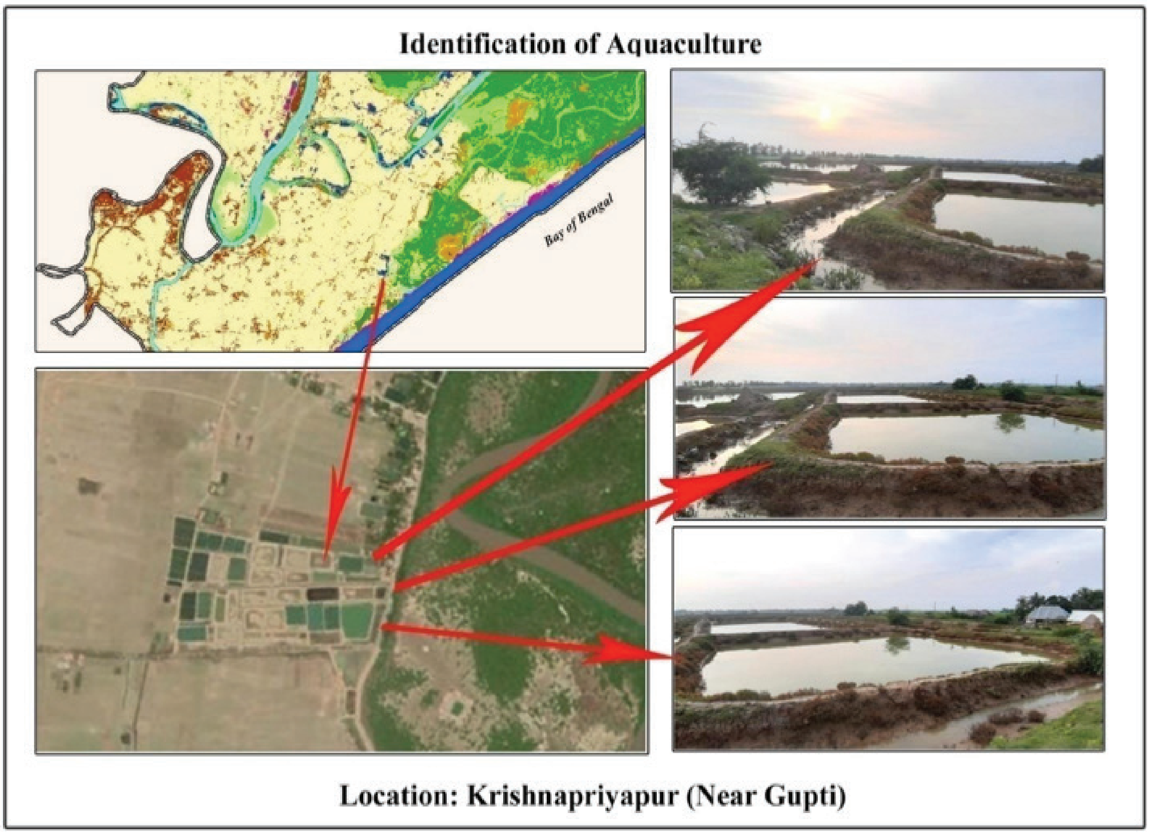


Figure 34 (b) *Ground truthing of LULC features (aquaculture and intertidal zone) inferred from satellite imagery and a field visit to Bhitarkanika Sanctuary in October 2020*

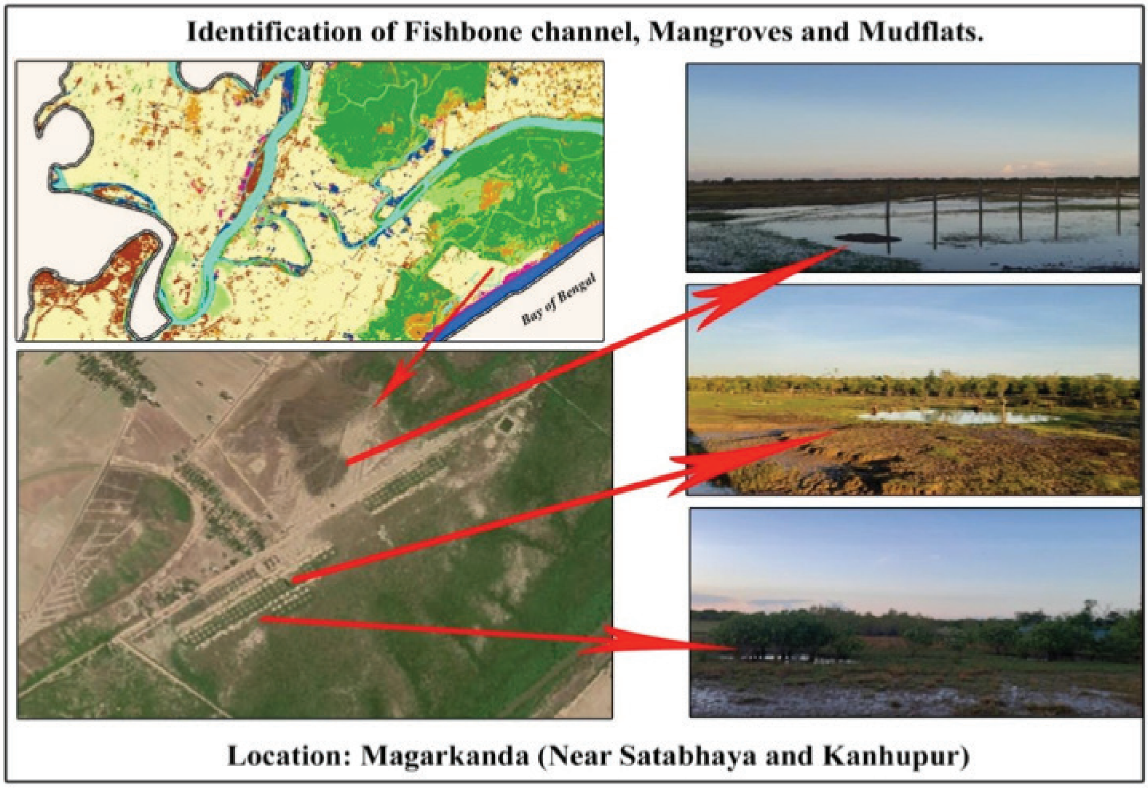


Figure 35 (a) *Ground truth of LULC features (mangroves, mudflats and fishbone Channel inferred from satellite imagery and a field visit to Bhitarkanika Sanctuary in October 2020*

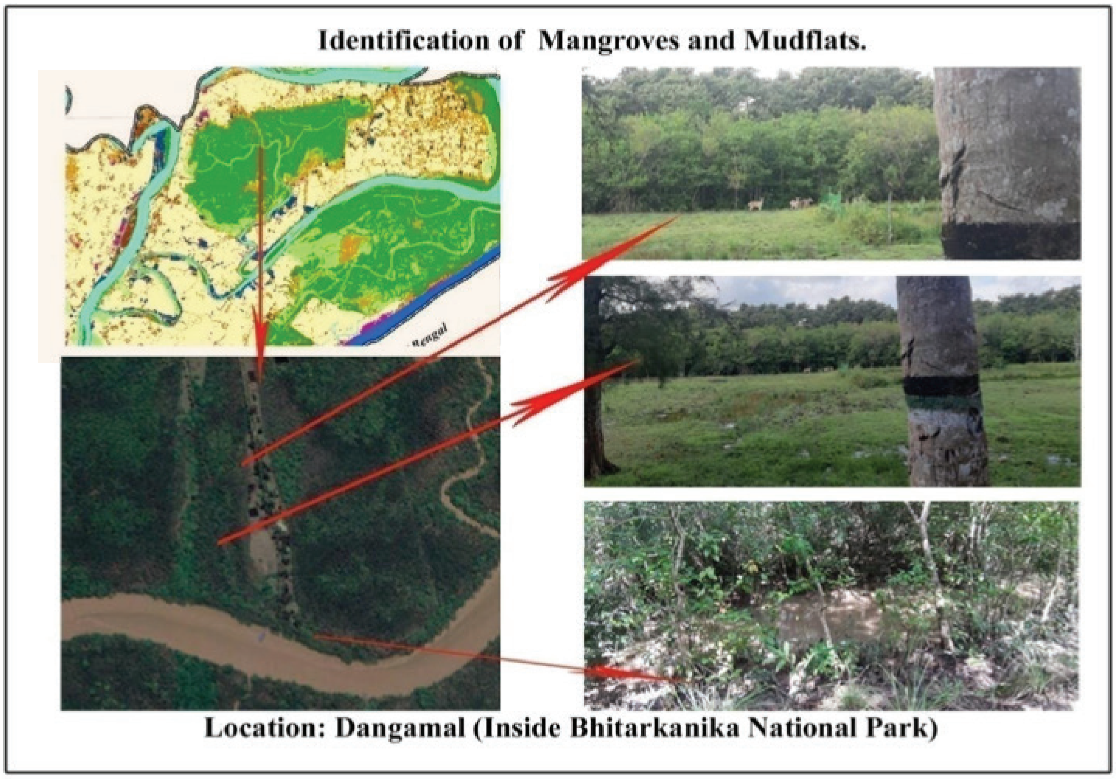


Figure 35 (b) *Ground truth of LULC features (mangroves, mudflats and fishbone Channel inferred from satellite imagery and a field visit to Bhitarkanika Sanctuary in October 2020*

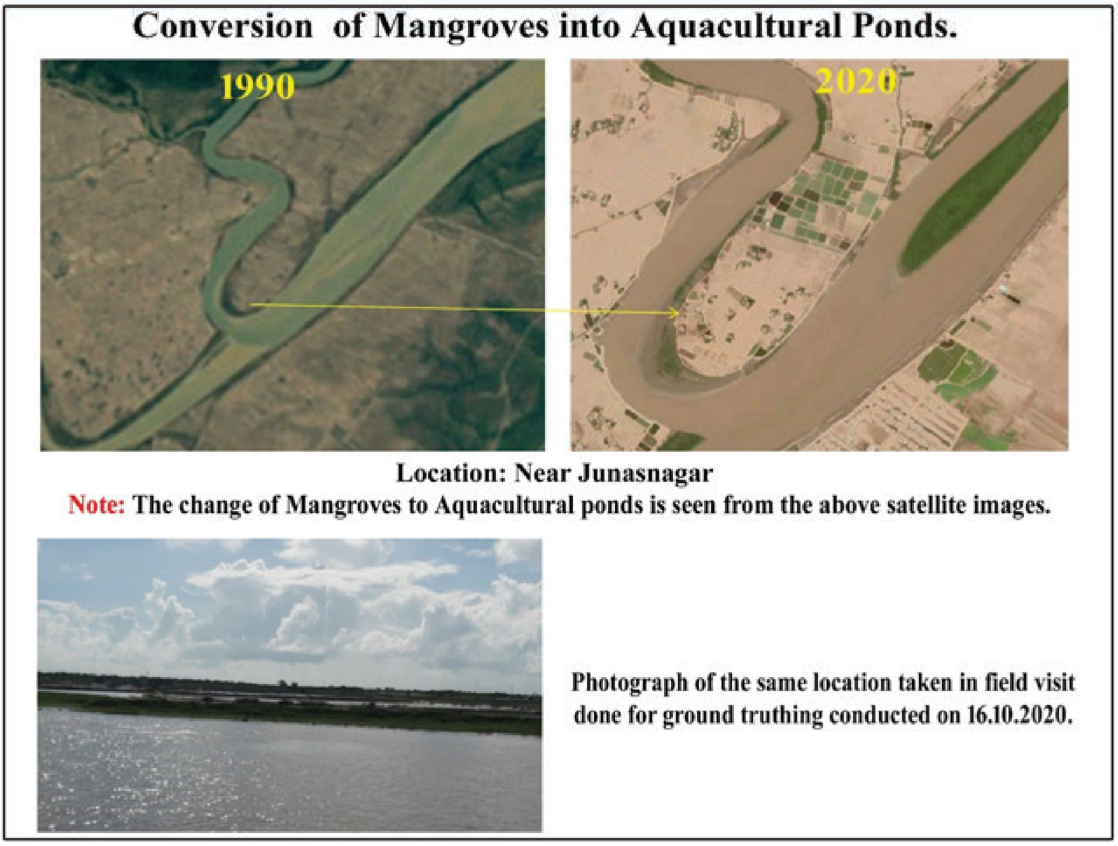


Figure 36 (a) *Field verification of conversion of mangroves to aquaculture ponds*

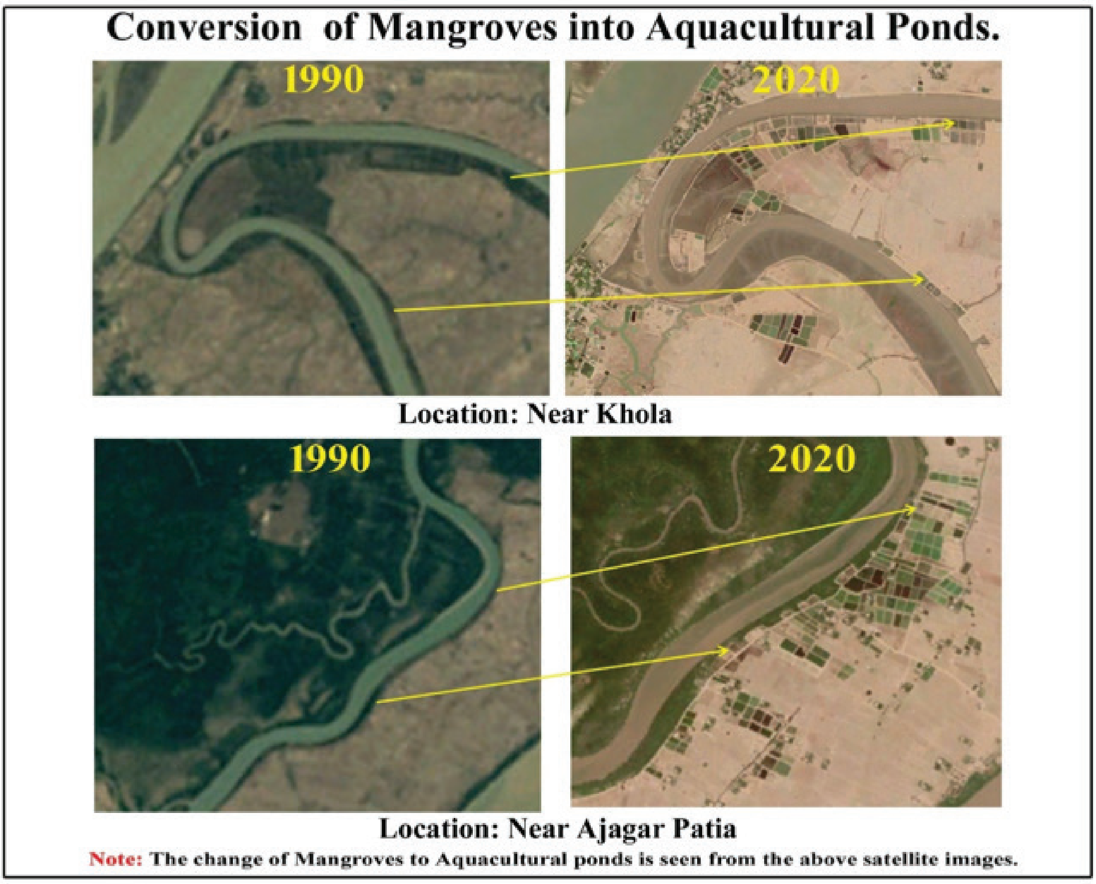


__Figure 36 (b)__ Field verification of conversion of mangroves to aquaculture ponds

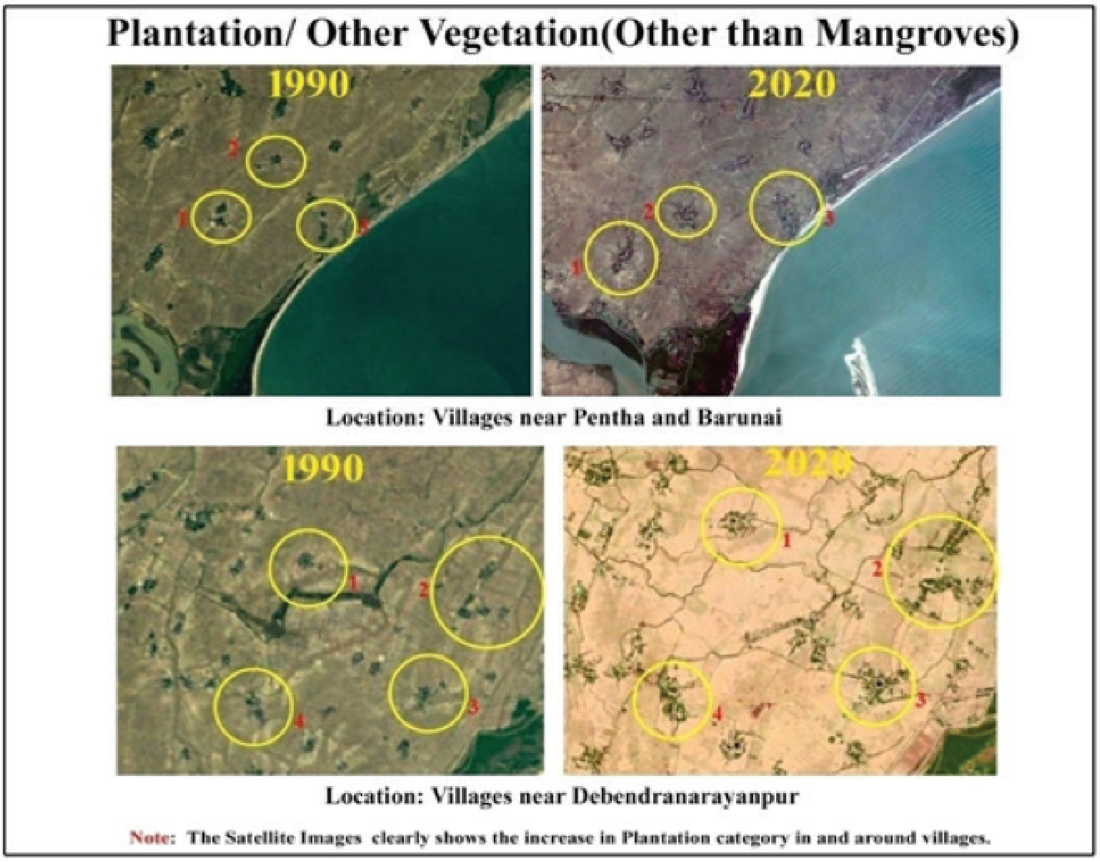


__Figure 37 (a)__ Field verification of Plantation and other vegetation

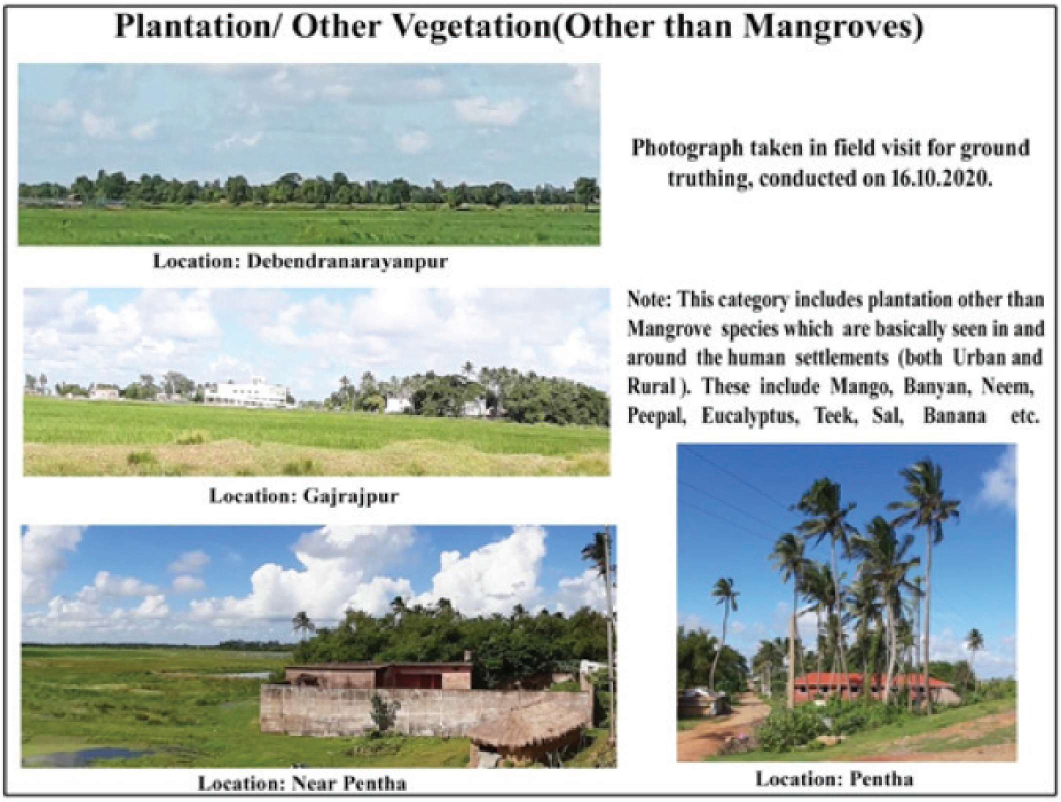


Figure 37 (b) *Field verification of Plantation and other vegetation*

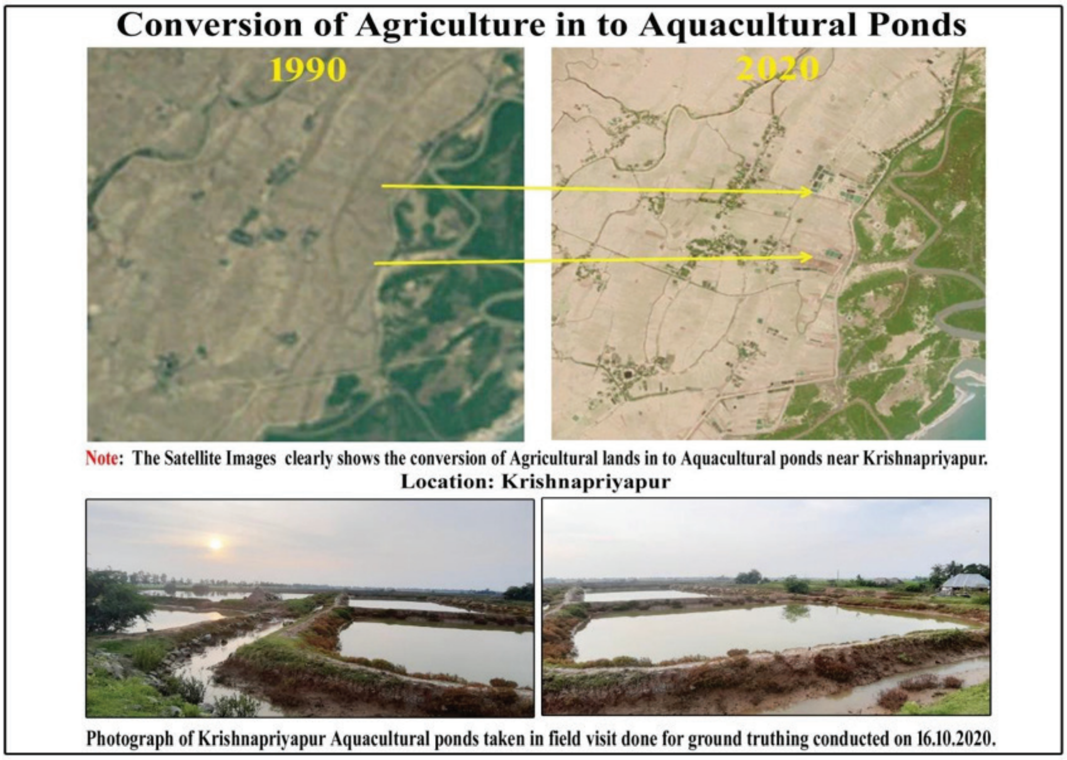


Figure 38 *Field Verification of Conversion of agriculture area to Aquaculture pond*

5.2 LULC of direct catchment of Bhitarkanika Sanctuary

Land use land cover changes in the catchment have a great role in influencing the physical climate system, biogeochemical cycles and the global hydrological cycle. Of the region. Modification of the LULC alters the fluxes of physical and biogeochemical systems and may eventually affect the water, food and environmental security. The LULC change of the direct catchment of the sanctuary was studied from 1975 to 2020. The processed LULC classes of India for 1985, 1995 and 2005 were obtained from Roy et al. (2016). The LULC classes for 1975, 2015 and 2020 were analysed by CDA using Landsat satellite images. The LULC classes of the direct catchment in different years (1975–2020) are depicted in Figures 40 to 45.

5.2.1 Mixed forest

Over the years, the extent of the mixed forest category has decreased in the direct catchment. In 1975, a total extent of 253.89 km^2 was under the mixed forest category, which declined to 165.61 km^2 in 2020 (Figure 39 and Table 11). In the post-independence phase, India had a huge dependence on forest resources, which ultimately led to a decline in the forest cover and in forest-associated species. Industrialisation and urbanisation in the 1970s fuelled rampant timber use by either legal or illegal processes. But with the introduction of government conservation policies and protection laws, the pace of deforestation has been somehow checked. The Indian Forest Act, 1927, the Wild Life Protection Act, 1972, Project Tiger (1973), Project Elephant (1992) and the Forest Conservation Act, 1980, are all based on the common principle that any human interference in a forest ecosystem will lead to its destruction.

A considerable reduction in the forest cover will lead to reduced evapotranspiration and amplified runoff, mainly due to reduced leaf area index values and reduced rooting depths. A reduction in evapotranspiration may lead to a reduced atmospheric moisture supply and therefore reduced water availability through precipitation (Marengo 2006). Mishra (2008) observed an increase in the annual stream flow of the Mahanadi River basin due to a decrease in the forest cover. (Patidar & Behera, 2018, and Babar & Ramesh, 2015) observed a net decrease in evapotranspiration due to deforestation in the Ganga River basin and Nethravathi River basin, respectively. The higher deforestation leads to reduced canopy evaporation as the canopy cover is reduced, with a decrease in Leaf Area Index leading to decreased interception and transpiration.

5.2.2 Crop Land

Crop land witnessed a net decline of 5.9% from 1975 to 2020 (Table 11). The phase of industrialisation and urbanisation, which gained pace in 2000, had an adverse effect on agriculture. Agricultural practices started to decline, and people, with their never-ending needs, started thinking of alternatives to agriculture for the sake of easy money. The increase in built-up land (urban and rural) also contributed to the decrease in crop land. The industrialisation and urbanisation process involved conversion of the crop land category to built-up areas. This involved industries, buildings and houses in and around the urban areas, which acted as hubs for population influxes.

The conversion of forest to crops, shrubs and plantations led to a decrease in surface roughness that ultimately resulted in increasing runoff due to decreased basin storage. Additionally, the absence of a deep rooting system due to deforestation and conversion of untilled land or other perennial cover crops to annual row crops led to less consumption of groundwater, which increased the base flow in the basin.

5.2.3 Built-up land

The increase in built-up land started from 253.44 km^2 in 1975, with a steady increase up to 2005. The increase in area had a steep boost from 2005 onwards: the area was 478.15 km^2 and 485.64 km^2 in 2015 and 2020 (Table 11).

Pressure from nearby areas and migration of people for livelihoods in urban areas was the driver of these changes. The build-up land increase was directly correlated with loss of land of the crop land category. Industrialisation and urbanisation, with good communication and road and rail networks, triggered a rapid increase in the built-up area in both urban and rural areas. The impact of industrialisation/urbanisation via an increase in the built-up area will be reflected in increased runoff, leading to urban flooding in the years to come in the region.

5.2.4 Fallow land

Fallow land area increased from 47.67 km^2 in 1975 to 220.10 km^2 in 2020 (Table 11).

5.2.5 Plantations

Planted area in the direct catchment has witnessed a net decline though the trends in the recent years depict a slow increase again. Planted area in the direct catchment has gone from 22.40 km^2 in 1975 to 20.14 km^2 in 2020, with dramatic decrease by 1985 and fluctuations in the following years, with increasing trend in last 10 years (Table 11).

5.2.6 Mangroves

Mangrove forests are mainly confined to the coastal and adjoining areas in the direct catchment area. The decadal analysis shows a decrease in area in mangroves from 1985 to 2020. Mangroves were 163.36 km^2 in 1975 further decreased to 161.10 km^2, 157.21km^2 and 156.45km^2 in 1995, 2005 and 2015 respectively. The total net change area is -6.34 km^2 areas comparing with 1975 to 2020. In 2020, the mangrove area was seen to have 157.03 km^2 in the whole direct catchment area (Table 11).

Table 11 *LULC net changes (km^2) during 1975–2020 in the direct catchment of Bhitarkanika Sanctuary*

LULC class	1975	1985	1995	2005	2015	2020	Net change (1975–2020)
Mixed forest	253.89 (4%)	250.41 (4%)	200.64 (3.2%)	168.02 (2.7%)	169.61 (2.7%)	165.61 (2.6%)	-88.28 (-34.8%)
Crop land	5082.76 (81%)	5087.24 (80.9%)	5169.10 (82.2%)	5197.55 (82.7%)	4799.52 (76.4%)	4782.14 (76.1)	-300.62 (-5.9%)
Built-up land	253.44 (4%)	257.74 (4.1%)	281.89 (4.5%)	285.65 (4.5%)	478.15 (7.6%)	485.64 (7.7%)	232.21 (91.6%)
Scrub land	96.40 (1.5%)	115.31 (1.8%)	83.40 (1.3%)	94.62 (1.5%)	88.99 (1.4%)	92.95 (1.5%)	-3.45 (-3.6%)
Fallow land	47.67 (0.8%)	49.73 (0.8%)	54.68 (0.9%)	55.66 (0.9%)	211.88 (3.4%)	220.10 (3.5%)	172.43 (+361.7%)
Wetland	356.45 (5.7%)	354.66 (5.6%)	324.00 (5.2%)	317.20 (5%)	359.22 (5.74%)	358.18 (5.7%)	1.73 (+0.5)
Plantations	22.40 (0.4%)	10.29 (0.2%)	12.97 (0.2%)	11.78 (0.2%)	19.77 (0.3%)	20.14 (0.3%)	-2.26 (-10.1%)
Mangroves	163.36 (2.6%)	162.42 (2.6%)	161.10 (2.6%)	157.21 (2.5%)	156.45 (2.5%)	157.03 (2.5%)	-6.34 (-3.9%)

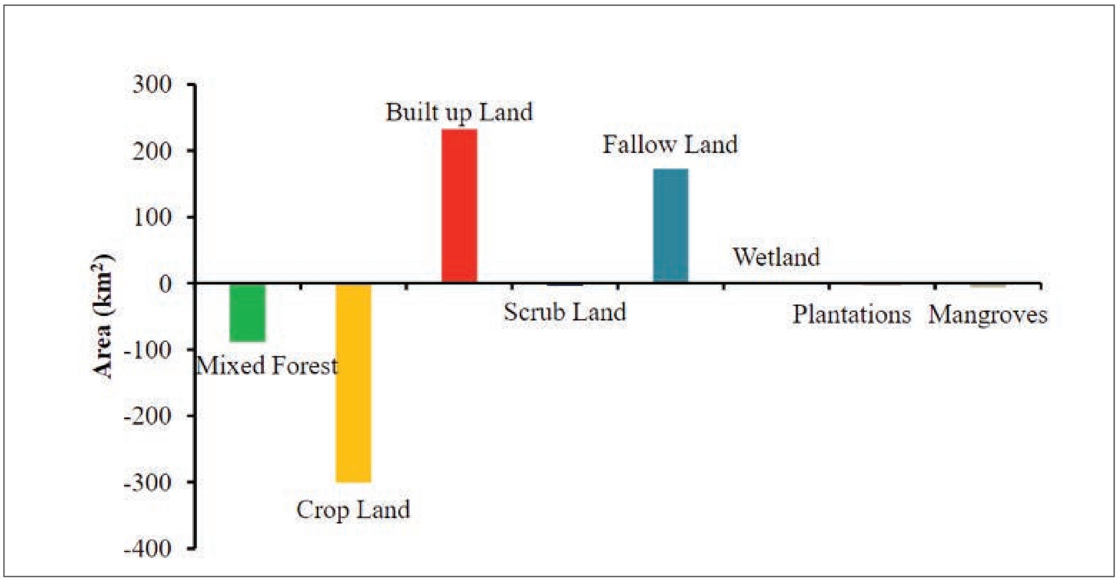


Figure 39 *Net changes in area (km2) of LULC classes in direct catchment (1985–2005) of Bhitarkanika Sanctuary*

India lost 40% of its mangrove area in the last century. The National Remote Sensing Agency (NRSA) recorded a decline of 7000 ha of mangroves in India within the six year period from 1975 to 1981. The increase in the human population in coastal areas is resulting in increased pressure on mangrove ecosystems in many countries, with the growing demand for timber, fuel wood, fodder and other non-wood forest products (NWFPs). To ensure the conservation of mangroves for environmental benefits, together with a sustainable supply of various forest and other products to meet the day-to-day requirements of local people, appropriate management of mangrove ecosystems is needed. Management can also open new avenues for self-employment such as eco-tourism, fishing, beekeeping and cottage industries based on mangrove forest products. They can help improve the socio-economic conditions of the local communities.

Recognising the importance of mangroves, the Government of India had set up the National Mangrove Committee in the Ministry of Environment and Forests in 1976 to advise the government about mangrove conservation and development.

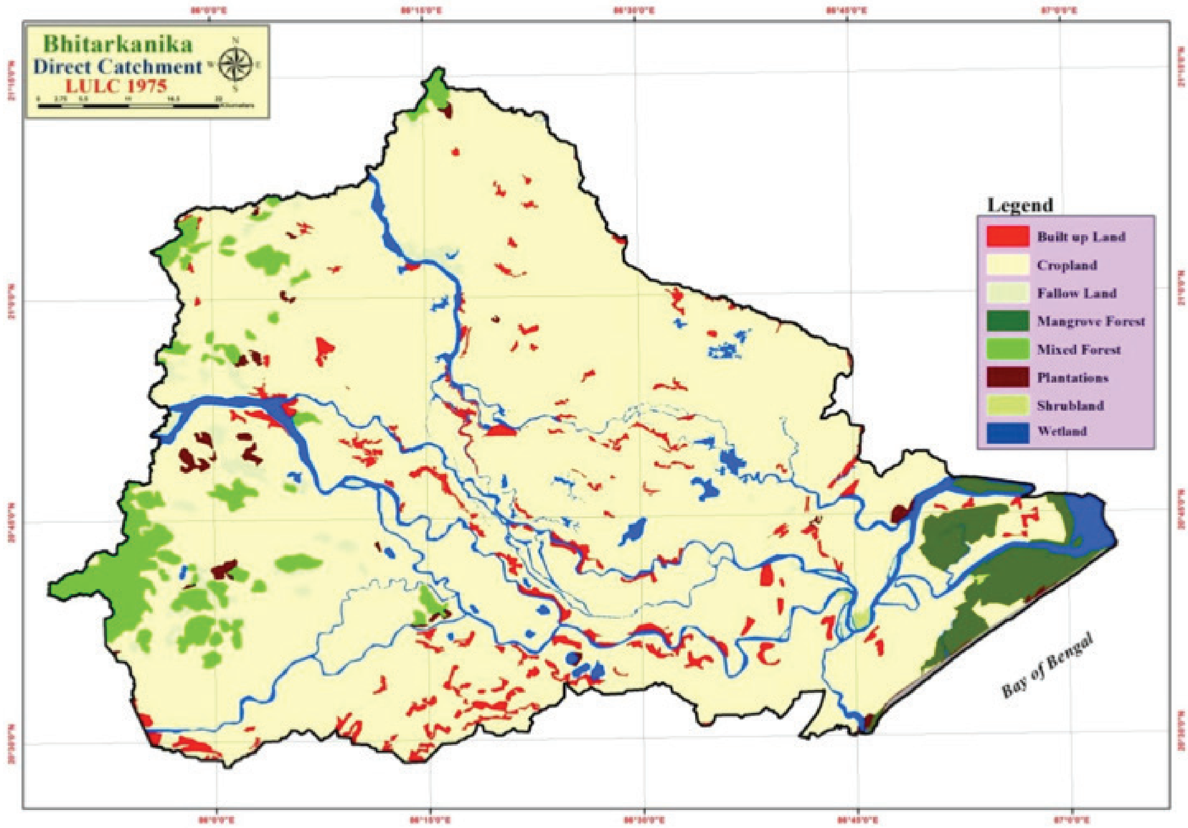


Figure 40 LULC in direct catchment of Bhitarkanika Sanctuary (1975)

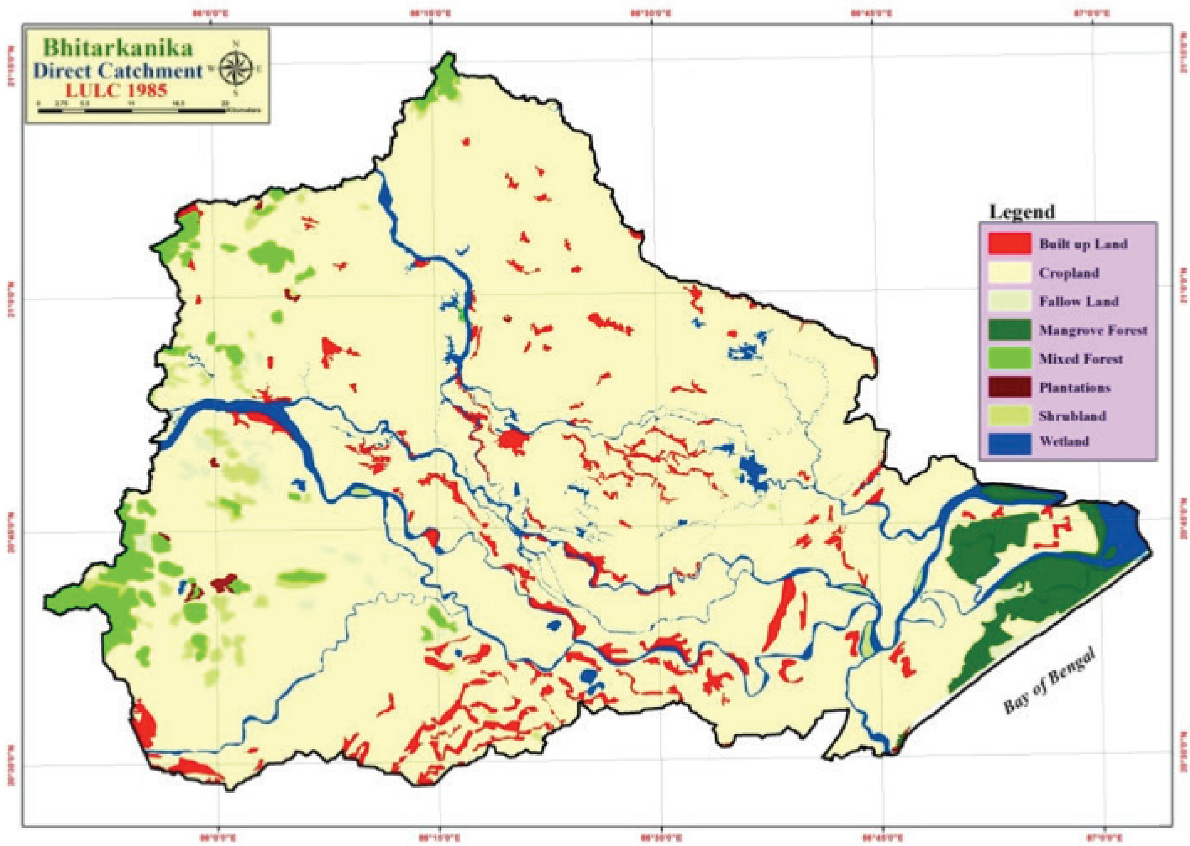


Figure 41 LULC in direct catchment of Bhitarkanika Sanctuary (1985)

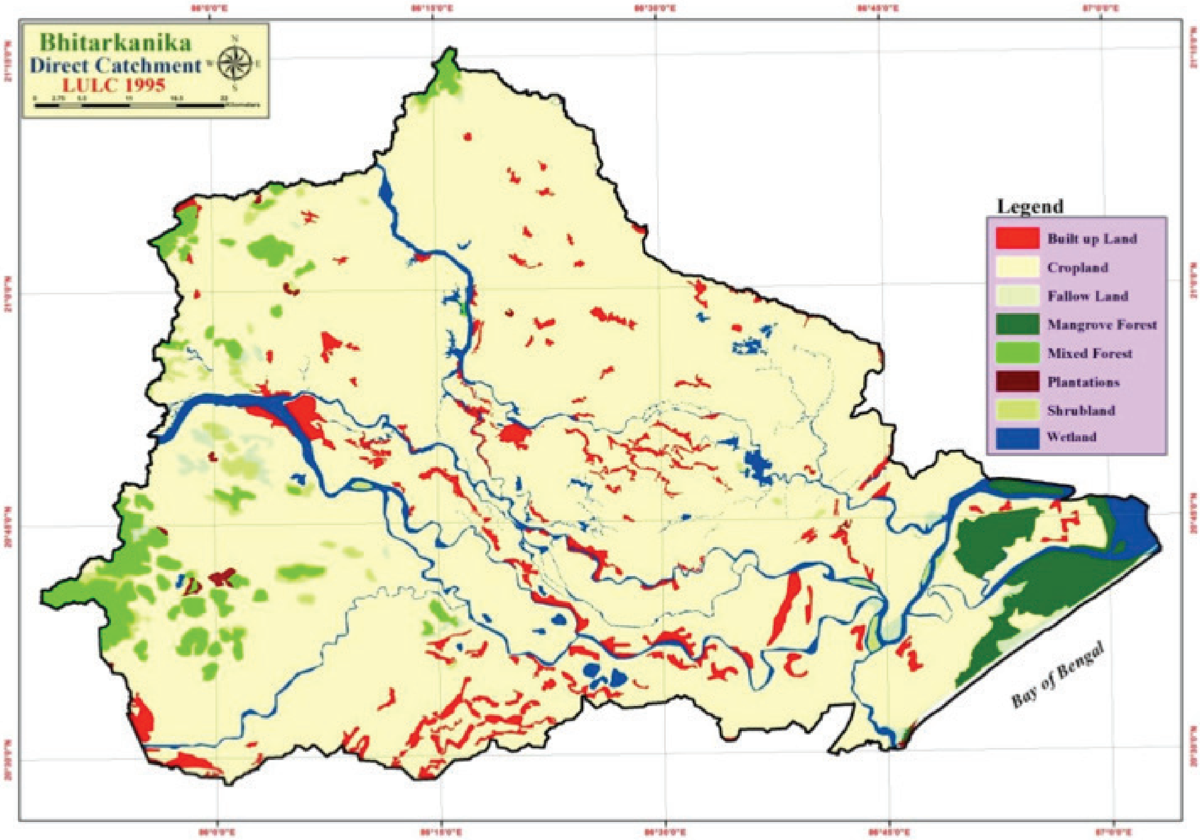


Figure 42 LULC in direct catchment of Bhitarkanika Sanctuary (1995)

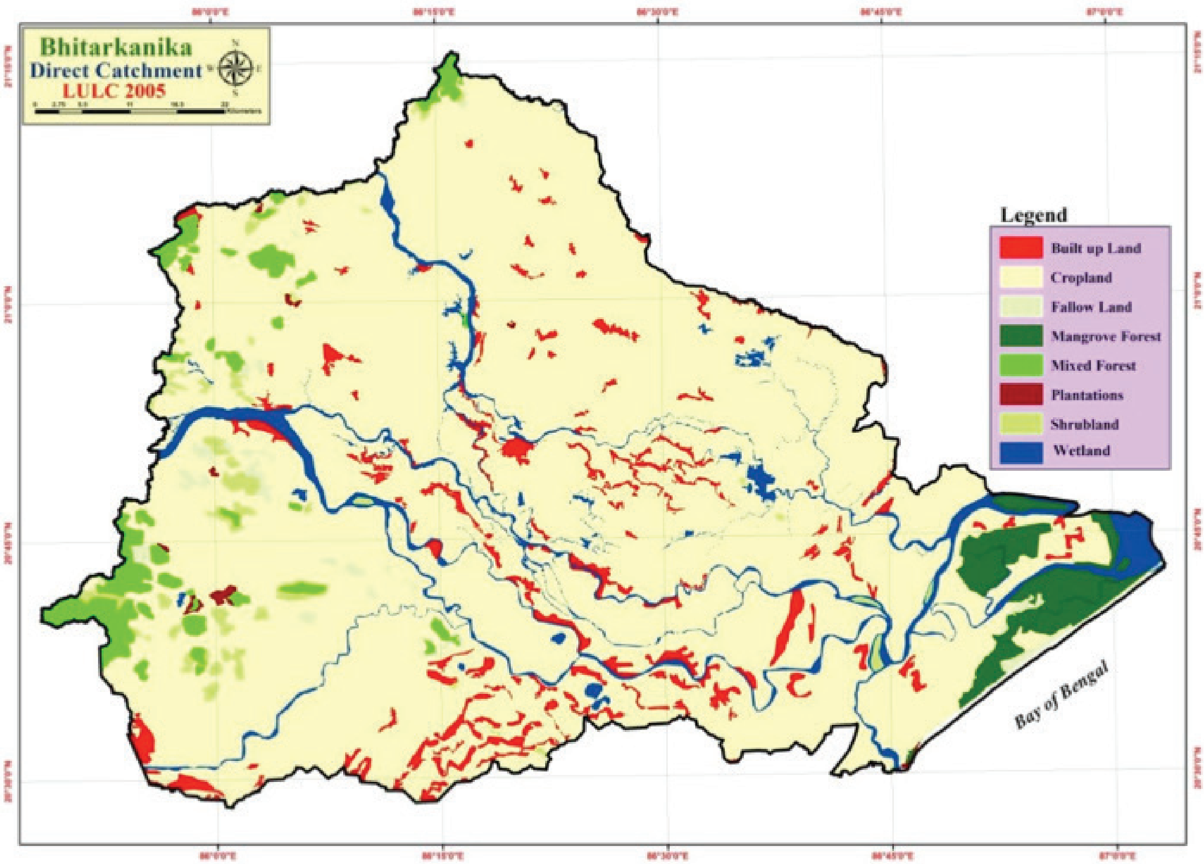


Figure 43 LULC in direct catchment of Bhitarkanika Sanctuary (2005)

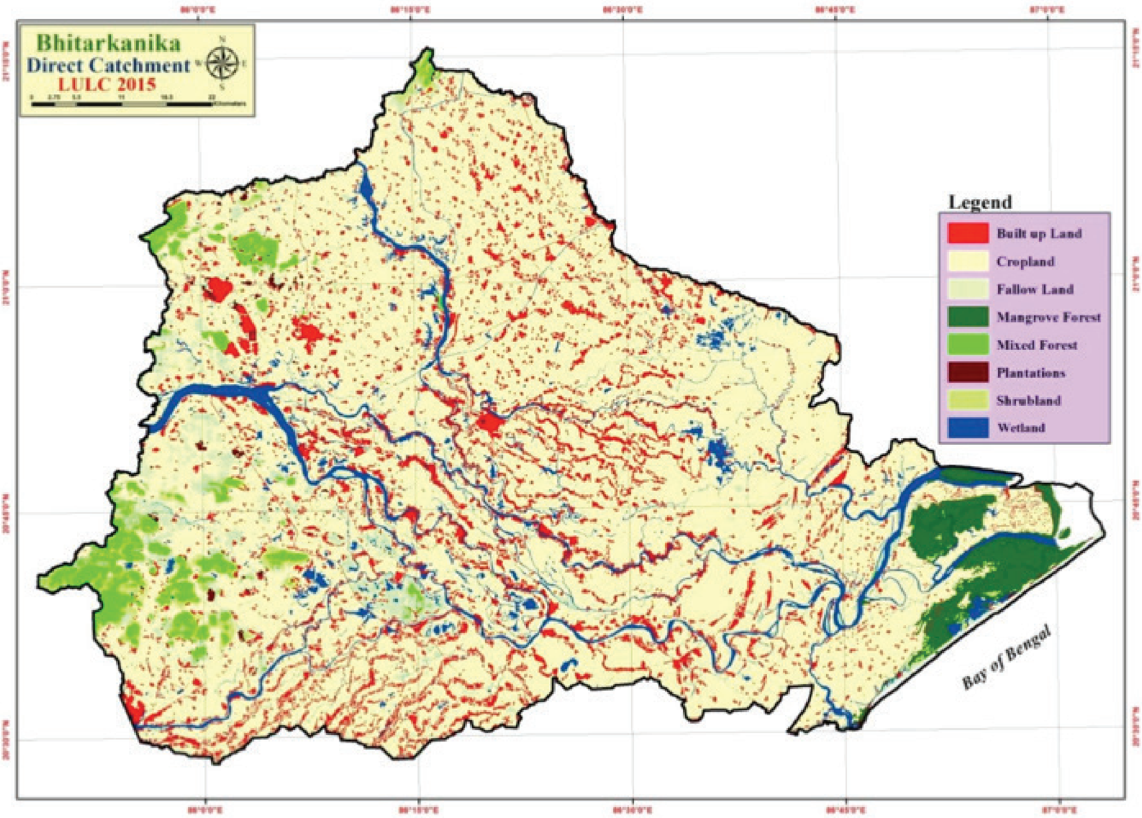


Figure 44 LULC in direct catchment of Bhitarkanika Sanctuary (2015)

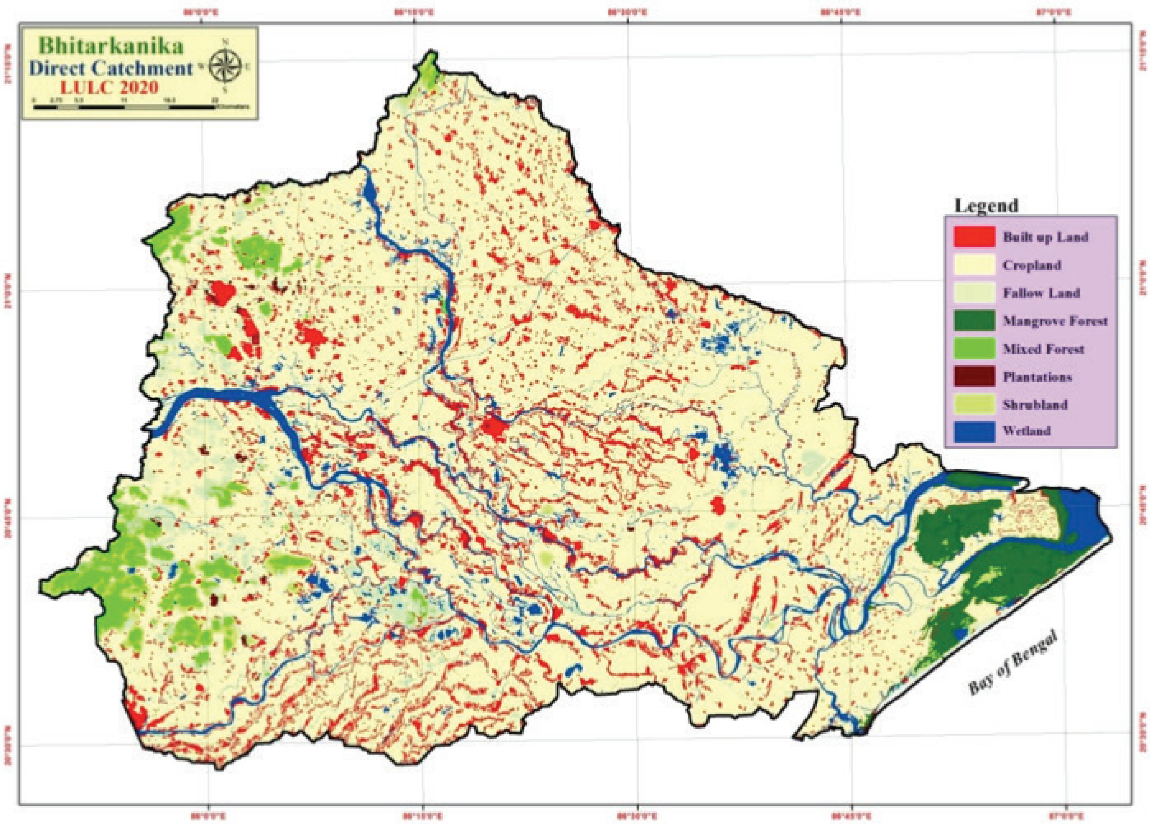


Figure 45 LULC in direct catchment of Bhitarkanika Sanctuary (2020)

6 HYDROLOGICAL ASSESSMENT

6.1 Surface water resources in Brahmani-Baitarani basin

The basin has an average annual water resource potential of 28.48 BCM and utilisable water resources of 18.30 BCM. 85.78% of the water bodies in the basin are tanks. Two abandoned quarries and 14 cooling ponds are reported to be located near the active mining area. There are three main reservoirs in the Brahmani–Baitarani basin. The Rengali, Salandi and Mandira reservoirs are the largest water bodies in the basin. The Madira reservoir is exclusively meant for the purpose of storing water for supply to the Rourkela Steel Plant, located about 24 km downstream along the river course. The reservoir area of Rangali is 44.94 thousand hectares. According to the data available in India-WRIS, Rengali is the largest reservoir in the basin in terms of storing capacity (GoI Ministry of Water Resource v. 2.0 Brahmani and Baitarini Basin. March 2014; Joint project report CWC and NRSC : INDIA-WRIS)

6.2 Groundwater resources in the Brahmani-Baitarani Basin

On the basis of the soil characteristics and the rainfall, which consistently increases from 1200 mm at the coast to 1400 mm in the western region, the groundwater availability is assessed as 5170.66 MCM (Department of Water Resources, Odisha).

6.3 Discharge in Brahmani River

The Brahmani-Baitarani basin has a total catchment area of 51,822 km^2 (CWC). For the Brahmani basin, flow data were obtained from Jenapur (CWC discharge station with catchment area of 36,300 km2) for the period from 1980 to 2017 (Source: CWC Report). For the Baitarani portion of the basin, flow data from Akhuapada (catchment area of 10,120 km^2) for the period 2000–01 to 2019–20 (collected from DoWR, Odisha) were used. The discharge flows were proportionately taken on the basis of the respective areas : Jenapur area to the total Brahmani basin (catchment area of 39,116 km^2) and Akhuapada to the total Baitarani basin (catchment area of 10,982 km^2). The annual freshwater discharge and sediment load of the Brahmani basin at different gauge points of the last 30 years have been reported by CWC in the water year book of the Brahmani basin (Vol-II) in 2018. Historical records of the annual freshwater discharge and sediment load runoff of Jenapur gauge station are available for the period 1980–2017. Analysis of the long-term dataset showed a declining trend in both annual freshwater runoff and sediment load at Jenapur, which is located at the beginning of the Brahmani river delta (Figure 46 and Table 12).

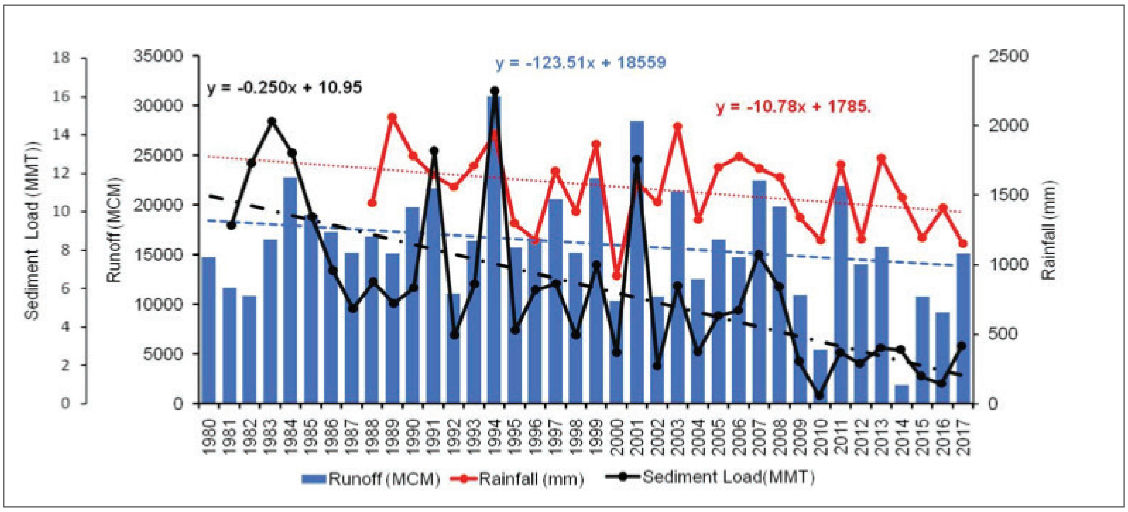


Figure 46 Annual runoff and sediment load in Brahmani River and rainfall trend at Jenapur

Table 12 *Annual runoff, sediment load in the Brahmani river and rainfall at Jenapur*

	Sediment load (MT)	Annual runoff (MCM)	Annual mean rainfall (mm)
Minimum	340936	1883	917
Maximum	16195448	30991	2058
Mean	5446292	16150	1532

A. Mean annual flow at Jenapur = 16,150 MCM

B. Total catchment area of the Brahmani basin = 39,116 km^2

C. Catchment area of basin up to Jenapur = 36,300 km^2

Mean annual flow of the entire Brahmani basin = (A × B)/C

= (16,150 × 39,033)/36,300

= 17,366 MCM

The calculation is based on the NRSC (2011) report.

6.4 Discharge in Baitarani River

Data on the annual freshwater discharge of the Baitarani River at Akhuapada and Khanditar were collected from Department of Water Resources, Odisha for 2000–2019. They indicate a non-significant increasing trend (Figure 47).

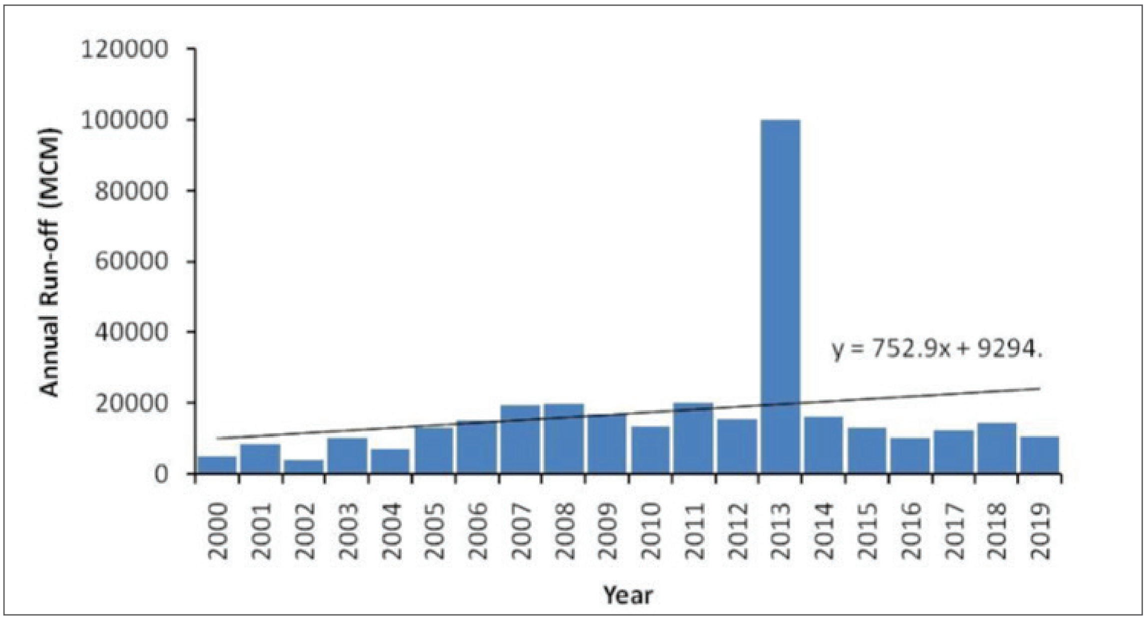


Figure 47 *Annual runoff from the Baitarani river at Akhuapada*

A. Mean annual flow at Akhupada = 12,984 MCM

B. Total catchment area of Baitarani Basin = 10,982 km^2

C. Catchment area of basin up to Akhuapada = 10,120 km^2

Mean annual flow for the entire Baitarani basin = (A × B)/C

= (12,984 X 10,982)/10,120

= 14,090 MCM

Mean annual flow of the Brahmani and Baitarani basins = 17,366 + 14,090

= 31,456 MCM

The calculation is based on the NRSC (2011) report.

6.5 Freshwater flow to Bhitarkanika Sanctuary

The daily discharge at three stations (Akhuapda, Khanditar and Indupur) (Figure 48) over 19 years (2000–2019) was obtained from Department of Water Resources, Odisha, and the monthly average discharge was evaluated. The cumulative discharges of the monsoon, summer and optimal period were calculated (Table 13).

Table 13 *Freshwater flow in Bhitarkanika Sanctuary (in MCM)*

	Akhuapada	Khanditar	Indupur	Total
Monsoon (Jul to Sep)	87,767	1,18,172	89,561	2,95,501
Summer (Apr to Jun)	11,856	21,007	5792	38,654
Optimal (Oct to Dec)	90,447	33,601	20,976	1,45,023

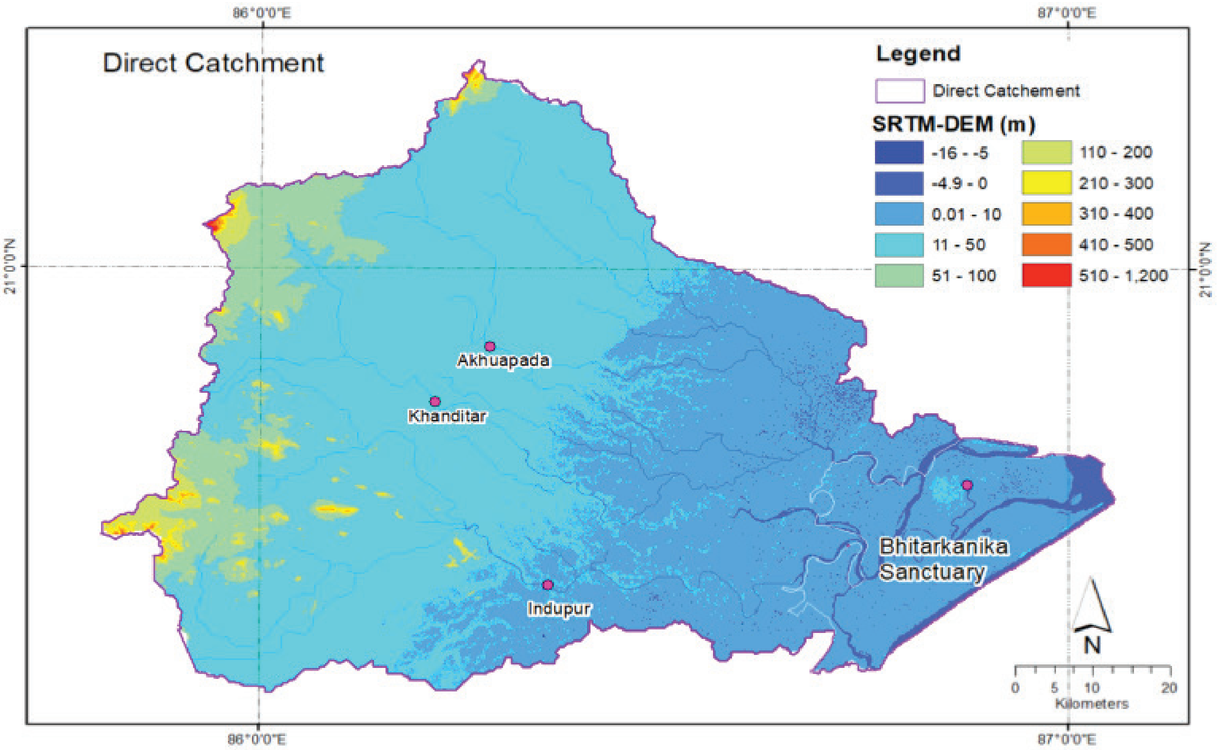


Figure 48 *Direct catchment of Bhitarkanika Sanctuary showing gauge station locations at Akhuapda, Khanditar and Indupur*

The Central Water Commission (CWC) has estimated that the annual renewable water resource of the Brahmani basin is 21,920 million cubic metres, which includes both surface water and groundwater resources (CWC 1988). Out of this, it is estimated that 16,618 MCM of water (about 75%) will continue to flow to the sea, indicating that the basin will not have any water shortage (CPSP, 2005).

7 POLICY-RELATED RECOMMENDATIONS

7.1 Need for a shift in the concept of water resources

The integration across different sectors such as nature sectors (forests, pastures and barren lands), people and industries must be constructed as it has a large impact on the availability of waters in the rivers and eventually into the wetlands. Integrated management of land and water is made possible through the application of models such as BHIWA (Basin-wide Holistic Integrated Water Assessment), which will help in taking a holistic view of the water needs and their impacts on the availability of water to the sanctuary. The Department of Water Resources, Odisha may be the implementing agency for such an exercise as they have technical expertise in this domain.

7.2 Accounting water use by sectors and their integration

The maintenance of water accounts, in terms of withdrawals, consumption and returns, separately for individual sectors (water for agriculture, people and nature) needs to be assessed and integrated in order to understand the real impacts of land and water use and management policies. The BHIWA model, which considers the entire land phase of the hydrologic cycle, provides the necessary framework, including assessment and accounting for sector-wise withdrawals and consumptive use, including their composition. The model considers the effect of land and water management policies on the magnitude as well as composition of consumptive uses of different sectors. The Department of Water Resources, Odisha may be the auditing authority for such accounting.

7.3 Water for people – dimensions of priority

The National Water Policy prioritises drinking water first. Industrial, environmental and navigational uses are given lower priorities than irrigation. The core water demands for drinking and those required for maintenance of the rich biodiversity of the Brahmani delta and the Bhitarkanika estuarine region may require to be given higher priorities. The Odisha State Forest Department and Department of Water Resources, Odisha must work in coordination to ensure that Bhitarkanika Sanctuary gets the required flow of water for the survival and sustenance of biodiversity.

7.4. Water for nature

Environment Flow Requirements (EFRs) need to be defined following further investigation to ensure optimal ranges for riverine ecosystems in water-rich basins. Better methods based on water regimes required by different species an on the trade-offs between environmental flow and uses, as preferred by society, need to be evolved. The Brahmani case has provided a situation where requirements of fisheries, maintaining biodiversity of the fragile mangrove ecosystems of Bhitarkanika, and possibly river navigation below, and industrial requirements in Angul-Talcher are to be met, apart from irrigation requirements of the deltaic region. This needs a special study to establish whether the existing Rengali reservoir operation can be modified to meet these complementary and competing uses. In such a cross-sectoral situation, the alignment of different government agencies such as the Department of Water Resources, Fishery Department, Forest Department, State Pollution Control Board and Department of Ports and Waterways is vital to ensure the optimum flow needed for various requirements.

7.5 Recognise and respect cross-sectoral issues

The interrelationships among issues such as aquaculture, loss of mangroves, coastal erosion, salt water ingress and loss of productivity of paddy fields should be recognised. Conservation of biodiversity and consequent restrictions on the livelihood options open to the resource-dependent population; development of ports; and loss of tourism beaches need to be realised, and adverse impacts need to be addressed and resolved. Where biodiversity conservation measures constrain livelihood activities, alternate livelihood sources need to be assured to the dependent coastal communities. In contrast to past thinking and past practices, environmental protection and development/livelihood opportunities cannot be considered as separate activities; each must incorporate the other.

There are several statutory laws for the management and improvement of coastal resources with the aim of controlling the allocation of resources between various users and minimising conflicts between them. There also exist several sectoral laws, controlled by different government agencies, which are being used to regulate various activities irrespective of whether these affect the ecological integrity of this ecosystem. Most of these agencies work in isolation, pursuing their respective departmental agendas while being largely unconcerned about the holistic picture. For example, in the Bhitarkanika area, forests and parts of the river that are within the protected area come under forest and wildlife legislation, but outside these areas, fishing and trawling are covered by the maritime, port and fisheries acts. The forest law can prohibit cutting of forests but cannot prevent the destruction or alteration of the forest. Neither can it control land use and developmental activities, outside its area of jurisdiction, which may have adverse impacts on the conservation values of the area, e.g., the resettlement of refugees and legalisation of illegal settlements in the sanctuary area by the Revenue Department. An example is the construction of Dhamra Port, which has an impact on the integrity of the entire ecosystem, including Gahirmatha Marine Sanctuary and Bhitarkanika. Developmental activities, viz., construction of jetties, roads that fragment ecosystems, defence structures, inshore fisheries by mechanised vessels and ports are crucial threats to Bhitarkanika National Park (Badola & Hussain, 2005).

In order to solve the existing and future problems arising from un-coordinated resource use and allocation, it is important to deal with the problems and issues on a spatial scale rather than addressing these sectorally. It is proposed that a dedicated Bhitarkanika Conservation Area Management Authority can be set up by the Mangrove Forest Division with adequate representation from the policy makers of the central and state governments, local communities and other government departments functioning in the area, apart from eminent scientists from reputed institutions (Kadaverugu et al., 2021).

The authority should:

- Set standards and objectives for the integrated management of the Bhitarkanika Conservation Area as a single unit and determine the cost of achieving these objectives.
- Establish a process of cooperation and collaboration among various stakeholders in the Bhitarkanika Conservation Area.
- Establish a research laboratory at Bhitarkanika Sanctuary to undertake a systematic physicochemical monitoring of the water and sediment quality of the sanctuary. Research projects on hydrodynamic modelling, biodiversity and climatic change should be undertaken on priority basis in the long-term management action plan. Building the capacities of the research personnel may be done through networking with other coastal research laboratory facilities such as the Wetland Research and Training Centre (WRTC), Chilika Development Authority, who have long-term experience in research and management of biodiversity hotspots of the Ramsar site, i.e. Chilika.
- Collect and collate existing information on the physical, biotic and socio-economic characteristics of the Bhitarkanika Conservation Area and identify the status and trends of landscape-level processes and functions within the Bhitarkanika Conservation Area.

- Identify current and future landscape disturbance regimes that are affecting or may affect the ecosystem.
- Establish a series of strategies, with time tables and benchmarks with detailed financial goals and budget projections, as well as criteria and methods for evaluating progress towards meeting the established goals.
- Prioritise strategies and specific actions to carry out required policy and legal changes and monitoring of compliance at regular intervals.

7.6 Community incentives through carbon offsetting and REDD+

REDD+ is a framework created by the UNFCCC Conference of the Parties (COP) to guide activities in the forest sector that reduces emissions from deforestation and forest degradation, as well as the sustainable management of forests and the conservation and enhancement of forest carbon stocks in developing countries. and PES (Payment for Ecosystem Services) can be successful tools and approaches for streamlining financial support to address poverty and livelihood concerns of the local communities while realising the benefits of mangrove restoration and increasing carbon stocks in the region (Kadaverugu et al., 2021). Degradation of mangroves by locals for petty and short-term economic benefits can be reduced by enabling them to avail carbon offset/ conservation payments approved under the climate change mitigation action plan to restore and protect these mangrove patches. There is a very important role of local administrative agencies in policy and decision making, especially in enforcement of policies that consider mangrove conservation and trust building among locals for participatory mangrove conservation and restoration.

Apart from the efforts of forest department in mangrove restoration, involvement of researchers is also necessary in identifying suitable sites for mangrove plantation. Potential mangrove plantation sites should ideally be selected close to cyclone-prone areas. Recognition of traditional rights (using socio-economic surveys) in mangrove growing areas is important when planning regulations to avoid conflicts and ensure active community participation in planting and providing post-plantation care (Kadaverugu et al., 2020).

7.7 Government buy-in

Many developmental policies of the government seek to achieve economic growth but fail to take into account the values of mangroves, which are interlinked with land uses and basin-level changes in hydrology. Large infrastructure and agricultural schemes may cause mangrove degradation and deforestation, causing loss of valuable fisheries resources, making coasts vulnerable to extreme events and eventually causing loss of natural and social capital. To ensure that mangroves are conserved and restored, the government agencies at different levels should recognise the economic values associated with mangroves and what they are worth, i.e., they are essential for nature and human well-being.

Raising awareness among political decision-makers about the importance of mangroves on a global scale is central for mangrove conservation. Mangrove conservation and restoration should be mainstreamed into relevant policies (such as National Mission for Green India, National Action Plan on Climate Change, National Conservation Strategy and Policy Statement on Environment and Development, Coastal Aquaculture Authority Act and Biological Diversity Act). The bottom-up approaches should include a participatory approach that involves local communities to put mangroves on their agenda. The top-down approaches, e.g., informing global and regional development strategies by influencing procurement policies of financial institutions or by strengthening policies that promote more sustainable supply chains for mangrove commodities should also be explored.

The economic evaluation of total ecosystem services associated with Bhitarkanika Sanctuary will inform policy makers, thereby providing strong arguments to protect and conserve mangroves. A toolkit of model policies, which can easily be adapted to different contexts and promotion of mangrove-based climate change adaptation and mitigation strategies, will be vital for conservation of mangroves.

7.9 Recommendation and polices for environmental management at the basin

- OSPCB has done the overall assessment of the environmental status of the Angul-Talcher area of the Brahmani basin using the BEES methodology (OSPCB Technical Report 2018; Carrying Capacity Study of Angul Talcher Area). It can be noted that even with the protection measures the overall environmental quality will deteriorate. The present industrial activities and those envisaged in future will impact all the components of the environment of the study area. This calls for devising measures for the effective control and management of the environmental parameters when taking care of the needs of the people and the requirements for social and industrial development.
- The surrounding areas of Angul-Talcher-Meramundali region have either dense forest lands or are in the Mahanadi delta, which is more suited for agriculture. The ensuing industrialisation in the study area will lead to wide-scale mobility from rural to urban centres, thereby further stressing the environmental components, if appropriate planning with respect to development of infrastructure and civic facilities is not taken up urgently. Formulation of the Regional Environmental Management Plan on the basis of the prevailing environmental situation and taking into account the proposed industrial development will be recommended.
- Waste generation due to the operation and expansion of mining and industrial activity in Angul-Talcher is going to be a serious negative impact on the water resource in the near future. But at same time the industrial effluents, mine drainage water, untreated sewage from urban settlements, runoff from agricultural field, mining areas and open defecation on the river banks have been contributing the pollution load on the river water. The vast expansion of coal mining, thermal power generation and associated industrial activities are expected to increase the pollution load of the river system.
- The industries in the basin come under the category “Grossly Polluting”, but they pose no serious problem to the aquatic life or other living beings in the environment because water is available and there is a sufficiently strong flow. There is a strong self-purifying capacity. However, the threat should not be ignored for long because several large industries are planned. So overall management of the water system is necessary, and the CPCB/SPCB rules should be strictly implemented before water is discharged back into the streams.
- The industrial and mining activities are all in the lower basins of four tributaries of the Brahmani, namely, the Tikra, the largest tributary in Odisha (3536 km^2), Singhdajhor (436 km^2), Banguru (131 km^2) and Nandira (595 km^2). A master plan for the integrated development of these basins for the nature, food and human sectors needs to be drawn up. If this is not done, an alarming situation will develop in Bhitarkanika. The SPCB should look at the distal impact of these grossly polluting industries in consultation with the Mangrove Forest Division, Rajnagar.
- At present there is no arrangement for monitoring the heavy metal content and presence of pesticides in the Bhitarkanika river water. Such an arrangement should be included in the monitoring scheme. The samples collected through the monitoring programme for assessment of heavy metals and pesticides can be analysed at laboratories having facilities to analyse the same, such as SPCB, Chilika Development Authority (CDA), or National Centre for Sustainable Coastal Management (NCSCM).
- The industrial/mining effluents of the Angul-Talcher region have affected the water quality of the Brahmani river. The river Nandira carries the bulk of the industrial effluents and has become a highly polluted stream. Immediate effort in terms of mitigating the impact of the effluents on the rivers is called for to treat all waste water before it is discharged into the streams. Each industry that is directly or indirectly impacting the water quality of the Brahmani/Baitarani River system, should treat its effluents, in accordance with the legal requirements, before

discharging these into the streams. OIf this is not done, the "polluter pays" principle should be implemented. It is essential to conduct a carrying capacity study before any new mine or industry comes up in the Brahmini–Baitarani basin. The water requirement of any proposed infrastructure should be analysed for its impact on dependent ecosystems such as Bhitarkanika.

- Old abandoned mines and quarries should be effectively reclaimed and converted into forest with water bodies and appropriate forms of land use. This need to be implemented strictly under the reclamation programme to minimise the impact of runoff and leaching from the overburden dumps. The State Forest Department and the Pollution Control Board should monitor the implementation meticulously.
- Water management at basin level Odisha is a state with about 33% of the population below the poverty line. The state has many districts where 58% to 70% of the people are below the poverty line. The Brahmani basin is a developed area, but the Baitarani basin has a high prevalence of poverty, and this requires that development be a priority in the state. This justifies the extraction of freshwater for developmental uses. Bhitarkanika National Park is also an important landmark of Odisha, and this system is making a great contribution to the economy and the safety of the state in many forms and needs to be preserved at any cost (OSPCB Technical Report 2018; Carrying Capacity Study of Angul Talcher Area):

(i) Assessment of the water requirement of the mines, industries, household activities, commercial activities, agriculture, etc. for their current activities and those planned in future should be done. Water being an important resource, all care should be taken in optimising the requirements of various components of the mines and industries.

(ii) Identification of sources of water and assessment of the availability from these sources. The assessment should also include the availability of water from rainfall and the measures taken for rain water harvesting.

(iii) Development of water resources in the process of underground and opencast mining, rain water harvesting and water shed management. It is well known that both opencast and underground mining damage the surface as well as underground water sources. This causes a marked reduction in the water availability. To take care of such impacts, both underground and opencast mines should be planned with provisions for development of surface and underground water bodies. To augment the availability of water on the surface, efforts should be made to develop small and medium-size surface water bodies utilising the watershed of various streams in the area.

(iv) Effluent management from mines, industries, commercial activities, agriculture, households, etc. Before discharging the effluents into the surface water bodies and on the soil, the impacts of such discharges on the quality of the sinks should be assessed, and only in the cases where the impacts are not harmful should the discharge be planned.

(v) Water treatment for household and other uses. The most important part of water management in the industrial areas is meeting the requirements of the quality and quantity of the water provided to households for human consumption. Hence, this aspect should be given proper attention. On average the domestic water availability should be 120-150 litres/head/day.

7.10 General Recommendations

- Mangrove species such as *Avicennia alba, Ceriops decandra, Xylocarpus granatum* and *Rhizophora mucronata,* which have higher phytoremediation potential with respect to heavy metal bioaccumulation in their tissues, should be given priority in plantation programmes. Studies should be undertaken by the Mangrove Wildlife Division, Rajnagar to evaluate their growth and survival in upstream river sites so that these mangrove species can be used to sequester heavy metals or other pollutants before they reach the downstream part of the sanctuary. This could mitigate the impact of heavy metal pollution on the ecology of Bhitarkanika and promote conservation of the mangrove ecosystem. Apart from the efforts of the Forest Department to restore mangroves, researchers need to be involved in the identification of suitable sites for mangrove plantation. Mangroves should be planted along the shoreline close to cyclone-prone areas (e.g., the villages of Satabhaya and Habalikhati) to mitigate the impact of the sea level rise and coastal flooding. Odisha Forestry Sector Development Society (OFSDS) has taken up plantation of mangroves along the Odisha coast and has developed a technical manual for restoration of mangroves that provides step-by-step guidance for successful restoration of degraded mangrove areas (OFSDS Technical Manual). The site manger should utilise such technical expertise that is available with the Government of Odisha.

- The tourism in the sanctuary needs to be regulated in order to reduce pressure on certain areas such as Dangamal and Gupti which are easily accessible by roads. All arrangements to accommodate the tourists should be located away from the sanctuary, and a proper eco-tourism plan needs to be developed for the park. Educating the urban and rural masses is another major step to put a check on the river water pollution. The masses should be made aware of the drastic consequences of pollution on their lives, both directly and indirectly. The Odisha Forest and Tourism departments are continuously working together on eco-development initiatives in Bhitarkanika Sanctuary for sustainable development of the coastal community.
- Resource extraction from Bhitarkanika National Park is not permitted under the current law (Wild Life Protection Act, 1972). However, the villages located inside the sanctuary have no option but to use the resources from the protected area. The use in this case is de facto, which is always indiscriminate. The national park i.e., the core zone, has to be maintained as a sanctum sanctorum, and all resource use therein will have to be stopped. The possibility of meeting the needs of the people who are actually dependent on the resources of the national park for their livelihoods, particularly those living within 1.5 km of the forest boundary, from the resources of the buffer zone has to be explored. The buffer zone in this case is a wildlife sanctuary, where resource extraction is not permitted. A policy to permit controlled resource extraction in this zone can be permitted, provided that it does not affect the ecological process of the system.
- The dependence of the local people on forest for fuel wood is also a threat to the mangrove forests as fuel wood extraction is one of the major causes of deforestation of mangroves in the region. Switching to other sources of energy can reduce pressure on the mangrove forests. Various non-conventional sources of energy such as solar cookers and biogas plants can be introduced in the area. Fuel-efficient chullhas can be distributed in the villages. Further, to reduce the pressure on the existing mangrove forest for fuel wood and timber, plantations should be initiated in the marginal lands available in the villages and on the sides of the dykes.
- The sanctuary boundary is quite artificial, and except at a few places where it is bound by the sea or a river, it does not follow any natural feature. Because of the presence of 410 villages (Census 2011) within the sanctuary and a lack of a final notification under Section-26 of Wildlife (Protection) Act, 1972, no attempt has ever been made to demarcate the boundary with boundary pillars. However, it is necessary that boundary pillars be provided along the sanctuary limits. The total length of the sanctuary boundary is about 320 km. The state forest department may look at the feasibility of demarcating the boundary of the sanctuary.
- On the basis of the LULC pattern and the forecasted risk, Bhitarkanika Sanctuary may be divided into planning zones for preservation, conservation and development. The vulnerable mangrove zones are indicated in Figure 43. The patches of mangrove along the south-west and northern coasts should be given top priority in the preservation and conservation programme by the Mangrove Wildlife Division, Rajnagar. Management and conservation approaches such as increased protection, plantation or other interventions may be initiated on the basis of habitat assessment.

- Constant monitoring of the LULC patterns in basin and Bhitarkanika Sanctuary will be crucial to understanding the land use and the reasons behind changes. This will allow preparation of models for regional and spatial patterns of the area as well as prediction of the implication of such changes in the future on the sanctuary. It is recommended that remote sensing with GIS be sued for monitoring the land use land cover changes. Public participation, education programmes and awareness initiatives are the foundation of the success of any sustainable development in the sensitive coastal region.
- Although there are known pollution-causing industries such as Oswal and PPL around Bhitarkanika that could affect the ecological soundness, no major problem relating to oil spills has been faced in the sanctuary so far. However, the presence of an oil refinery close by and the use of a large number of trawlers are cause for concern. No arrangement exist to tackle any mishap that may take place due to oil spills. The ports should have appropriate contingency plans to tackle spills of about 100 tons of oil. It is understood from the details of the facilities available with the Paradeep port that it has capabilities to combat oil spills. Even though, this may be adequate considering the vessels visiting at present, taking into account its future expansion programmes, the location of the ecologically sensitive Bhitarkanika mangroves and the Olive Ridley sea turtle nesting grounds at Devi and Gahirmatha, it is necessary to upgrade the equipment and the manpower to tackle spills at least up to 100 tons.

8 BHITARKANIKA AS A SOURCE OF POLITICAL CAPITAL AND INTER-LINKAGES WITH HYDROLOGY AND MANGROVE ECOLOGY

The Bhitarkanika Mangroves provides a range of ecosystem services that play a critical role in sustaining life and the livelihoods of communities living in and around. They primarily serve as a buffer to coastal storms, tsunamis and cyclones and contribute immense provisioning and cultural ecosystem services for human well-being.

8.1 Provisioning services

The commercial fisheries, economic uses of mangrove and forestry products and inland navigation (especially for the island villages) utilise the provisioning services. Hussain and Badola (2010) carried out an economic evaluation of different forestry and fishery resources of the Bhitarkanika mangrove ecosystem. The total fish catch from Bhitarkanika Sanctuary was 3.77 kg/h with a market price of US$2.25. It was also found that mangrove sites have a considerably higher fish yield, 123.34 kg/h (earning US$ 44.62/h), compared with sites without mangroves, where the yield was 17.89 kg/h (earning US$ 2.62/h) (Table 14).

Table 14 *Economic evaluation of forestry and fishery products derived from Bhitarkanika Sanctuary*

Resources	Uses	Mean quantity (kg household^{-1} annum^{-1})	Monetary value (US$ household^{-1})
Fuel wood	Total consumption of fuel	2205 ± 104.2	88.34
	Fuel wood from the park	312 ± 32.2	12.5
	Fuel wood from homesteads	21.0 ± 23.5	0.84
	Cow dung and farm refuse	1949.0 ± 375.0	-

Resources	Uses	Mean quantity (kg household-1 annum-1)	Monetary value (US$ household-1
Fish	Fish caught from the park	98.0 ± 28.3	68.6
Timber	Used as rafters	343.0 ± 36.9	15.6
	As roof supports	27.0 ± 4.3	4.5
NWFP	Honey	525.0 ± 239.7	3.6
	Thatching material *(P. paludosa)*	49.0 ± 8.7	2.5

(Source: Badola and Hussain, 2003)

8.2 Cultural services

These services are related to the religious and touristic values. They are important contributions to the livelihoods. Bhitarkanika, with its rich biodiversity and scenic beauty, is one of the important tourist destinations of Odisha (Table 15).

Table 15 *Tourist flow and revenue generation from Bhitarkanika Sanctuary*

Year	Number of tourists visiting the sanctuary/park			Revenue collected (₹)
	Indians	Foreigners	Total	
2010–11	47,976	287	48263	15,86,383
2011–12	39,295	275	39,570	13,86,868
2012–13	47,014	203	47,217	15,48,989
2013–14	48,212	226	48,438	
2014–15	56,078	088	56,166	
2015–16	77,229	216	77,445	
2016–17	74,225	173	74,398	
2017–18	74,947	211	75,158	
2018–19	69,282	279	69,561	
2019–20	61,411	318	61,729	

(Source: Management Plan of Bhitarkanika Wildlife Sanctuary and National Park 2020–2030)

8.3 Regulating services

These services include sediment trapping, nutrient uptake, carbon sequesteration, protection from floods and storms and stabilisation of coastal land and reduction of the erosion of the shoreline and riverbank. These services sustain economic activities in the coastal areas. Bhitarkanika is vulnerable to frequently occurring extreme weather events, and the impacts have been profound in the last few years. The Bhitarkanika mangroves are effective shoreline stabilisers, offering protection against extreme weather events. Badola and Hussain (2005) assessed the storm protection functions of the Bhitarkanika mangrove ecosystem. They found that the loss incurred per household was greatest (US$153.74) in villages that were not sheltered by mangroves but had embankments, which were followed by the villages that were neither in the shadow of mangroves or had embankments (US$44.02) and the villages that were protected by mangrove forests (US$33.31). Hussain and Badola (2008) carried out an economic evaluation of the nutrient retention ecosystem services of the Bhitarkanika National Park area and estimated that each hectare of soil from the mangrove area contains additional nutrients worth US$232.49 compared with soil from non-mangrove areas. The difference in nutrient content between mangrove and non-mangrove soils gave a value of US$3.37 million for the nutrients in 145 km^2 of mangrove forests. Thus, the mangrove ecosystem also contributed to the productivity of the local agro-ecosystem.

9 ASSESSMENT OF WATER AND SEDIMENT QUALITY OF BHITARKANIKA SANCTUARY AND MAJOR DRAINAGE RIVERS

From the management point of view, it is very important to know the current status of the health of the ecosystem as compared with the past as seen from the available records. There are several water and sediment quality parameters that indicate the health status and suggest if there is a need for any management action to recover the ecosystem if the ecosystem is deteriorating with time. Therefore, during the monsoon (October 2020), water and sediments samples were collected from 41 stations, of which 37 stations were in the sanctuary (stations 1 to 37) and four (stations 38 to 41) were from the major river basins, the Brahmani basin (Patamundai, Aul, Hansua) and the Baitarani basin (Chandbali), as shown in Figure 49.

During winter (December 2020), sampling was done from 39 stations as station 6 and station 35 were not covered due to logistic issues. Physico-chemical parameters were measured at each station to understand the present health status of the sanctuary and whether there is a need for any management action. Since there could be some heavy metal pollution from upstream rivers, copper (Cu), cadmium (Cd), lead (Pb), zinc (Zn), manganese (Mn) and iron (Fe) levels were measured at 33 stations in the sanctuary.

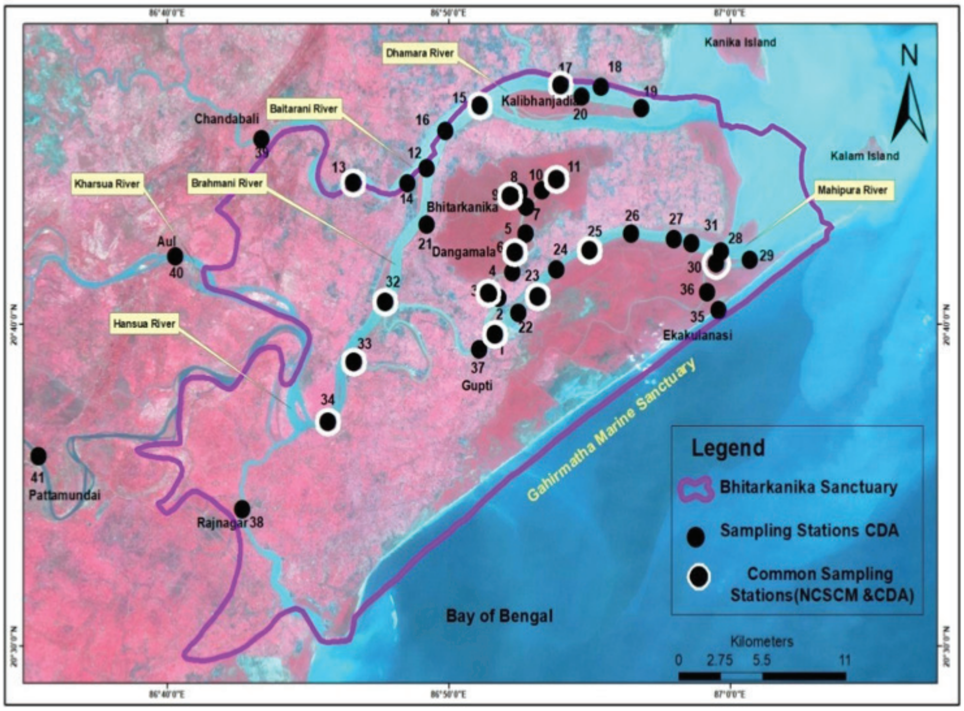


Figure 49 Water and sediment sampling locations in Bhitarkanika Sanctuary and the major river basins, Odisha

9.1 Methodology followed for water and sediment quality analysis

The details of the water and sediment quality pararmeters tested along with the methods employed are listed in Table 16.

Table 16 *Details of water and sediment quality parameters and methods used in present survey*

Parameters	In-situ / Lab	Method	Equipment used
Physico-chemical (water)			
Air/water temperature	In-situ	Thermometer	Thermometer
pH		Probe – electrode	913 Metrohm pH meter
Salinity		Probe – conductivity	Orion star A212 bench top conductivity meter
Total dissolved solid (TDS)		Probe – conductivity	
Transparency		Light attenuation	Secchi disk
Total alkalinity (TA)	Laboratory analysis	Titration	
Dissolved oxygen (DO)		Titration	Winkler's titration method
Biochemical oxygen demand (BOD)		Titration	Winkler's titration method
Nutrients and chlorophyll-a			
Nitrite	Laboratory analysis Laboratory analysis	Colorimetry	SKALAR San++ - Continuous flow analyser
Ammonium			
Nitrate, total nitrogen			
Phosphate, total phosphorous			
Silicate			
Chlorophyll-a		Colorimetry	UV–visible Spectrophotometer
Faecal coliform		Most probable number (MPN)	Laboratory analysis
Sediment			
Total organic carbon		Titration (Walkley-Black method)	Laboratory analysis
Available nitrogen		Titration (alkaline permanganate method)	KEL PLUS nitrogen distillation apparatus
Soil texture		Sieve method	63-micron test sieve
Heavy metals		Spectroscopy, flame	Atomic Absorption Spectroscopy (AAS)

In situ measurements of water quality parameters in the field

Analysis of DO and BOD in WRTC lab

Analysis of Chl-a using instrument facility at WRTC

Fixing of DO samples immediately after collection

Filtration of water samples using vacuum pump in field

Preparing the media for FC analysis

Performing the presumptive test for FC analysis

Analysis of Heavy metals using Atomic absorption spectrophotometer (AAS)

Measurement of water flow using velocity probe

Collection of water samples

Measuring the depth and transparency by Secchi disc

Collection of sediment samples

Collection of sediment samples

Figure 50 *Some photographs of the field and laboratory work*

9.2 Physico-chemical parameters of water

9.2.1 Salinity of Bhitarkanika Sanctuary

Understanding the salinity dynamics of the sanctuary is crucial from the management prospective as it is a crucial parameter that controls the biodiversity in coastal aquatic ecosystems, wetlands and mangrove ecosystems. Any significant change towards higher or lower salinity levels could be responsible for deterioration of the ecosystem and will need immediate management actions. The coastal flora and fauna are acclimatised to wide variations in the salinity range; however, sudden changes in salinity, such as those caused by cyclones, etc. may cause stress to them. Changes in the salinity range due to changes in the freshwater supply or sea water intrusion could impact the mangrove biodiversity and species composition and change the distribution/migration patterns of crocodiles and other plants/animals in this mangrove system. Hence, it is very essential to record the salinity patterns with respect to space and time.

The long-term salinity trend could not be retrieved from the data in the literature and the present study due to the following reasons:

- The results reported in different publications are for different locations (such as estuarine areas, riverine-influenced areas or national park areas).
- The number of stations covered in the survey are variable
- All the studies did not cover all the seasons or months for comparison
- The timing of sampling with respect to the tides plays a major role in understanding the salinity gradient, and the published values are not sufficiently consistent for trend analysis. Salinity data are available for Bhitarkanika Sanctuary for 2007, 2009, 2011-2012 and 2017 (Chauan & Ramanathan, 2008; Nayak et al., 2009; Dash & Das, 2014), but they are sporadic in the sense that the sampling was done from a limited number of stations or merely cover a single season. The only systematic data available are for the period 2018–19, from the study carried out by NCSCM.

The results showed that there was a more than two-fold reduction in salinity in the sanctuary in winter 0.1-15 Practical Salinity Units (PSU) ; average: 6 PSU) compared with the monsoon (0.1-12; average: 3 PSU) due to the decline in the freshwater input from the rivers. The seasonal trend, salinity range and spatial distribution pattern (shown in Figure 51) were similar to the corresponding observations made by NCSCM.

- The salinity values recorded in the present study fall in the low-salinity/ oligohaline (0-5 PSU) and mesohaline (5–18 PSU) ranges. In general, low salinity is a favourable condition for luxuriant growth of mangrove vegetation (Kathiresan et al., 1996). Hence, no human intervention is needed to maintain the salinity gradient in the present environmental conditions as it is maintained naturally.
- In both the monsoon and winter, the salinity gradient showed an increasing trend from the rivers towards the sea. This spatio-temporal pattern was attributed to seasonal precipitation, river discharge fluctuations and the tidal regime.
- This study recommends that the salinity be monitored on a long-term basis at a minimum of 16 locations on a seasonal basis (summer, winter and monsoon). Out of the 16 locations, 4 stations can be from major river/freshwater inputs, 2 stations may be from major saline water inputs and 2 stations could be from estuarine regions and rest may be from major and minor creeks in the Bhitarkanika Sanctuary.

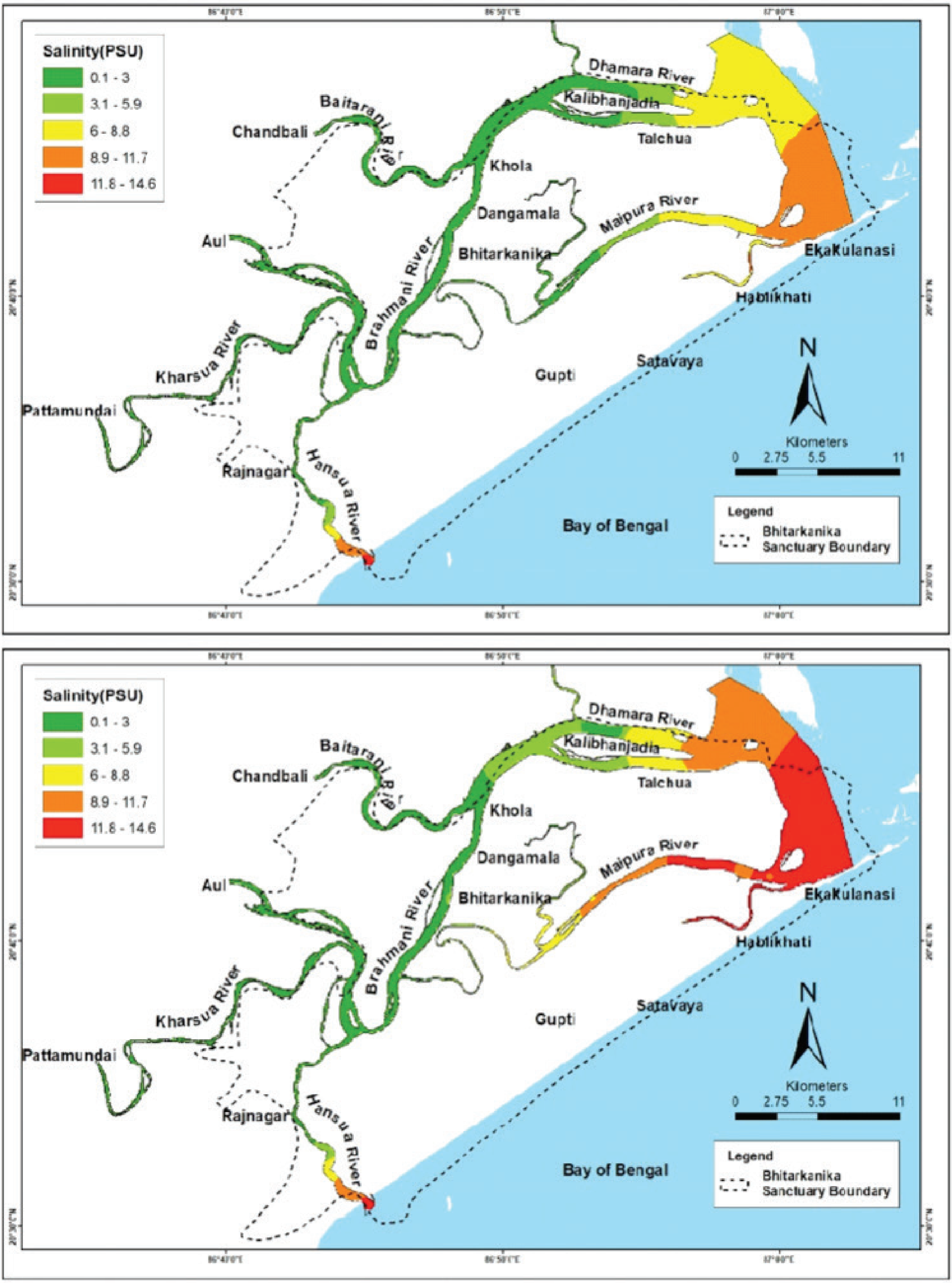


Figure 51 *Variations in the salinity distributions of Bhitarkanika Sanctuary and the major rivers (a) during the monsoon and (b) in winter*

9.2.2 Salinity distribution from estuary mouth to river upstream

Formulation of policies for the brackish wetlands is a challenge for the site managers as the salinity fluctuates due to the influx of saline water from the sea. Such river waters can be used for specific purposes depending on the salinity, and accordingly policy decisions should be made. Estuaries are zones where rivers and seas interact. The the salinity contributed by the tides to the fresh, turbid water of the river makes an estuarine system dynamic. The dynamic processes that exist at the near-shore region, such as coastal currents, tides, tidal currents, internal and surface waves, storm surges and tsunamis can alter the estuarine characteristics. Changes in hydrological characteristics due to dams, water diversion and coastal infrastructure may have a serious impact on the estuarine environment due to changes in freshwater flow and water quality affecting the biodiversity and ecology of the entire system (Mahanty et al., 2016). In order to know the salinity variations in such systems, it is crucial to know the distribution of salinity from the estuary mouth to the upstream stretches of the rivers, which need to be monitored constantly for managing the ecosystem sustainably.

A 2D hydrodynamic coupled advection Ddspersion model was used by CDA to examine the salinity distribution at Dhamra, Maipura and Hansua estuary and the river upstream of the sanctuary. Bathymetric data of the near-shore region and river were collected from the State Project Management Unit, ICZMP, Bhubaneswar, Odisha. The predicted tide was used as the offshore boundary condition. The upstream discharge data of the Brahmani and Baitarani rivers were collected from the Department of Water Resources, Bhubaneswar, Odisha and given as source input to the salinity model. The weather input (wind, precipitation and temperature; source: IMD) were also given as input parameters to this model. The simulation was carried out for monsoon and winter, and the results were compared with the observed (in situ) salinity, which showed a good correlation of 75% and 77% in the monsoon and winter, respectively.

The spatial distribution indicated that the maximum salinity was observed in the near-shore region and gradually decreased upstream. Freshwater dominates over the sea water intrusion, and thus the salinity gradually reduces upstream. The salinity data at selected points along the rivers (Dhamra, Maipura and Hansua) from the estuary mouth upstream were extracted from the model to examine the longitudinal distribution of salinity across the river in summer (May), during the monsoon (October) and in winter (December). The simulated salinity levels from the estuary mouth upstream for each river are presented in Figures 52–54 for summer, the monsoon and winter, respectively. During summer (May 2020), the salinity was higher at estuary, decreased upstream and was comparatively higher than other seasons due to less freshwater discharge. during the monsoon (October 2020), the salinity level of the Dhamra river decreased upstream up to the confluence of the Brahmani and the Baitarani, and it increased further upstream towards Chandbali. Similarly, the salinity data along the river from Dhamra to the Brahmani river were extracted, and it was seen that the salinity level decreased upstream. The maximum level was 12 ppt, near the Dhamra estuary, decreasing to 5 ppt at an upstream point (BT2).

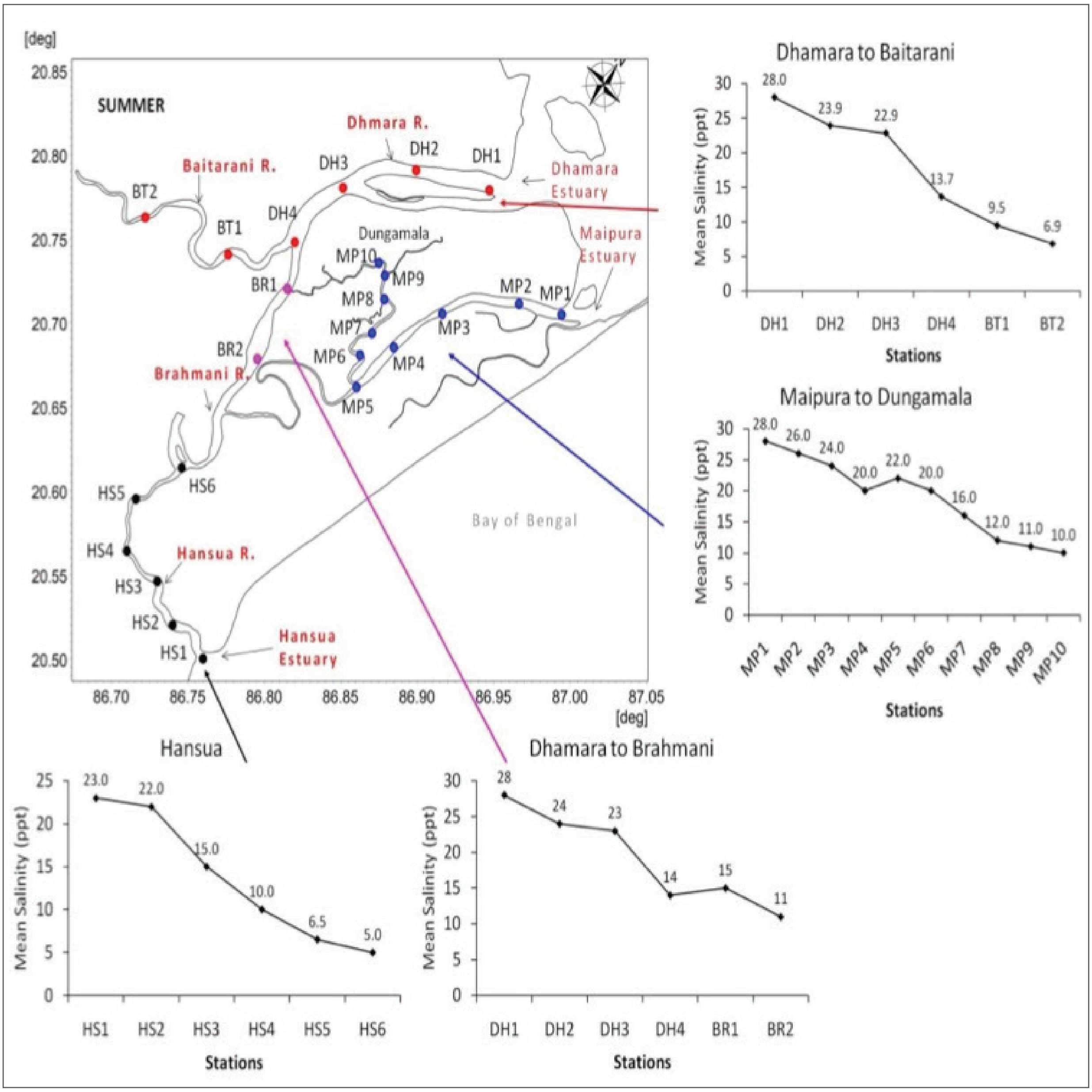


Figure 52 *Monthly mean salinity (over 31 days of May 2020) along the rivers (estuary mouths upstream)*

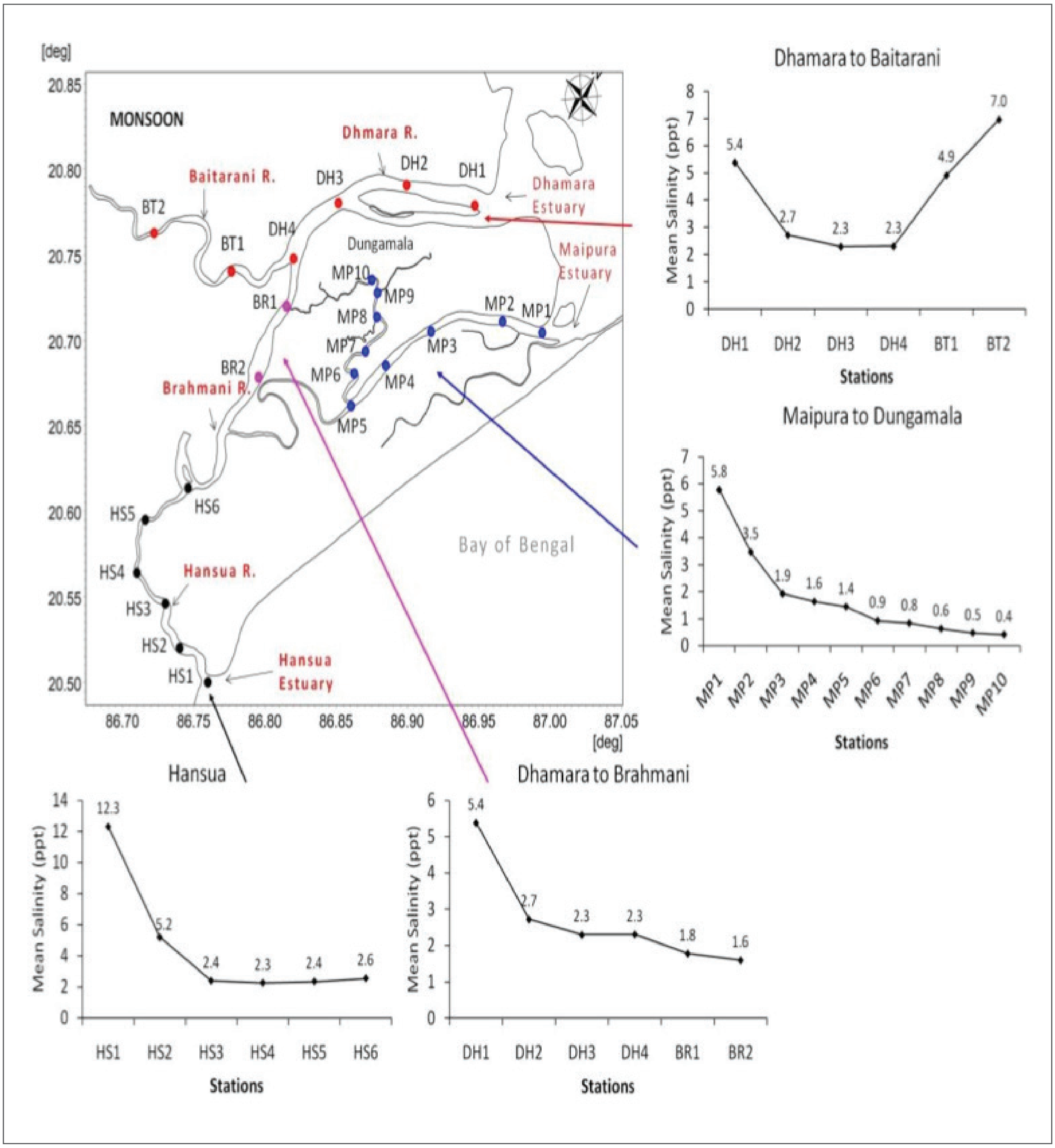


Figure 53 *Monthly mean salinity (over 31 days of October 2020) along the rivers (estuary mouths upstream)*

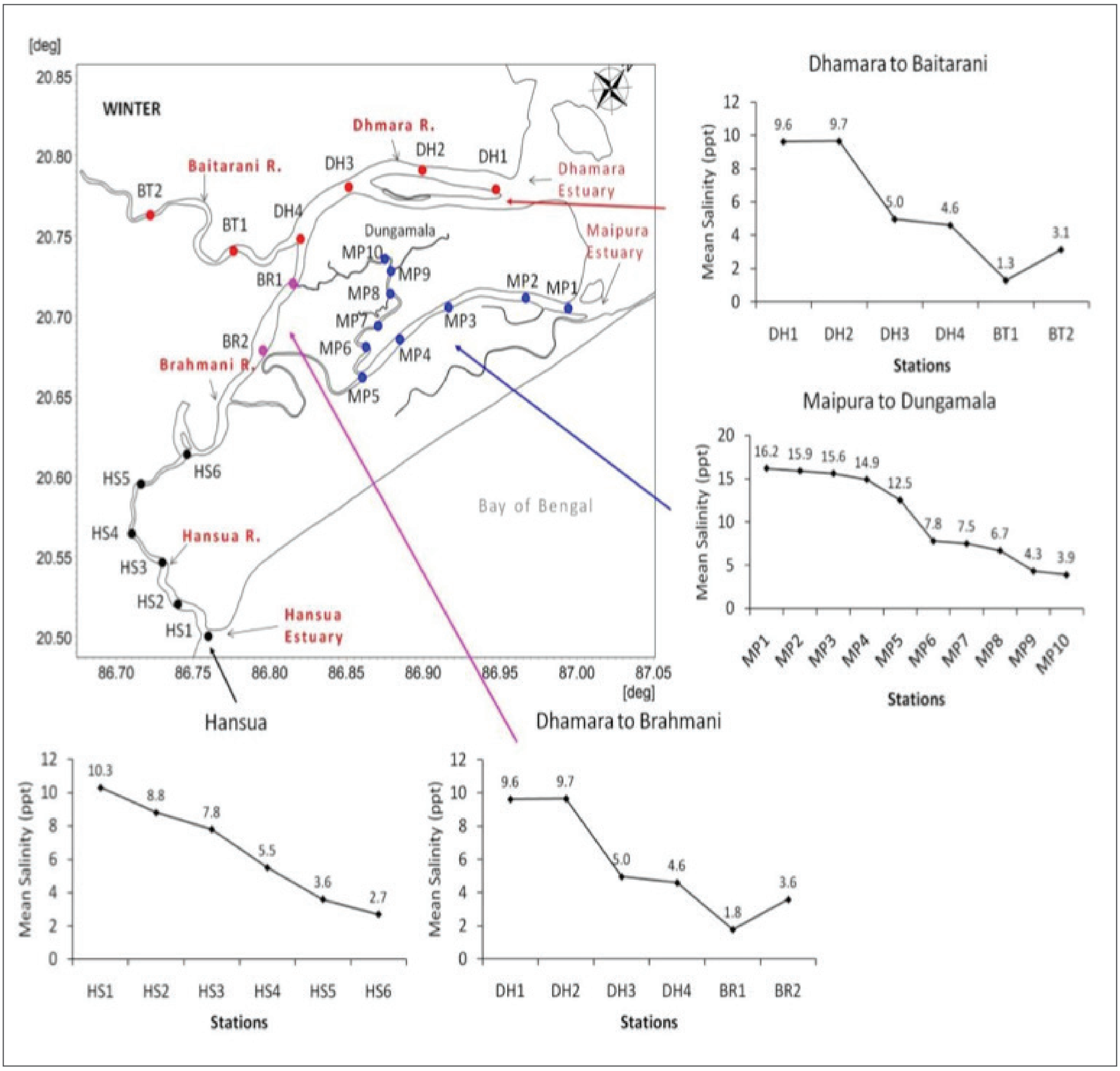


Figure 54 *Monthly mean salinity (over 31 days of December 2020) along the rivers (estuary mouths upstream)*

9.2.3 Variability of turbidity in Bhitarkanika Sanctuary

Turbidity plays a significant role in balancing the metabolic activities of an aquatic ecosystem. It is influenced by a combination of hydrodynamic, physico-chemical and biological processes. The water turbidity controls the dissolved oxygen (DO) concentration as it hinders the light penetration into the water column, thereby reducing the photosynthetic activity and oxygen production. Variations in DO concentrations can have a direct impact on the ambient nutrient stoichiometry, primary productivity and food chains. Hence, consistently higher turbidity levels may lead to serious management issues as the water quality starts degrading and the productivity and biodiversity decline.

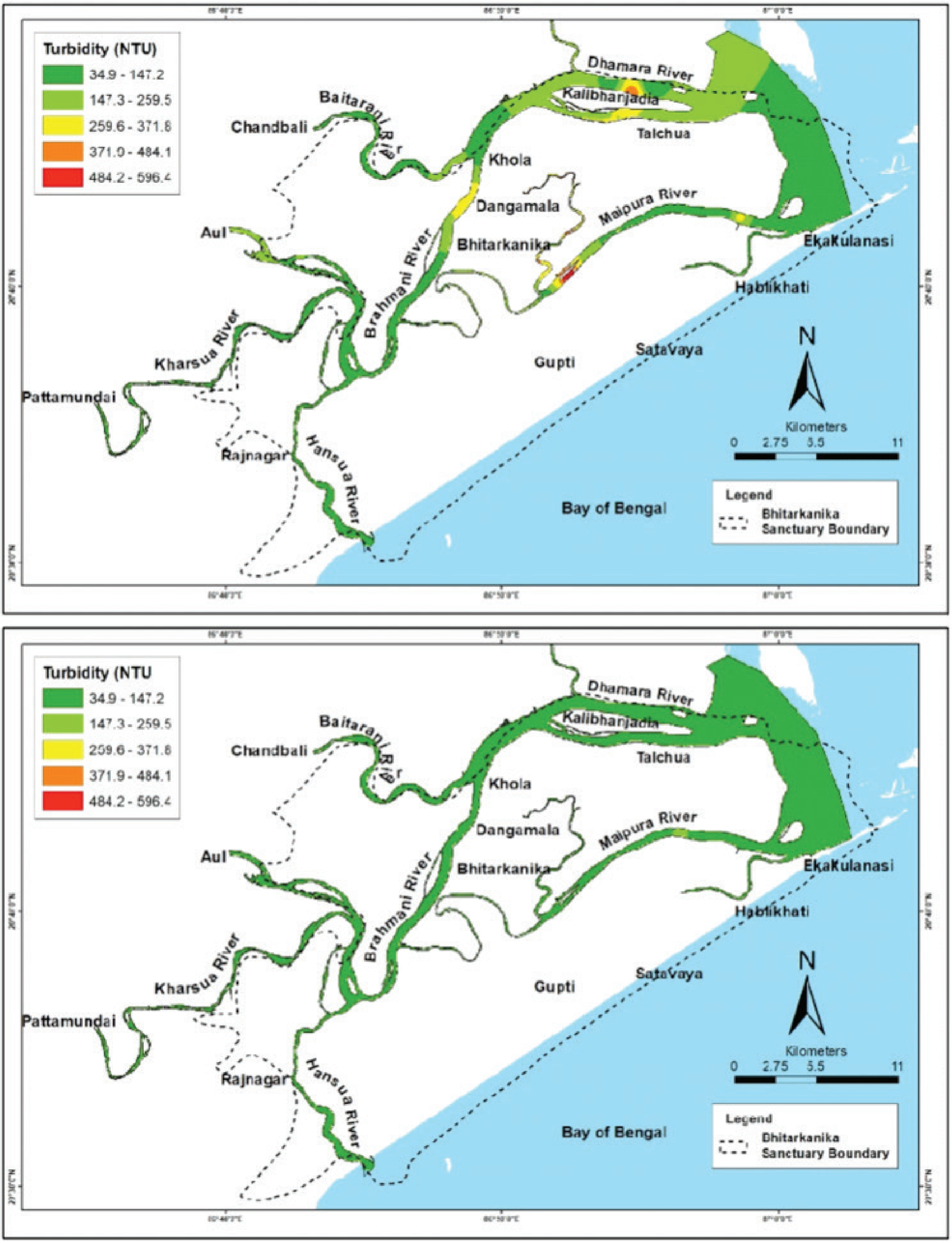


Figure 55 *Variation in water turbidity at Bhitarkanika Sanctuary and major rivers during (a) the monsoon and (b) in winter*

In Bhitarkanika, there are strong seasonal shifts in the turbidity level due to changes in the riverine sediment load. During the survey in the monsoon, the water of the sanctuary was highly turbid (34 to 600 NTU, with an average of 195 NTU) and the turbidity level of the rivers ranged from 95 to 173 NTU, with an average value of 132.25 NTU (Figure 55). In winter, the turbidity level declined substantially to values between 7 and 16 NTU (average, 30 NTU). During the monsoon, the turbidity crossed the threshold limit (30 NTU) prescribed by CPCB, New Delhi for the propagation of wildlife and fisheries at all the sampling locations. The spatial distribution showed that the turbidity was low towards the estuaries and high in the creeks of the sanctuary. This could be due to the surfing of riverine and sea water during tidal fluctuations.

The turbidity of the water influenced the transparency of the water column (measured as Secchi disk depth, SD) in the monsoon and winter. In the present study, the water transparency varied between 0.09 m and 0.42 m, with an average of 0.16 ± 0.08 m during the monsoon. It increased significantly in the winter (1.4–11.2 m, with an average of 3.76 ± 2.17 m). SD is used as a proxy for water quality and is used as an index to define the overall health status of the sanctuary as described in the sections on the trophic level index and the health status of Bhitarkanika Sanctuary.

9.2.4 Variability of nutrient concentration in Bhitarkanika Sanctuary

Understanding the nutrient dynamics of an aquatic ecosystem helps the wetland managers formulate policies for maintaining the productivity and biodiversity of the ecosystem as excessive levels of nutrients may lead to eutrophication and formation of toxic algal blooms, which reduce the water quality and affect the biodiversity. Nutrients are the raw material for the marine food chain and the main source for nutrients into the Bhitarkanika Sanctuary is drainage from estuaries, rivers and exchange from sea. The source of nutrient can be both autochthonous and allochthonous. Besides seasonal variability, nitrate and phosphate concentrations also show distinct spatial variability. The nutrient distribution in the sanctuary is mainly dependent on the season, tidal condition, freshwater influx and detritus and litter from mangrove vegetation.

There are very few studies that have focused on the nutrient dynamics of the sanctuary. Chauhan et al., (2008) studied the dynamics in 2005, Balakrishnaprashad et al., (2011) in 2008, Palit & Das (2020) during 2016-2018 and NCSCM (2019) in 2018 and 2019. The earlier sporadic data, except those of NCSCM, were not suitable for examining any trends in nutrients due to the differences in sampling location, differences in sampling period and low numbers of samples. The nutrient data collected in the present study are helpful in assessing the present status of the sanctuary with respect to the nutrient level in different seasons.

9.2.4.1. Nutrient flux into Bhitarkanika Sanctuary

Formulation of a management action plan always requires scientific data on the nutrient input from the different sources such as the riverine discharge into the ecosystem of interest as this largely influences the trophic status and overall health of the ecosystem. Brahmani and Baitarani are the two major rivers which contribute nutrients to Bhitarkanika Sanctuary. The nutrient data of sampling points Aul and Hansua (station numbers 40 and 38, respectively) were considered for the Brahmani river, and data of Chandbali (station numbers 39) were considered for Baitarani river for estimating the nutrient flux. The nutrient flows in the monsoon and in winter were estimated using the data collected in our study. Since, summer was not covered in our survey, the NCSCM nutrient data for the summers of 2018 and 2019 (NCSCM report, 2018, 2019) were used to estimate the flux. The average nutrient value of the summers of 2018 and 2019 was taken into account.

The nutrient flux from the Brahmani river in the form of dissolved inorganic nitrogen (DIN) or dissolved inorganic phosphorous (DIP) was higher than that of the Baitarani river. The average DIN and DIP concentrations in the sanctuary did not show significant change with respect to seasons. The spatial distribution of nutrients in terms of DIN and DIP has been shown in Figure 56 and 58.

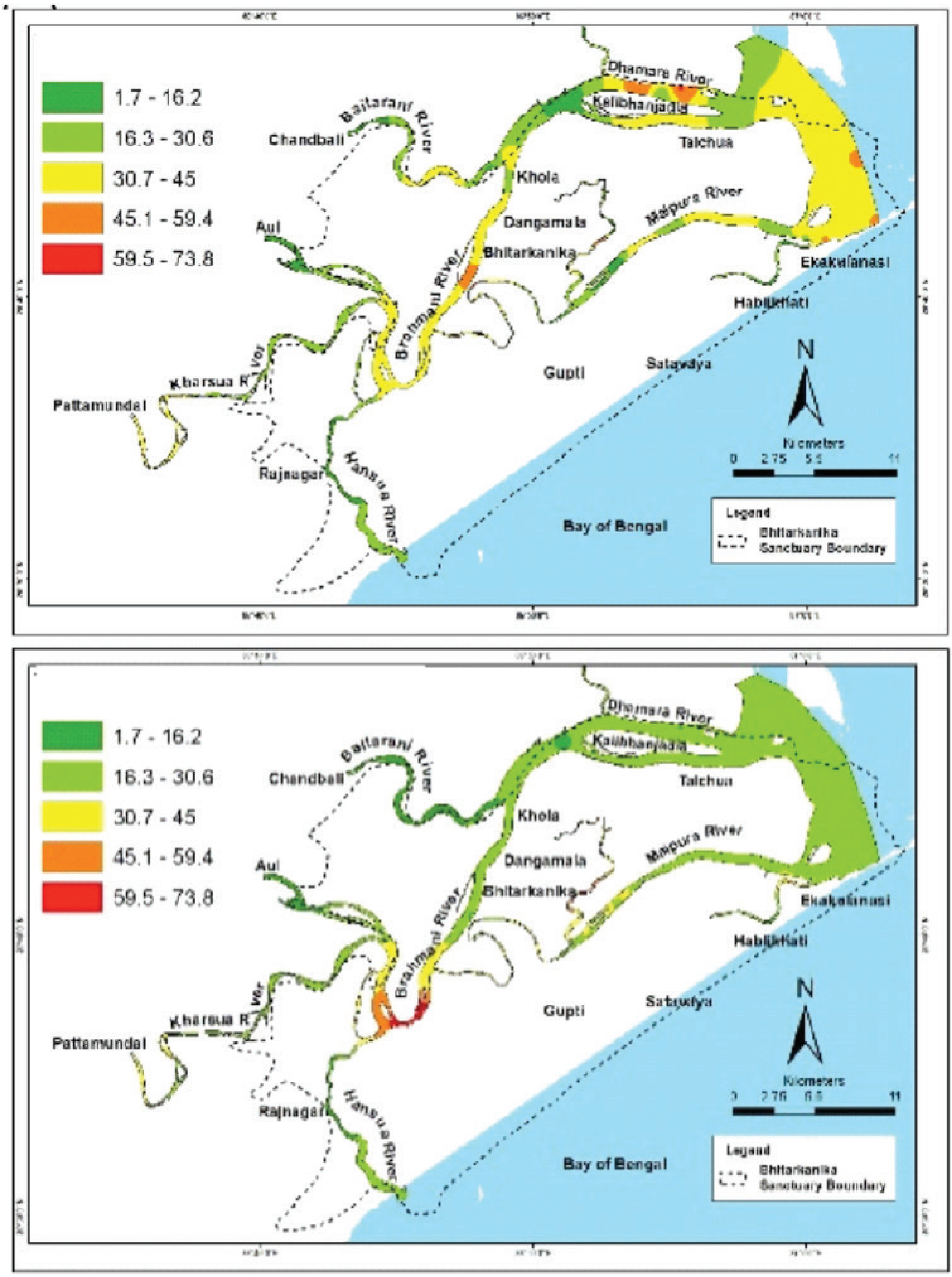


Figure 56 *Spatial variation of DIN in Bhitarkanika Sanctuary (a) during the monsoon and in winter*

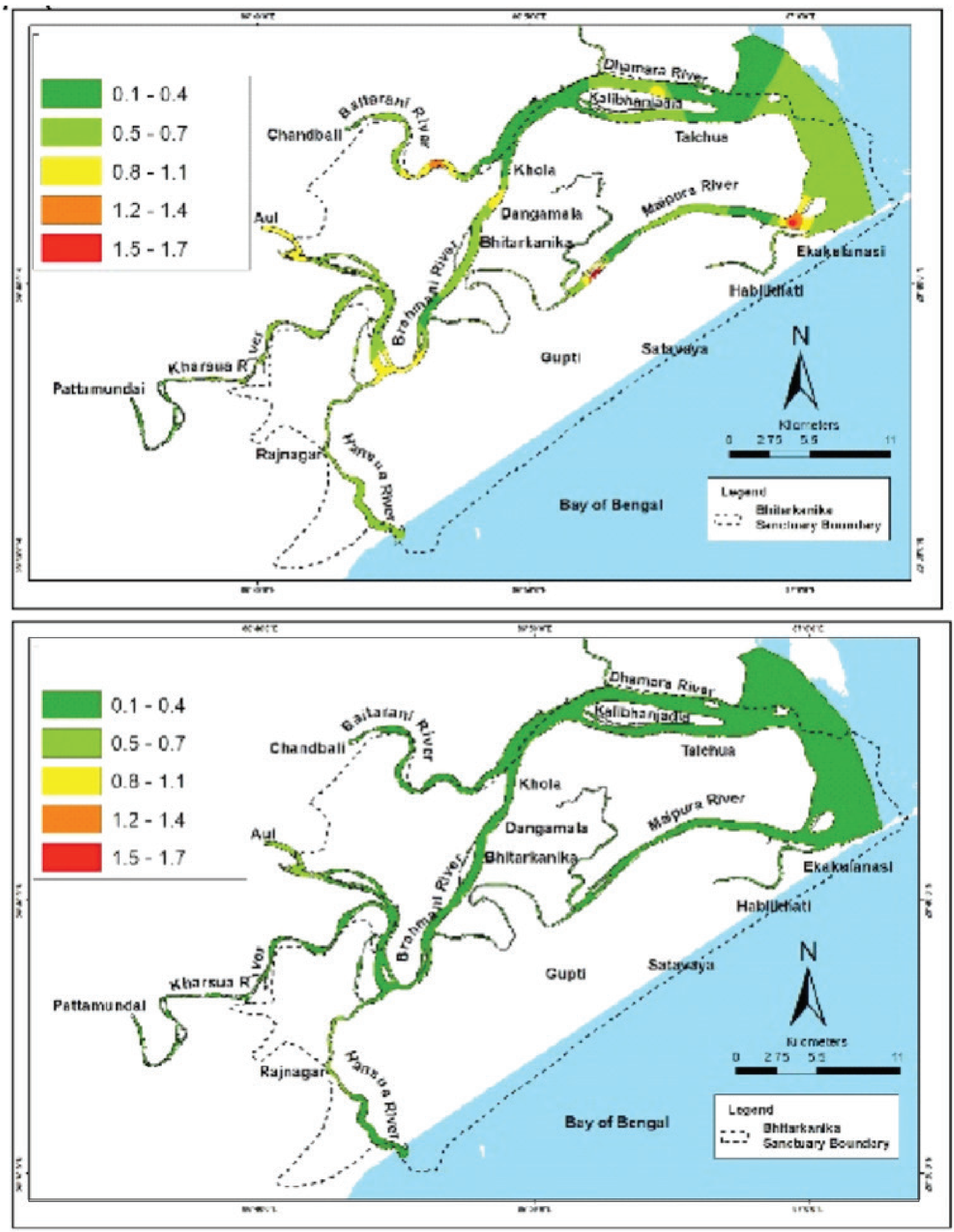


__Figure 57__ Spatial variation of DIP in Bhitarkanika Sanctuary (a) during the monsoon and in winter

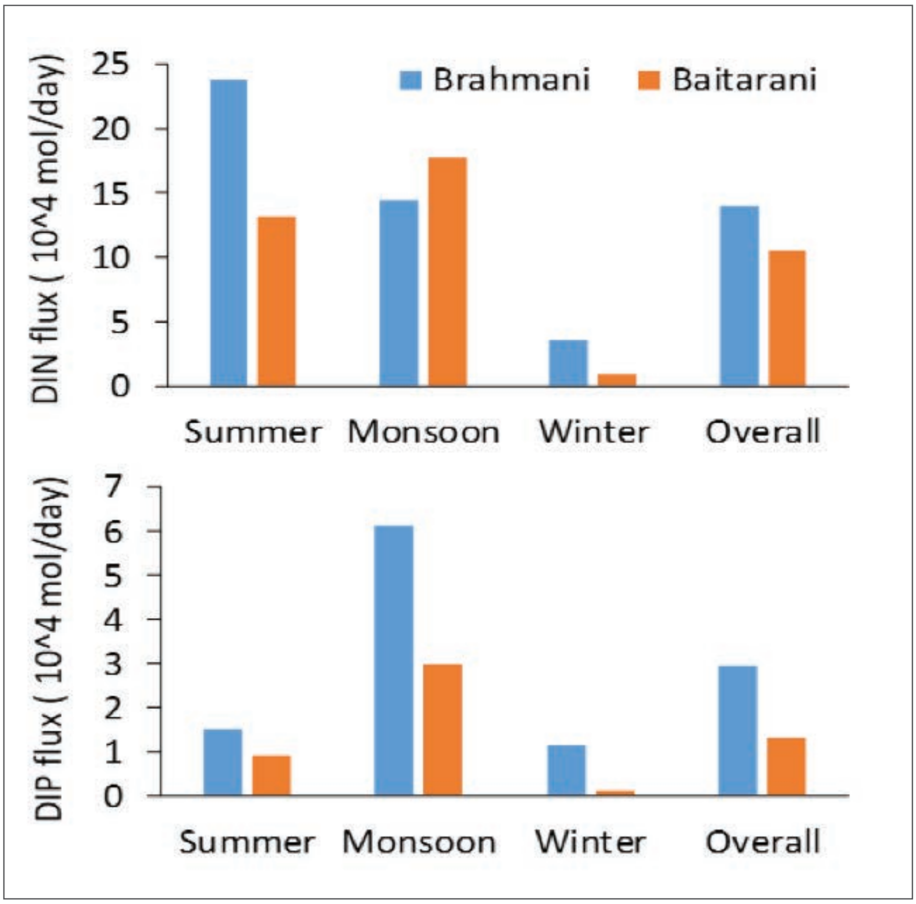


Figure 58 *Dissolved Inorganic Nitrogen (DIN) and Dissolved Inorganic Phosphorus (DIP) fluxes to Bhitarkanika Sanctuary from the major rivers, i.e., the Brahmani and the Baitarani*

9.2.4.2 Trophic status of Bhitarkanika Sanctuary

- The trophic status indicates if the ecosystem needs any management action, depending on the trends observed for a long period. For example, if any aquatic ecosystem remains in a eutrophic or hyper-eutrophic condition consistently for years, it needs attention of wetland managers.
- The trophic status of the sanctuary, i.e., oligotrophic, mesotrophic, eutrophic or hyper eutrophic, was evaluated on the basis of the trophic level index (TLI) in the monsoon and winter, following Burns et al. (2005) using the Secchi disk depth, chlorophyll- a concentration. total nitrogen and phosphorous.
- During the study period, the overall TLI was found to be 4.1 which is very close to the level of the eutrophic condition (TLI = 4), which indicated that the sanctuary was in a nutrient-enriched state.
- In winter, the sanctuary remained in a mesotrophic condition (TLI = 3.9), which indicated a moderate elevation in nutrient concentrations. However, it switched over to a eutrophic condition (TLI = 4.3) in the monsoon, which indicated a nutrient-enrichment state. The eutrophic status maintained during the monsoon is not alarming as the index value is just close to the eutrophic regime. Further, the shift in nutrient regime is due to seasonal variability.
- The trophic status of the sanctuary with respect to sampling locations in monsoon and winter has been shown in the diagram below, which clearly shows that almost all the locations in winter are within the mesotrophic range, whereas it switches to a eutrophic regime during the monsoon.

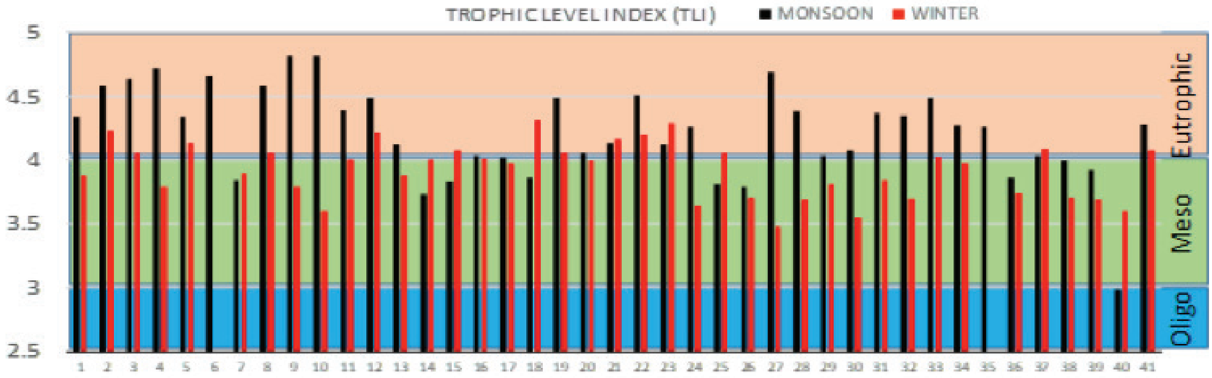


Figure 59 *Trophic level index (TLI) of Bhitarkanika waters during the monsoon and in winter*

9.2.5. Variability of DO level in Bhitarkanika Sanctuary

A very low DO level may be lethal to aquatic animals and is an indication of a deterioration of the ecosystem that requires immediate steps. Hence, it is a vital indicator parameter of the health of the ecosystem. A DO level >3.0 mg/l must be maintained for the survival of aquatic lives, propagation of wildlife and fisheries as per the environment protection rules of India (CPCB New Delhi 1986). In Bhitarkanika Sanctuary, the DO varied between 3.11 and 9.65 mg/l, with an average of 5.97± 1.50 mg/l during the monsoon. In winter, the DO level was significantly raised (4.69–12.6 mg/l, with an average Of 8.56± 1.64 mg/l). The overall DO recorded during the study period was 7.12 ± 2.02 mg/l (3.11–12.6 mg/l), which is in the desirable range (>3 mg/l) prescribed by CPCB.

During the monsoon, the DO saturation (DO%) of the sanctuary were found to be mostly under-saturated, except at

a few locations close to the Maipura river and Aul (Figure 60). However, the sanctuary water remained super saturated in winter as we recorded a DO% value of 109%, varying from 57% to 156%, with ~70 of data shown super-saturated. It is a good indication of the ecosystem health. The under-saturated condition in the monsoon could be due to high turbidity, which hinders light penetration and photosynthetic activity, the source of oxygen in the pelagic compartment. Further, the reduced DO level also could be attributed to the increasing oxygen consumption for decomposition of organic matter in highly turbid waters. A similar observation of DO saturation shifts between the monsoon and winter also been reported by the latest study conducted by the NCSCM, in 2019. The spatial variation in the DO% can be clearly observed from the plot below.

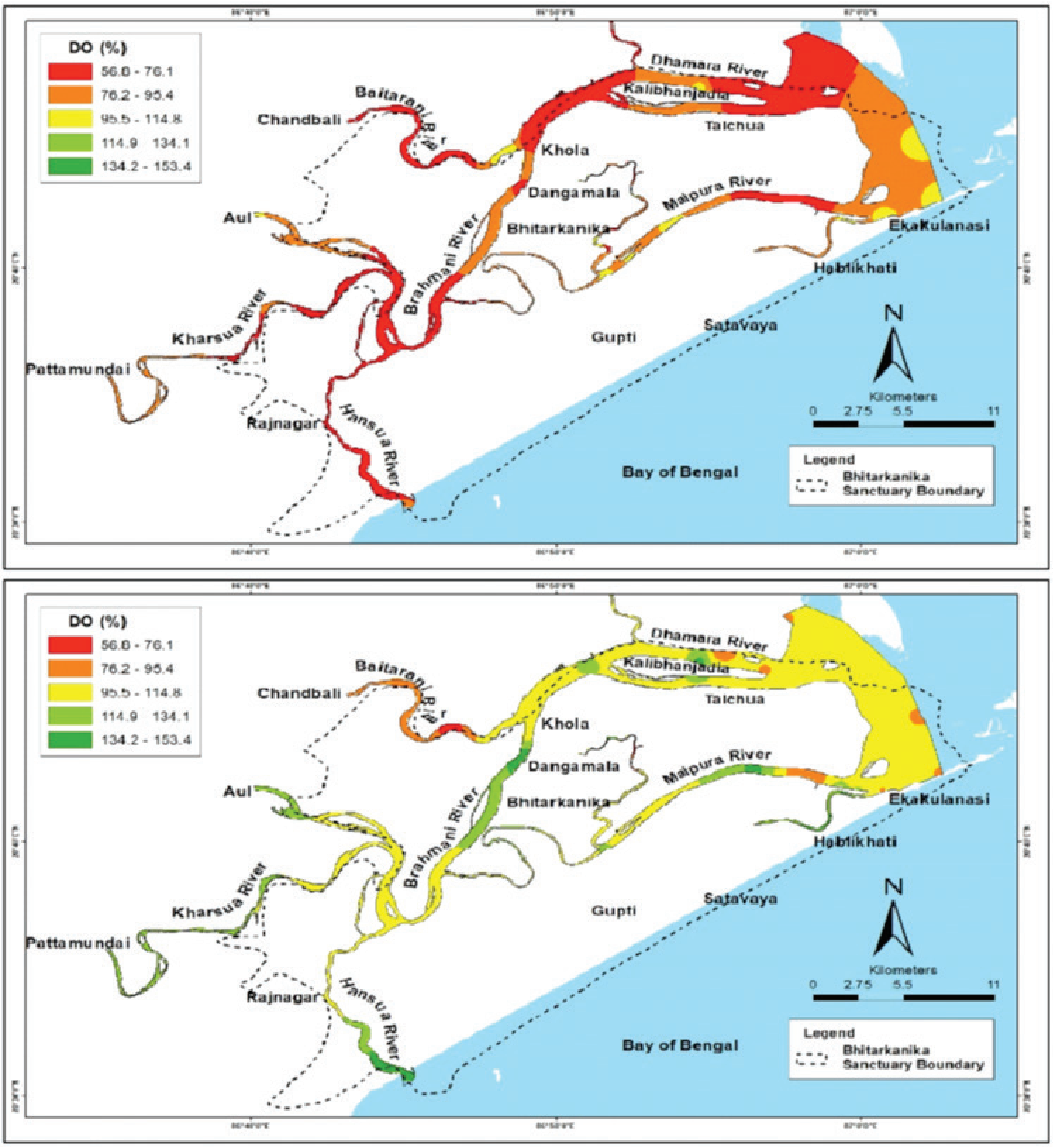


Figure 60 *Spatial distribution of DO% (DO saturation) in Bhitarkanika Sanctuary and major rivers*

9.2.6 Spatial distribution of FC in Bhitarkanika Sanctuary and major rivers

The presence of faecal contamination is an indicator of a potential health hazard to individuals exposed to the water. FC may occur in ambient water due to spillage of domestic waste water or non-point sources of human and animal waste. FC concentrations of the Bhitarkanika Sanctuary and major rivers were compared with CPCB guidelines for Class SW-II waters (> 100 MPN/100 ml, threshold value).

The MPN index of most of the Bhitarkanika stations (Station 2, 5, 6, 7, 10, 11, 16, 17, 30, 32 and 39) displayed > 100 MPN/100 ml in presumptive test during the monsoon. However, all of the stations of Bhitarkanika showed below 100 MPN/100 ml in winter as shown in the Figure 68. Only Station. 5, 7, 11 and 17 in monsoon and Station 10, 21, 32 and

41 in winter showed positive confirmatory result (presence of green metallic sheen colonies on EMB agar plates). The average MPN index of Bhitarkanika Sanctuary was found to be significantly higher in the monsoon (327) than in winter (6). For rivers, the average MPN index values in the monsoon and in winter were 61 and 2 MPN/100 ml, respectively. The monsoon rains bring a heavy load of surface runoff, including coliform bacteria (mainly of faecal origin), into the sanctuary. Due to the influx of surplus agricultural, industrial and domestic waste water discharges, higher FC counts may be observed during the monsoon. Chandran and Hatha (2003) demonstrated that sunlight is a major inactivating factor of FC in estuarine waters. This could be the reason for the declined FC levels in the non-monsoon months.

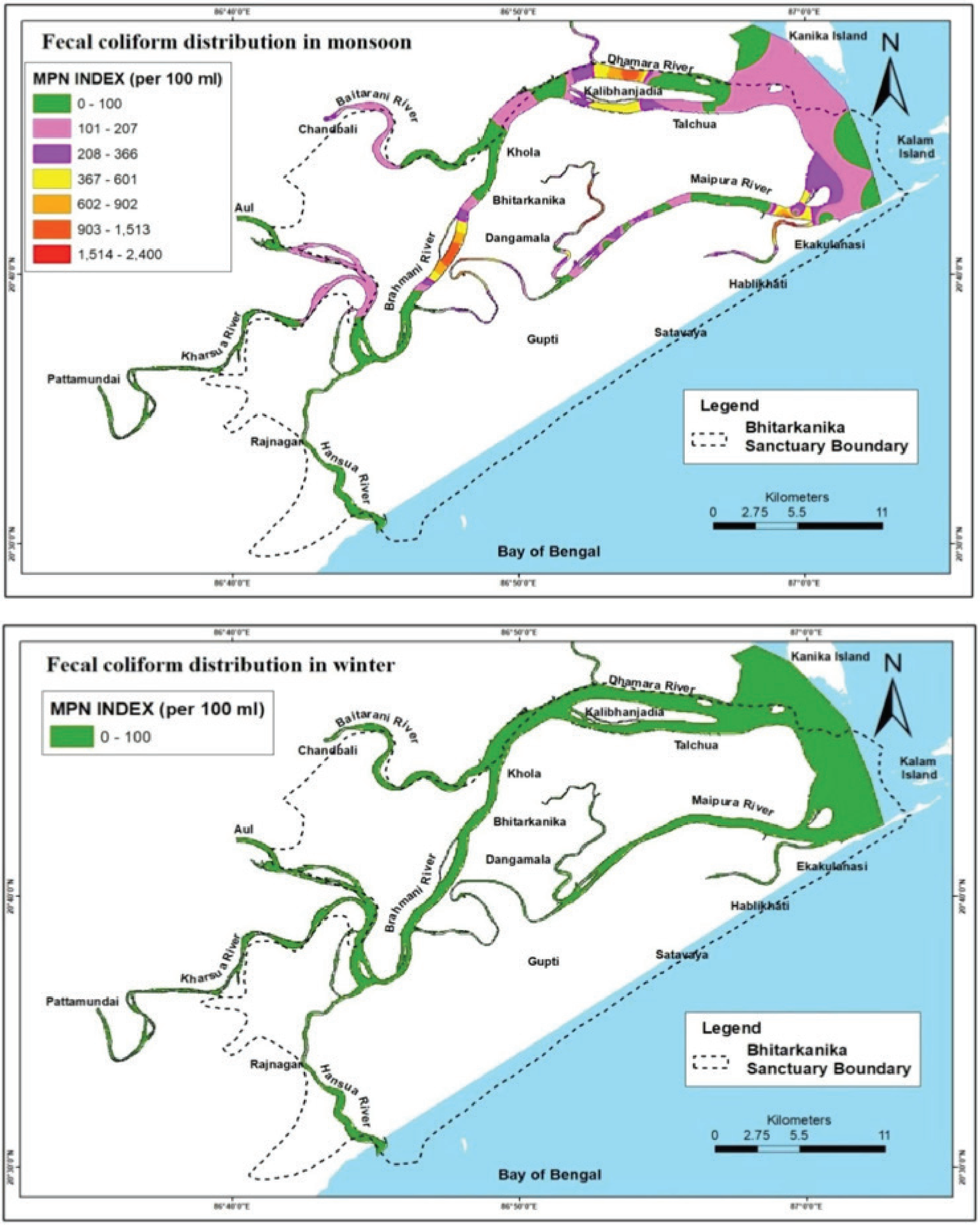


Figure 61 Spatial distribution of FC in Bhitarkanika Sanctuary and major rivers

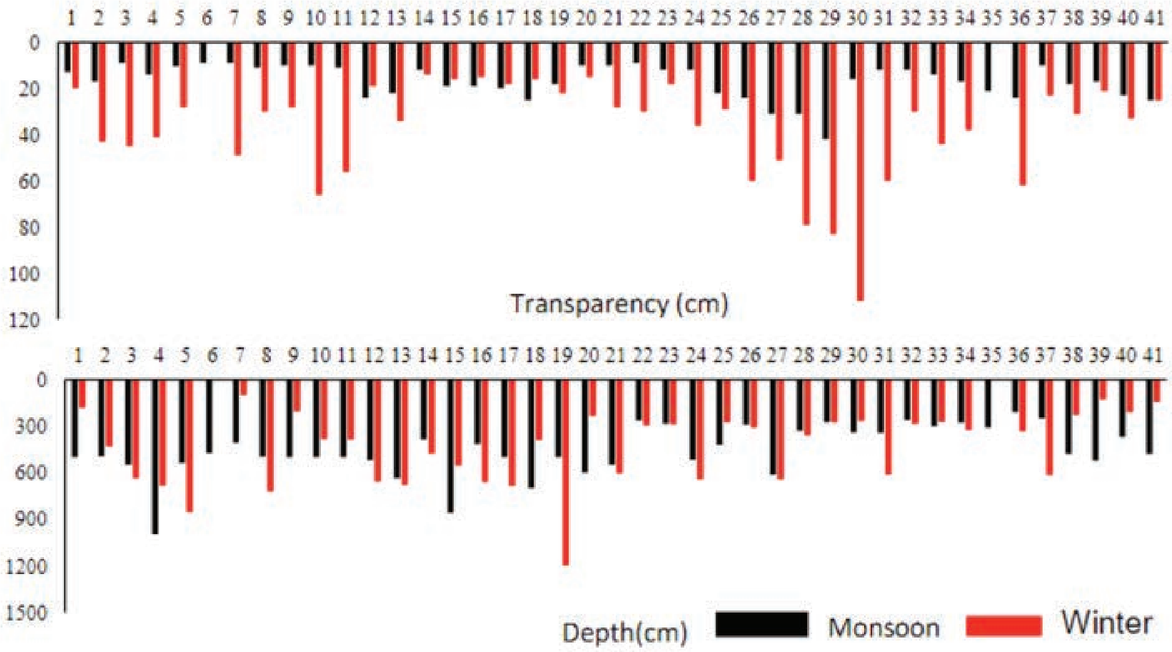
9.2.7 Variability of other physico-chemical parameters in Bhitarkanika Sanctuary and major rivers

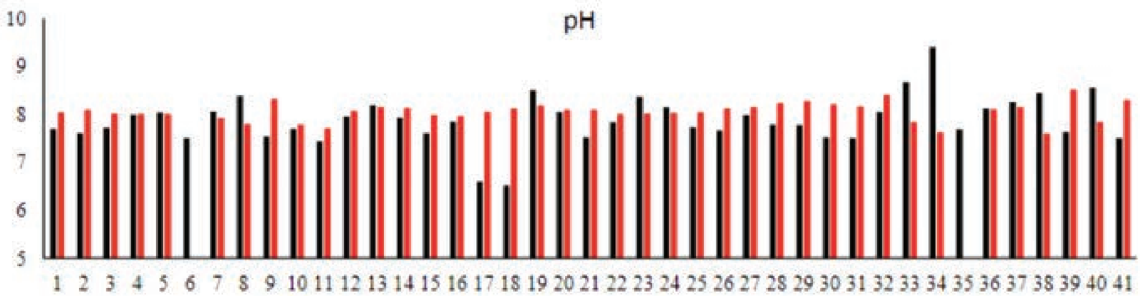
- Depending on the values and services of an aquatic ecosystem, the variability of the physico-chemical parameters plays a crucial role in maintaining the health of the ecosystem. Significant deviations from the safe limit or threshold consistently for a long period indicate that the ecosystem needs the attention of the responsible management authority.
- The basic water quality parameters were compared with the thresholds prescribed by the environment protection rules of India (CPCB New Delhi, 1986) for the propagation of wildlife and fisheries. The results, summarised in the table 17, indicated that all the parameters were within the thresholds.

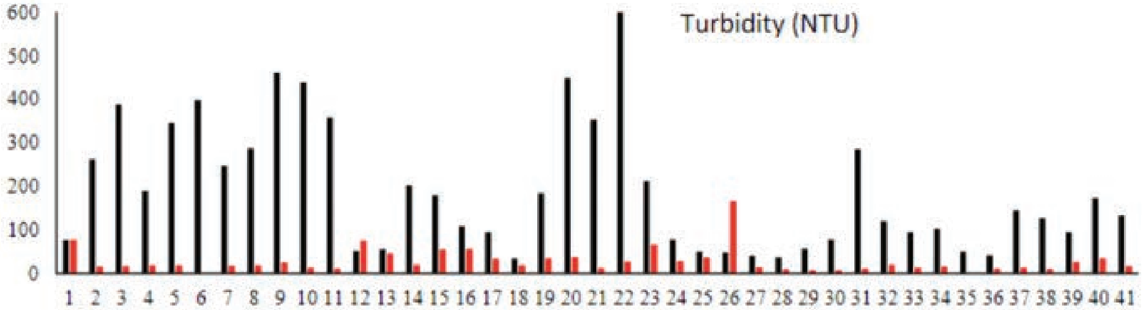
***Table 17** CPCB thresholds used in Bhitarkanika Health Report Card assessment*

	pH	DO	DO saturation	BOD	FC
CPCB threshold	6.5 to 8.5	> 4 mg/l	> 50%	< 3 mg/l	<100/100 ml (MPN)
Monsoon	7.38	5.93	81.25	1.33	327
Winter	7.56	8.56	109.30	1.76	6
Overall	7.47	7.25	95.28	1.54	166.5

- The temperature can play a critical role for mangrove growth rate in Bhitarkanika. In the present study, during the monsoon the air temperature (AT) of Bhitarkanika was in the range from 29°C to 37°C, with an average of 32.47 ± 2.02°C, while in winter it dropped down to 29.32 ± 2.72°C (25°C to 33.5°C). In both the seasons the AT > 20°C, which is favourable for mangrove growth.
- Similarly, the water temperature (WT) ranged between 30°C and 34°C, with an average of 31.31°C ± 1.13°C in the monsoon, and dropped to 25.42°C ± 1.73°C (23°C to 30°C) in winter. Hence the WT difference between the seasons was ~5°C, which will be tolerable for the mangroves of the sanctuary as a higher temperature difference could inhibit the growth of the mangroves.
- The present study recorded an insignificant change in the TA during the monsoon (1.07 to1.98 mmol/l, with an average of 1.55 ± 0.25 mmol/l), and in winter (1.03 to 2.03, with an average of 1.48 ± 0.21 mmol/l) which indicated that the climatic and geological factors and changing the type and amount of ions transported from the rivers and rivulets (that drain into the sanctuary) had a minor role that could have changed the buffering capacity of the water. The recorded values match well with those of the recent survey, conducted during 2018–19 by NCSCM (NCSCM Annual Report), as well as other published values for Bhitarkanika Sanctuary (please refer to the status and trend table).
- The variability of the water quality parameters at all the stations in the two seasons is shown in the accompanying bar plot. (Figure 62 & 63)


Transparency (cm)
Depth(cm)
Monsoon
Winter


pH


Turbidity (NTU)

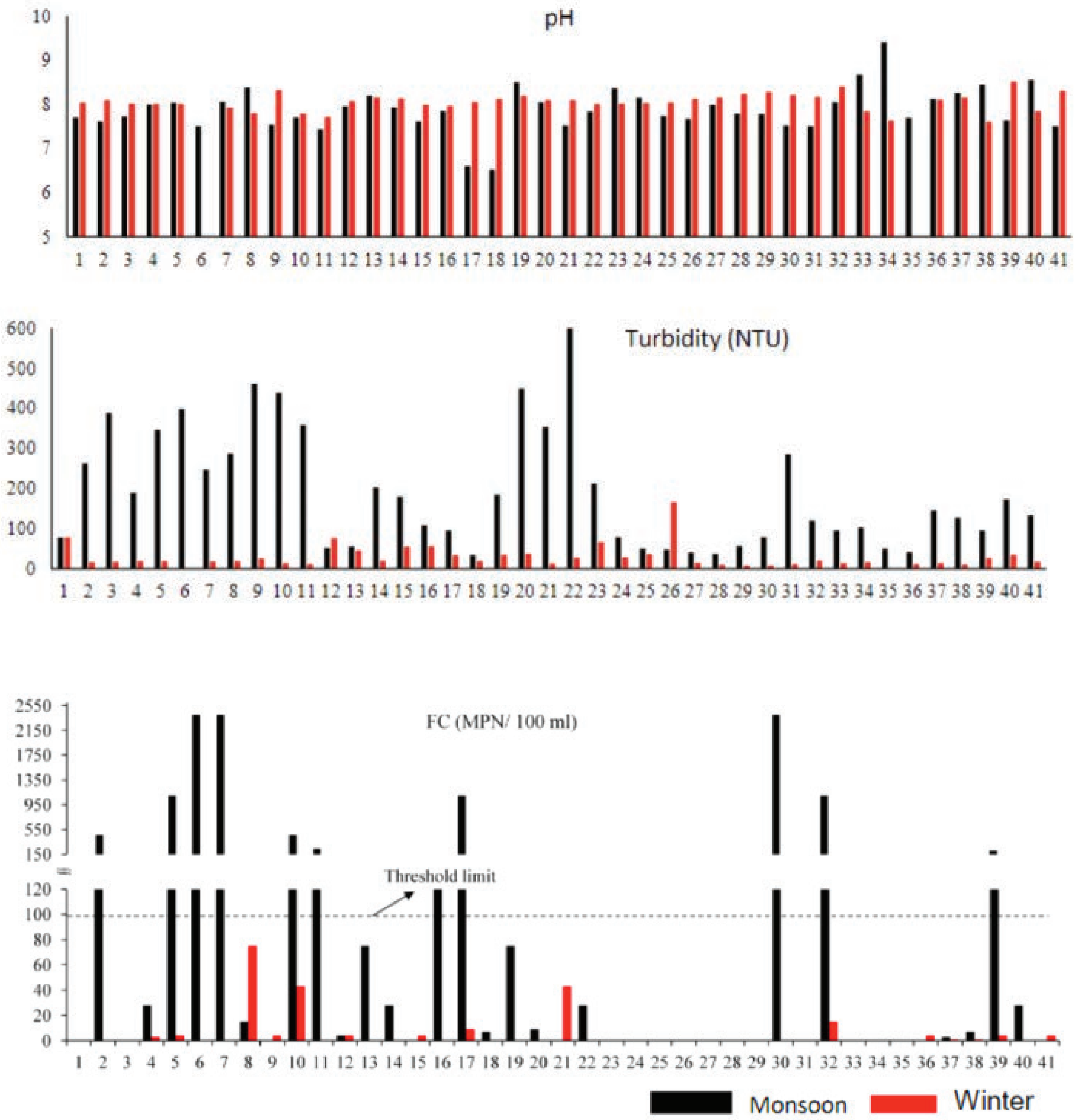
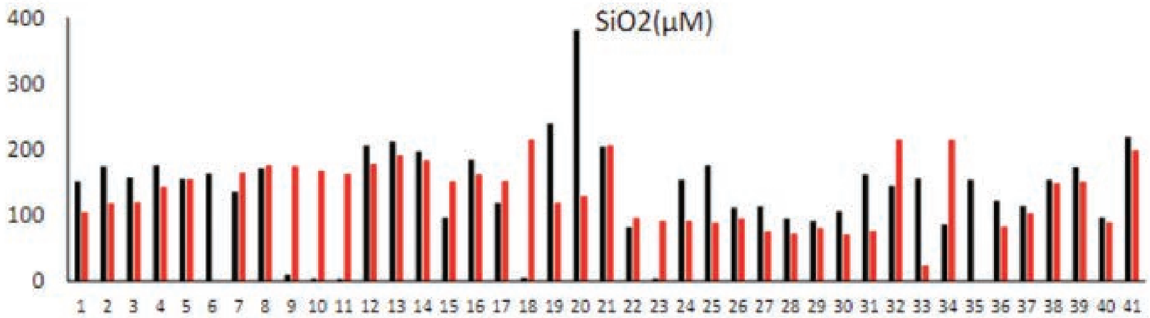
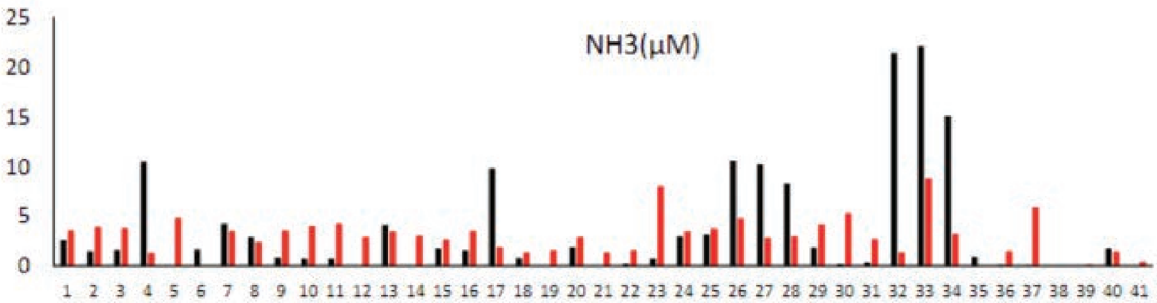
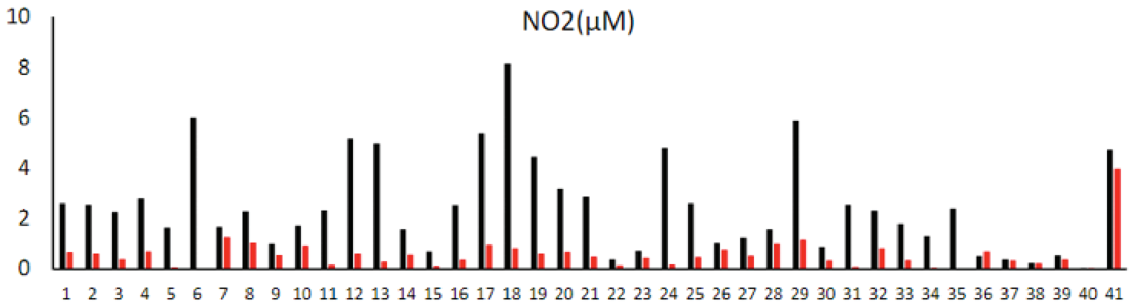
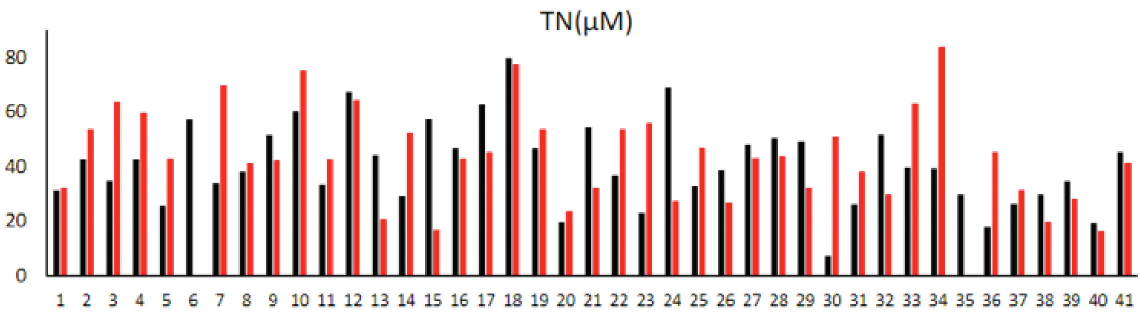


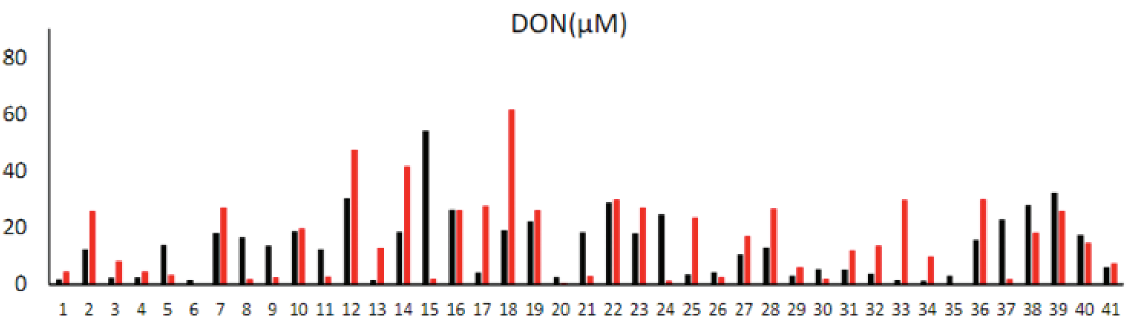
Figure 62 *Variation of physico-chemical parameters of Bhitarkanika Sanctuary and major rivers during the monsoon and in winter*


SiO2(μM)
400
300
200
100
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41


NH3(μM)
25
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41


NO2(μM)
10
8
6
4
2
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41


TN(μM)
80
60
40
20
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41


DON(μM)
80
60
40
20
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41

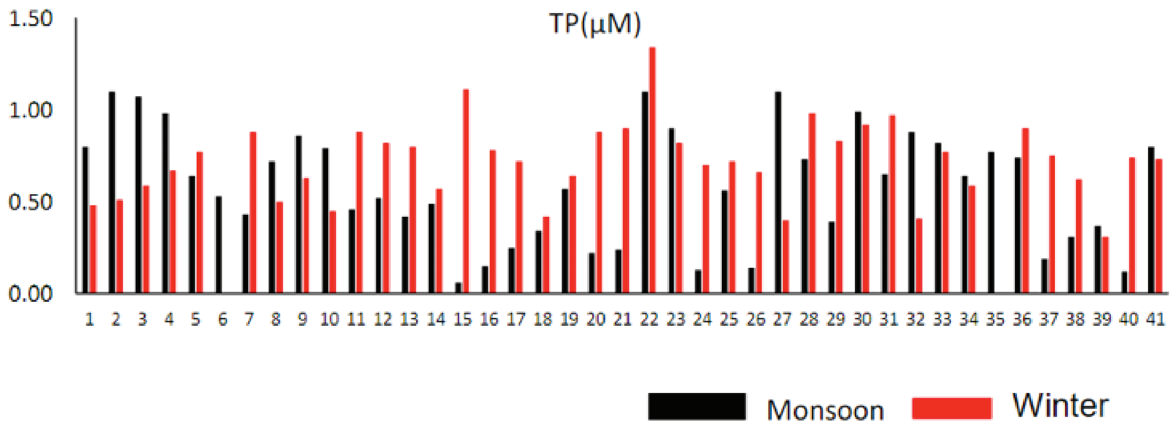


Figure 63 *Variation in nutrient concentration of Bhitarkanika Sanctuary and major rivers during the monsoon and in winter*

9.3 Physico-chemical analysis of sediments

9.3.1 Total organic carbon

The TOC in the sediments collected from the sanctuary ranged from 1.725% to 2.295% during the monsoon and in winter. This indicated the blue carbon storage potential of the Bhitarkanika mangrove forests, which serve as a carbon sink (Bal & Banerjee, 2019). Mangrove sediments store carbon from litter, roots, dead plants and animals, tidal allochthonous material, etc. in the sanctuary. Mukherji et al., (2019) have shown that the major source of organic carbon (OC) in sanctuary is of terrestrial/mangrove origin, followed by marine sources.

Bal & Banerjee (2019) reported that the average concentration of soil organic carbon was 3.73 ± 2.10 tonnes ha−1 and that the average litter carbon was 0.59 ± 0.20 tonnes/ha. The total stored carbon in the stems of some selected species of Bhitarkanika Sanctuary was found to be 61.97 tonnes/ha (Mukherji et al., 2017). According to Banerjee et al. (2019), the total carbon (AGB + soil organic carbon) storage potential in Bhitarkanika Sanctuary is 149.07 ± 38.32 tonnes/ha, which was estimated considering five species of mangrove, i.e., *Avicennia marina, Avicennia officinalis, Excoecaria agallocha, Rhizophora mucronata* and *Xylocarpous granatum.*

9.3.2 Available nitrogen (AN)

The AN concentration in the sediments of Bhitarkanika Sanctuary was found to be 0.022 ± 0.035% during the monsoon and 0.010 ± 0.006% in winter. The available nitrogen was found to be 0.010% in Bhitarkanika sediments in 2015 (Behera et al., 2018), which is consistent with our result. The percentage of AN recorded in most of the sanctuary regions was higher than in the rivers.

9.3.3 Soil texture (sand and silt/clay)

Sediments of Bhitarkanika Sanctuary displayed loamy sand, and those of the major rivers displayed sand (coarse in texture). During the monsoon and in winter, sand dominated the sediments, i.e., 87.40% to 87.84%, whereas the silt/clay content was 12.60% to 12.14% in the sanctuary. This finding is consistent with a previous study conducted in 2015 in the sanctuary, which showed a sandy texture both during the monsoon (71.04% ± 4.50%) and in winter (77.62% ± 6.06%) (Behera et al., 2018). During the monsoon and winter, sand dominated the sediments, i.e., 94.10% to 91.02%, whereas the silt/clay component was 5.90% to 8.99% in the river sediments. The percentage of sand was higher in the major river stations compared with the sanctuary regions.

Table 18 *Comparison of chemical parameters of sediments in Bhitarkanika Sanctuary during the monsoon and in winter in 2020*

Location	Parameters	Monsoon		Winter	
		Mean	Range	Mean	Range
Sanctuary	TOC (%)	1.725 ± 0.775	0.134–4.219	2.295 ± 1.357	0.344–5.703
	Silt/clay (%)	12.60 ± 6.09	3.18–26.98	12.16 ± 6.58	1.76–36.86
River	TOC (%)	1.786 ± 1.089	0.603–2.746	2.061 ± 1.586	0.481–4.123
	Silt/clay (%)	5.90 ± 0.87	5.36–6.90	8.99 ± 2.98	7.14–13.38

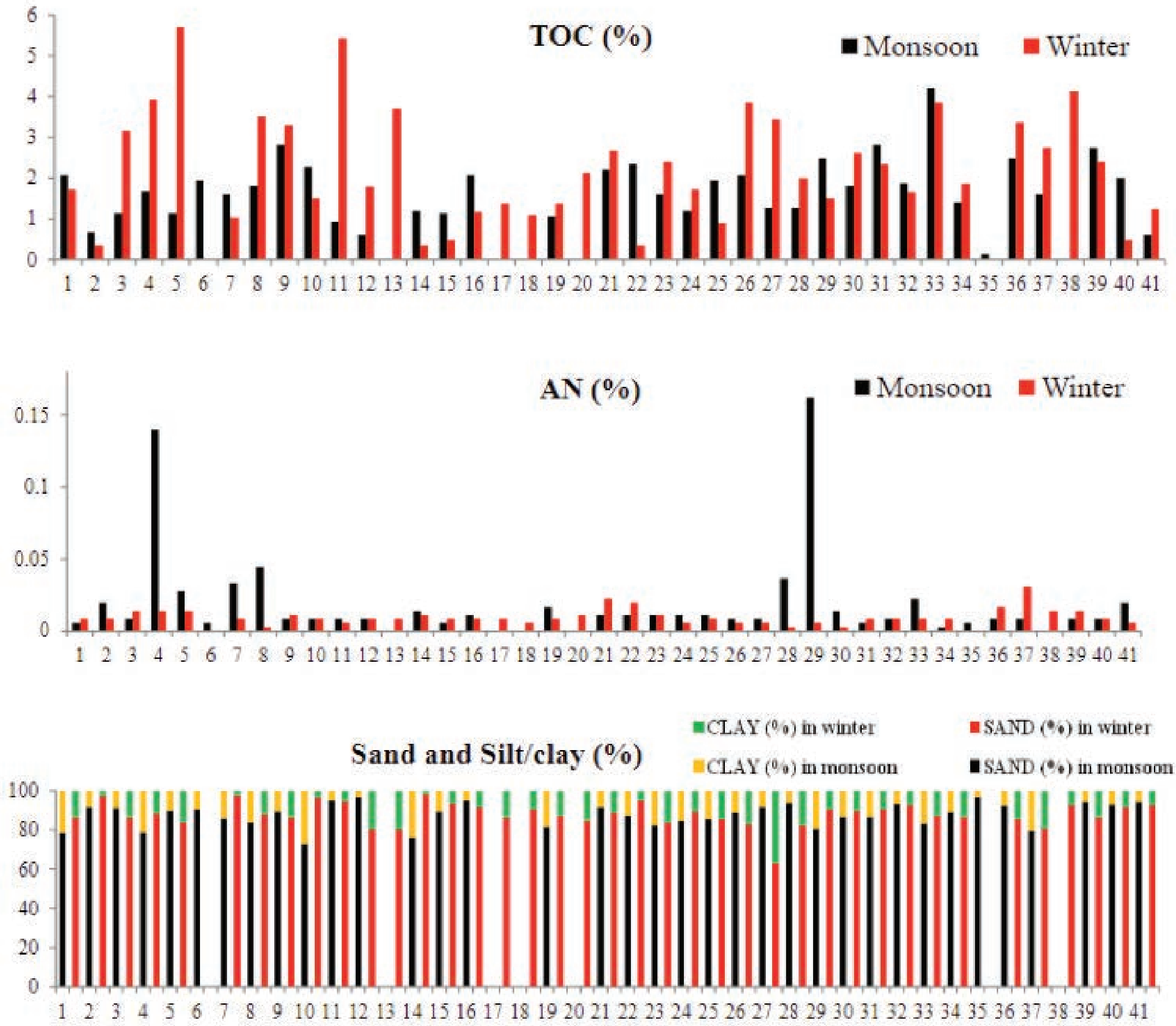


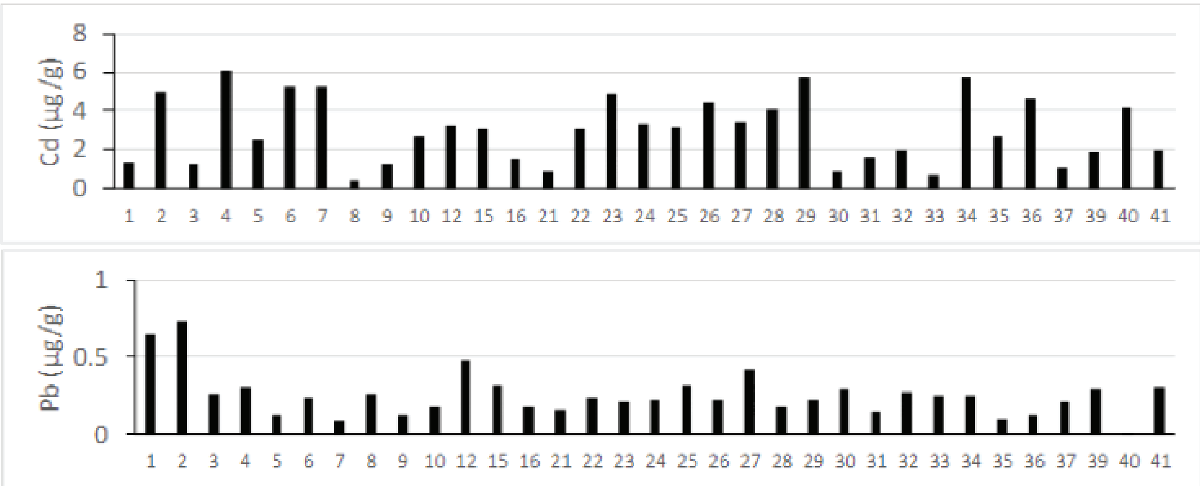
Figure 64 *Variation in sediment quality parameters of Bhitarkanika Sanctuary and major rivers during the monsoon and in winter*

9.3.4. Assessment of heavy metals in sediments of Bhitarkanika Sanctuary

- Assessment of pollution status is a key to the formulation of a management action plan. Since river water is vulnerable to several anthropogenic inputs, including trace metals, it must be monitored to know the pollution level in the rivers as well as in the estuarine and coastal ecosystems it passes through.
- To assess the pollution status, the sediment samples were collected from 33 stations during the monsoon to determine the Cu, Cd, Pb, Zn, Mn and Fe levels. The variations with respect to season are shown as a bar plot, and a comparison of the average value against the standards prescribed by USEPA is shown in table 19.
- Sediment samples were collected from 33 stations during the monsoon for determining the Cu, Cd, Pb, Zn, Mn and Fe levels. The variations with respect to season are shown as a bar plot, and a comparison of the average values against the standards prescribed by USEPA is shown in the accompanying table.
  - ~ The ranges of all metal concentrations in Bhitarkanika sediments were found to be below the standards prescribed by USEPA.
  - ~ An excess of heavy metal could have an adverse effect on the mangroves of Bhitarkanika such as (i) inhibition of the growth process of the above-ground and underground parts and early deterioration (Prasad et al., 2006), (ii) reduction in carbon assimilation, survival and reproduction (Vangronsveld et al., 1994) or (iii) decreasing the chlorophyll content in mangrove species (Yan et al., 2017).

Table 19 *Heavy metals in the sediments of Bhitarkanika as compared with standards set by USEPA*

Heavy metals	Present study range (μg/g)	USEPA (1999) sediment standards (μg/g)
Cu	0.07–2.1	31.6
Cd	0.44–6.1	0.99
Pb	0.01–0.73	35.8
Zn	0.6–13	121
Mn	2–11	N/A
Fe	58–426	N/A



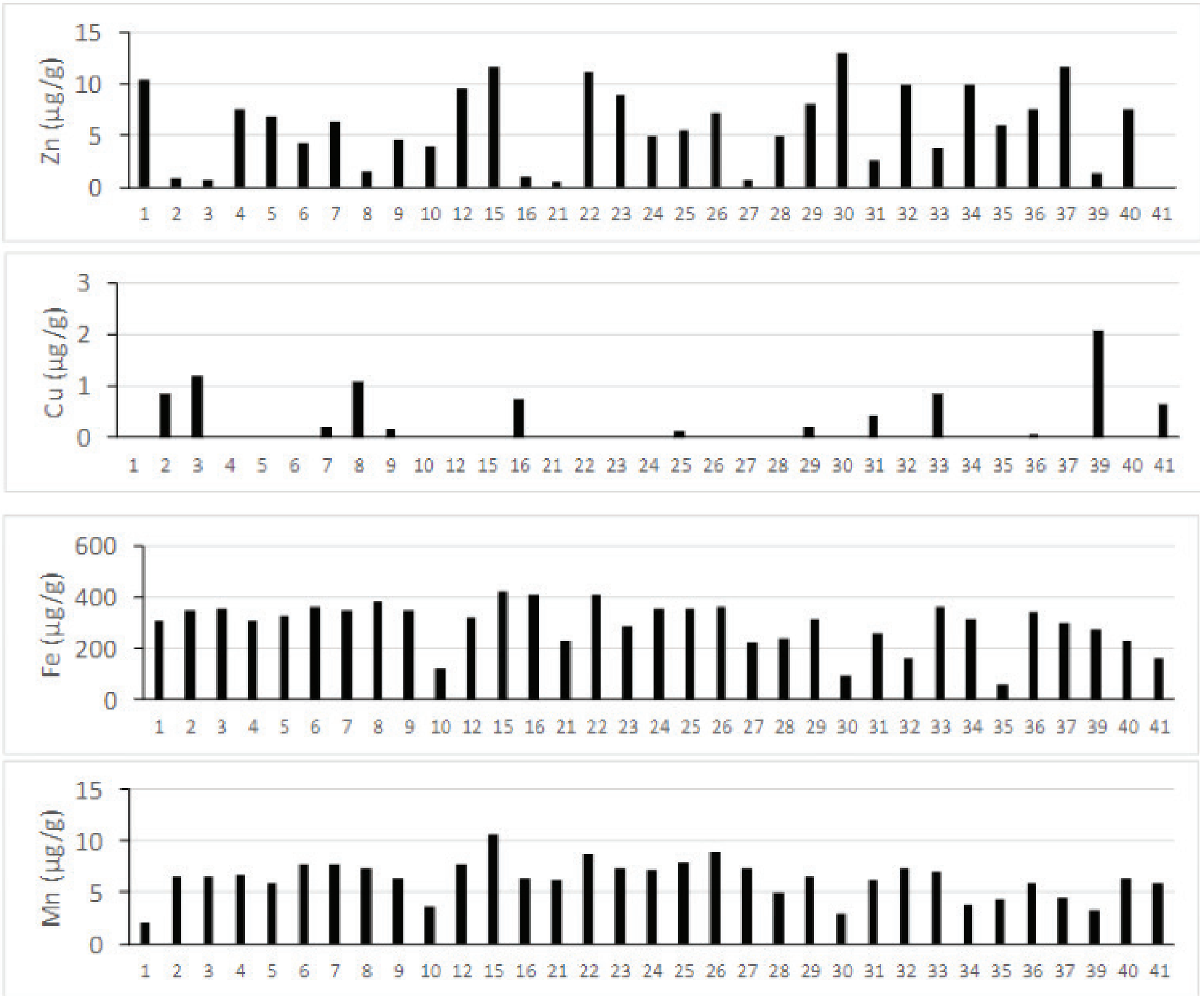


***Figure 65** Variation of trace metal concentration in sediments of Bhitarkanika Sanctuary and major rivers during the monsoon. The bars with zero values indicate that the particular metal concentration was below the detection limit.*

9.4 Health status of Bhitarkanika Sanctuary with respect to water quality

Long-term scientific data on the health status of an ecosystem help wetland managers understand the ecosystem behaviour as well as the adverse factors influencing the health of the ecosystem. Developing such a database is very useful when making a management action plan for the ecosystem of interest. The health report card is the simplest form of complex scientific data presentation. It can be easily understood by all stakeholders. Data collected by CDA during the monsoon and in winter in 2020 were considered for the purpose of preparing the health report card. In situ water quality parameters, viz., pH, DO, transparency, BOD, DIN, DIP and FC, were considered for the score calculation as shown in table 20. The thresholds considered were the following:

***Table 20** Water quality parameters and their threshold values used in health status assessment of Bhitarkanika Sanctuary*

Parameter	Units	Values / range in the mangrove region	Published / prescribed threshold values
pH		6.5–8.5	CPCB, 1978
Trans	cm	≤ 20	U.S. EPA ,1976

Parameter	Units	Values / range in the mangrove region	Published / prescribed threshold values
DO	mg/L	> 3	CPCB, 1978
BOD	mg/L	≤ 3	CPCB, 1979
Chl a	mg/L	< 3.4	NCSCM, 2019
DIN	µM	≤ 30	Bricker et al., 2003
DIP	µM	<1.75	Bricker et al., 2003
FC	MPN/100 ml	≤ 100	CPCB, 1993

Grades are assigned + or – (e.g., B+ or B-) if the attainment scores are within 4% of the cut-off between grades. For example, 87% will equate to B+, whereas 82% will equate to a B- and 92% will equate A-.

Table 21 *Grade, colour code and scores used in water quality score assessment of Bhitarkanika Sanctuary*

Report card grade	Indicator	Percentage of data Score	
A		90 – 100	Excellent
B		80 – 90	Good
C		70 – 80	Moderate
D		60 – 70	Poor
E		0 – 60	Very poor

- The overall score of the sanctuary was 87%, which indicated that the ecosystem maintained good health during the study period.
- During monsoon, the sanctuary scored B-, indicating “good” health of the ecosystem, which turned to “excellent” in winter.
- The lower transparency (higher turbidity) of the water was the major factor responsible for lowering the scores required for “excellent” water quality during both the seasons.

Table 22 *Scores obtained by individual water quality parameters*

	DO	BOD	Chl-a	pH	Transparency	DIP	DIN	FC	Overall
% obs (monsoon)	95	100	100	95	32	100	51	73	81
% obs (winter)	100	100	100	100	74	100	70	100	93
% obs (overall)	98	100	100	98	51	100	61	87	87
Threshold	>= 4 mg/l	< 3	< 3.4	> 6.5	> 20 cm	≤ 30	<1.75	≤ 100	
Grade (monsoon)	A	A	A	A	E	A	E	C	B-
Grade (winter)	A	A	A	A	C	A	C	A	A-
Grade (overall)	A	A	A	A	E	A	D	B	B+

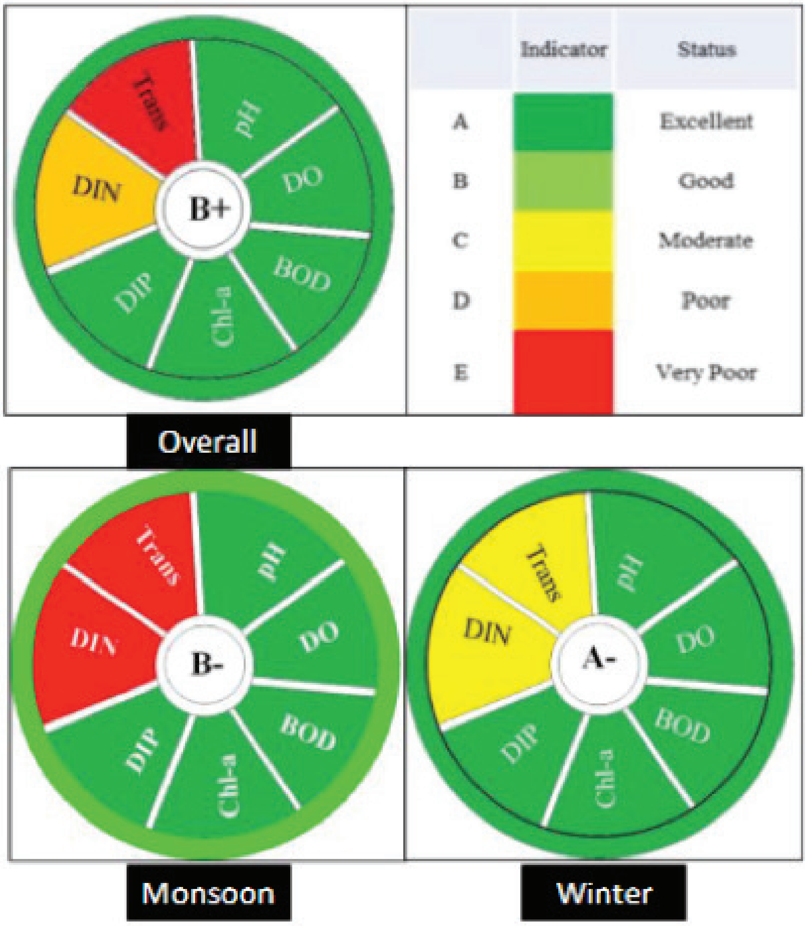


Figure 66 Pictorial representation of scores obtained by water quality indicators of Bhitarkanika Sanctuary (B+, B- and A- indicate that the scores attained (87%, 82%, 92%, respectively) are within 4% of the cut-off between grades)

9.5 Key highlights of water and sediment quality assessment

- The health status of Bhitarkanika Sanctuary was found to be "good", with a score of 82% (grade B-) during the monsoon and "excellent", with a score of 92% (grade A-) in winter with respect to water quality indicators. The overall status was "good", with 87% of the parameters within the desired threshold ranges.
- Most of the water quality indicators (pH, DO, BOD, Chl-a and DIP) indicated an "excellent" status (score > 90%).
- The water turbidity of the sanctuary and rivers was found to be higher than the threshold limit prescribed by CPCB, New Delhi (not suitable for wildlife propagation and fisheries) during the monsoon but was within the range in winter. Although the high turbidity indicated a very poor health status (32%), there is no cause for alarm as the turbidity is due to the seasonal monsoonal flow and subsides in the dry season, when there is no freshwater inflow.
- The organic load (presented in terms of BOD) in Bhitarkanika Sanctuary was within the threshold limit both during the monsoon and in winter.
- A trend analysis according to the SPCB data indicated there has been a significant decline in the organic load (in terms of BOD) in the Brahmani and Baitarani rivers in the last 17 years (2002–2019).
- The sanctuary experienced a more than twofold decline in salinity in the monsoon compared with winter due to the freshwater input from the rivers.

- The overall nutrient flux into the sanctuary from the Brahmani river was higher than that of the Baitarani river.
- The TLI indicated that in winter the sanctuary is in a mesotrophic condition (TLI = 3.9), which shifts to a eutrophic condition (TLI = 4.3) during the monsoon. The overall TLI was 4.1, which indicated that the sanctuary was in a eutrophic condition during the study period. The eutrophic condition in Bhitarkanika Sanctuary is not alarming as it is due to seasonal variability and is a reflection of the in situ biogeochemical process.
- The FC concentrations of both the sanctuary and the rivers were found to be higher than the limits allowed by CPCB (100 MPN/100 ml) during the monsoon but were within the range in winter.
- The water quality results of the major rivers and Bhitarkanika Sanctuary recorded during the monsoon and in winter in 2020 were within the range of values recorded in 2018 and 2019 by NCSCM, which are the only systematic water quality data available from after 2002, when the sanctuary was designated a Ramsar site.
- The TOC content of the sanctuary and rivers was found to be higher in winter compared with during the monsoon.
- A relatively low AN content was found in the sediments of Bhitarkanika and the major rivers both during the monsoon and in winter.
- The sediment texture in Bhitarkanika Sanctuary showed loamy sand, whereas the sediment of major rivers showed a sandy texture, indicating that most of the soil samples were rich in sand.
- All the metal concentrations in the Bhitarkanika sediments were within the ranges of the USEPA-prescribed standards.

9.6 Recommended parameters for hydrological monitoring and health report card, periodicity and methodology

The present study recommends having long-term wetland monitoring covering river input points, sea mouths and core areas of the sanctuary.

- **Where does it need to be done?**

  A total of 17 sampling locations covering the entire Bhitarkanika Sanctuary, including the proposed Mahanadi mangrove area and major rivers, has been proposed in the map (Figure 67), from which sampling may be carried out as per the recommended periodicity.
- **What parameters?**

  A total of 14 parameters are recommended for continuous monitoring as mentioned in Table 23. Parameters 1 to 8 can be used to prepare the health report card on an annual basis.
- **When and what frequency?**

  As mentioned for each parameter in Table 23.
- **What resources are required?**

  A monitoring laboratory facility in Bhitarkanika Sanctuary is recommended for undertaking systematic physico-chemical monitoring of the water and sediment quality of the sanctuary.

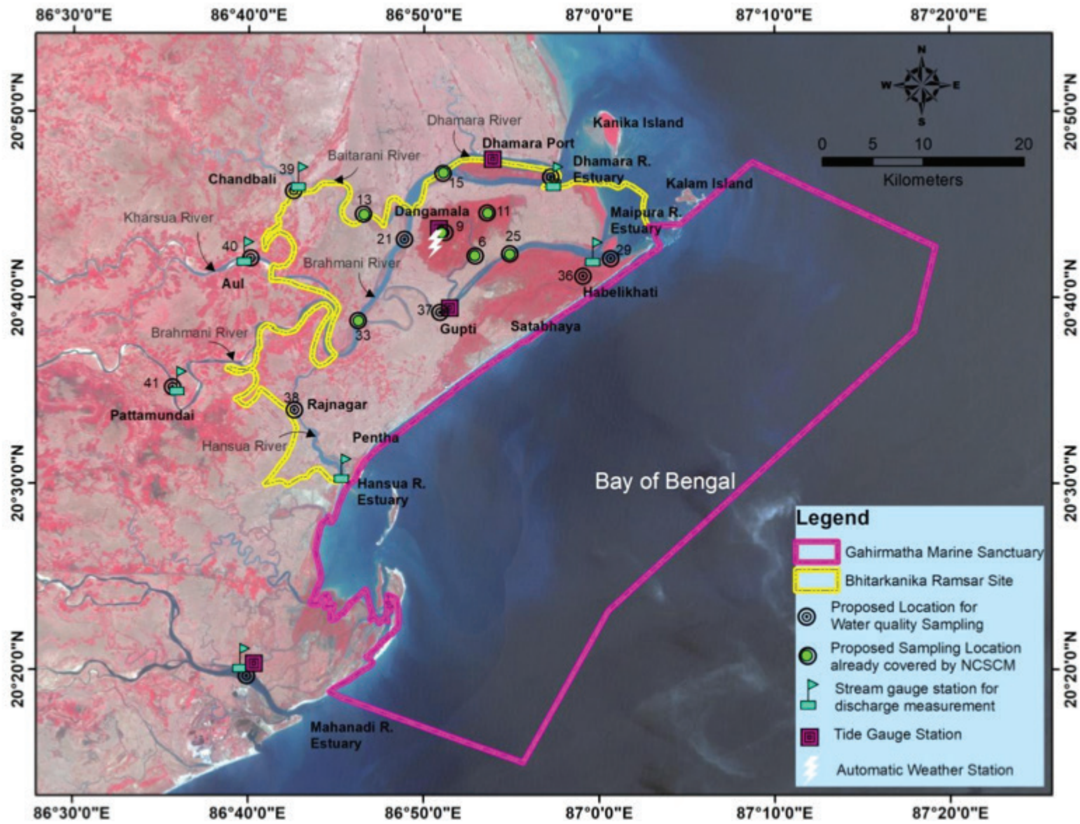


***Figure 67** Proposed sampling locations for long-term hydrological monitoring of Bhitarkanika Sanctuary*

***Table 23** Recommended parameters for monitoring and health report card assessment*

Sl. No	Parameters for wetland monitoring and preparation of health report card	Periodicity	Equipment to be used	Recommended protocol	Purpose
Physico-chemical					
1	Transparency	Seasonal	Secchi disc	-	General monitoring and health report card assessment
2	Salinity	Seasonal	Refractometer or conductivity probe/electrode	-	
3	DIN	Seasonal	Spectrophotometer	Methodology as as described in Grasshoff et al. (1999) for manual analysis	
4	DIP	Seasonal	Spectrophotometer	Methodology as described in Grasshoff et al. (1999) for manual analysis	
5	DO	Seasonal	Titration setup	APHA (2005)	
6	BOD	Seasonal	Titration setup	APHA (2005)	

Sl. No	Parameters for wetland monitoring and preparation of health report card	Periodicity	Equipment to be used	Recommended protocol	Purpose
Physico-chemical					
7	Chlorophyll-a	Seasonal	Spectrophotometer	Strickland and Parsons (1972)	
8	Faecal coliform	Seasonal	MPN method	Using coliform test kit	
9	Trace metals	Once in 3–5 years	Atomic absorption or optical emission spectroscopy	Thermo	General monitoring
10	Pesticides	Once in 3–5 years	Gas Chroma-tography-mass spectroscopy	Agilent/Thermo	
11	C, N, O isotopes	One time	Isotopic ratio mass-spectroscopy	-	
12	Organic and inorganic carbon	Seasonal	TOC analyser and Coulometrics	-	
Flora					
13	Mangrove diversity and distribution	Annual	Ground survey and remote sensing	-	
14	Phytoplankton diversity and distribution	Seasonal	Microscopic analysis	Monographs and taxonomic keys	

Research projects on hydrodynamic modelling, biodiversity and climatic change should be undertaken on a priority basis for the long-term management action plan. Alternatively, the analysis of the physicochemical parameters can be carried out through outsourcing to the State Pollution Control Board, Wetland Research and Training Centre (Chilika Development Authority) or to the National Centre for Sustainable Coastal Management (NCSCM), Chennai. Building the capacity of the research personnel may be done through networking with other coastal research laboratory facilities such as WRTC and NCSCM who have long-term experience in research and management of coastal Ramsar sites. The funding can be secured from the Odisha Forest and Environment Department and MoEFCC, Government of India.

10 COASTAL PROCESSES

10.1 Shoreline change

A shoreline change analysis was carried out for the coast of Bhitarkanika Sanctuary for the period from 1975 to 2020 using the Digital Shoreline Analysis System (DSAS) by CDA. The entire coast of the Bhitarkanika Sanctuary region (north of the Hansua river to Ekakula Nasi), of length 38 km, was considered for shoreline change analysis.

The shoreline changes in the last 45 years (1975–2020) were analysed to understand the erosion and accretion pattern. With reference to the baseline, the erosion (landward movement of the shoreline) and accretion (seaward movement of the shoreline) were identified. A small stretch north of the Hansua river mouth shows accretion during 1975–2020 at a maximum rate of 12.43 m/year, while the remaining part (91.94%) of the coast is experiencing erosion (Table 24). The maximum erosion observed during 1975–2020 was -748.4 m, at transect id number 86 (near Pentha), and the maximum accretion was 486.5 m, at transect number 23 (north of the Hansua river) (Figure 68). 69.35% of the coast (Pentha to Satabhaya) was under high erosion, whereas the accretion was much less (Figure 69).

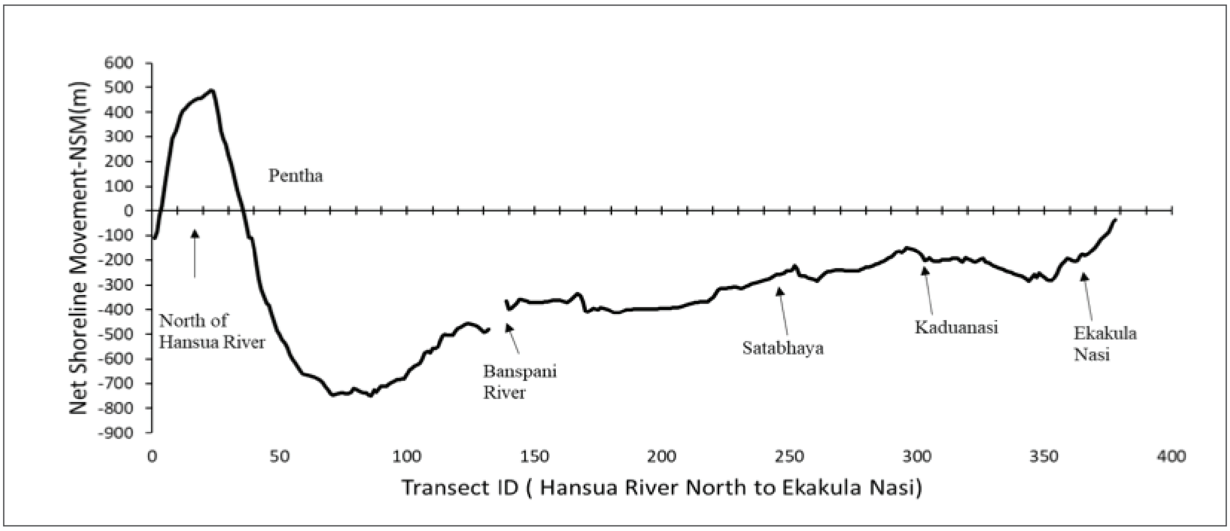


Figure 68 *Shoreline change rate along Bhitarkanika coast during 1975 -2020*

Table 24 *Shoreline change statistics (1975 -2020*

Shoreline change statistics (1975–2020)	
Shoreline length (km)	37.8 (372 transects, at 100 m distance)
Mean shoreline change rate (m/year)	-6.81
Maximum erosion rate (m/year)	-17.16
Maximum accretion rate (m/year)	12.43
Coast under erosion (%)	92% (3.4 km)
Mean erosion rate (m/yr)	-8.16
Coast under accretion (%)	8%, 0.32km
Mean accretion rate (m/year)	7.44
Maximum erosion (m)	-748.4
Maximum accretion (m)	486.5

In order to examine the changes in the shoreline since 2002 (Ramsar site designation), the shoreline changes were analysed further for the period 2005–2020. The shoreline 2 km north of the Hansua river mouth showed erosion at a mean rate of -19.2 m/year during 2005–2020. Further 2 km up to Pentha, accretion at a mean rate of 27.9 m/year was observed.

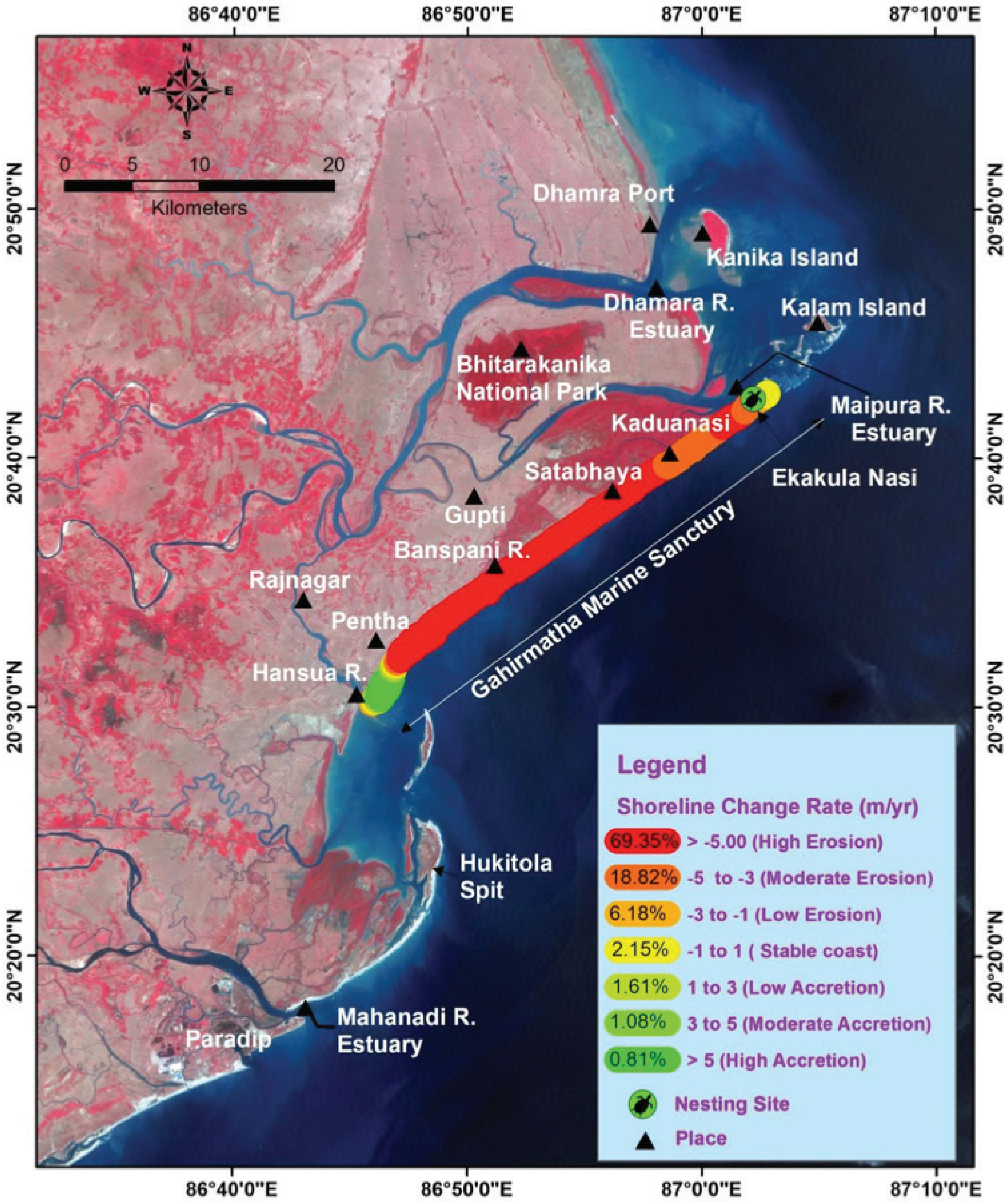


Figure 69 *Shoreline change rate along Bhitarkanika coast during 1975–2020. The classified map of the shoreline changes shows different rate of erosion along the Bhitarkanika coast. (Source : CDA, 2020(*

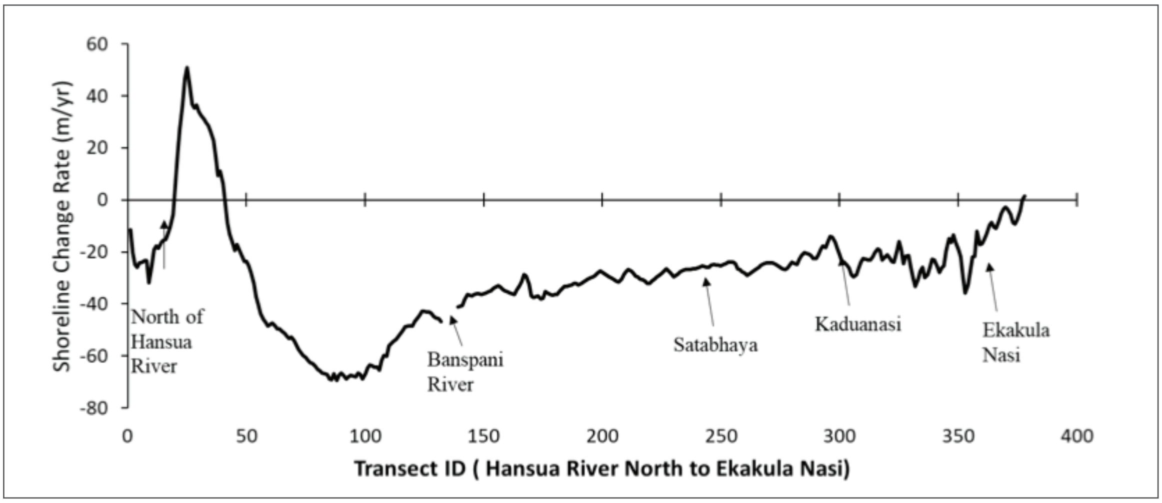


Figure 70 *Shoreline change rate along the Bhitarakanika coast during 2005-2020*

However, the coastal stretch from Pentha to the Banspani river mouth experienced a high erosion rate, with maximum erosion rate of -67m/year, and the coastline from north of Banspani river to Ekakula Nasi experienced erosion at a mean rate of -26m/year (Figure 70). The shoreline change statistics (Table 25) along the Bhitarkanika coast indicate that 34.9 km of the coast is under erosion, while only 2.3 km of coastline experienced accretion.

Table 25 *Summary of shoreline change statistics of the period 2005–2020*

Statistics	Value
Mean shoreline change rate (m/year)	-28.81
Maximum erosion rate (m/year)	-69.36
Maximum accretion rate (m/year)	50.95
Coast under erosion (km)	34.9
Coast under accretion (km)	2.3
Mean erosion rate (m/year)	-32.39
Mean accretion rate (m/year)	25.55
Maximum erosion (m)	-354.97
Maximum accretion (m)	260.78

10.1.1 Causes of shoreline changes along Bhitarkanika coast

Possible causes that trigger the coastal erosion along the Bhitarkanika coast are:

- The S and SE wave approach round the year leads to erosion of the coast.
- The long shore transport at the Bhitarkanika coast is northerly round the year.
- The coastal part of the Brahmani and Baitarni lies in the track of cyclonic storms that originate in the BoB during April-November and move westwards. Droughts and floods are recurrent phenomena in Odisha, and Bhitarkanika is not an exception in this regard. These influence the sanctuary, its shoreline and salinity regime, which will affect the mangrove ecosystem.

- Steep waves generated during cyclonic storms cause coastal erosion.
- Storm surges and wave overtopping trigger the erosion processes.
- The reduction in sediment supply is due to
  - Developmental activities, including irrigation and damming projects, in the river basin.
  - Illegal sand mining from the river bed in the Kendrapara region is an alarming issue. Indiscriminate sand mining in the river has threatened the embankment and changed its flow. (SANDRP, 2020)
- Dam construction, irrigation projects, development of coastal infrastructure (such as Dhamra Port).

Cyclonic disturbances along the BoB are an unusual phenomenon causing severe damage to the coast of Odisha. The frequency of the cyclones and their landfall in general are more frequent over the BoB as compared with cyclones over the Arabian Sea (Mahala et al., 2014) as the surface temperature is higher than in the Arbian Sea. Severe cyclones have been followed by flooding along the Odisha coast (108 instances), resulting in massive destruction of life and property almost every year (Figure 71 and Table 26). Storm surges associated with cyclonic storms also cause serious damage to the coastal structure and are responsible for the landward movement of the shoreline and for coastal erosion (Figure 72).

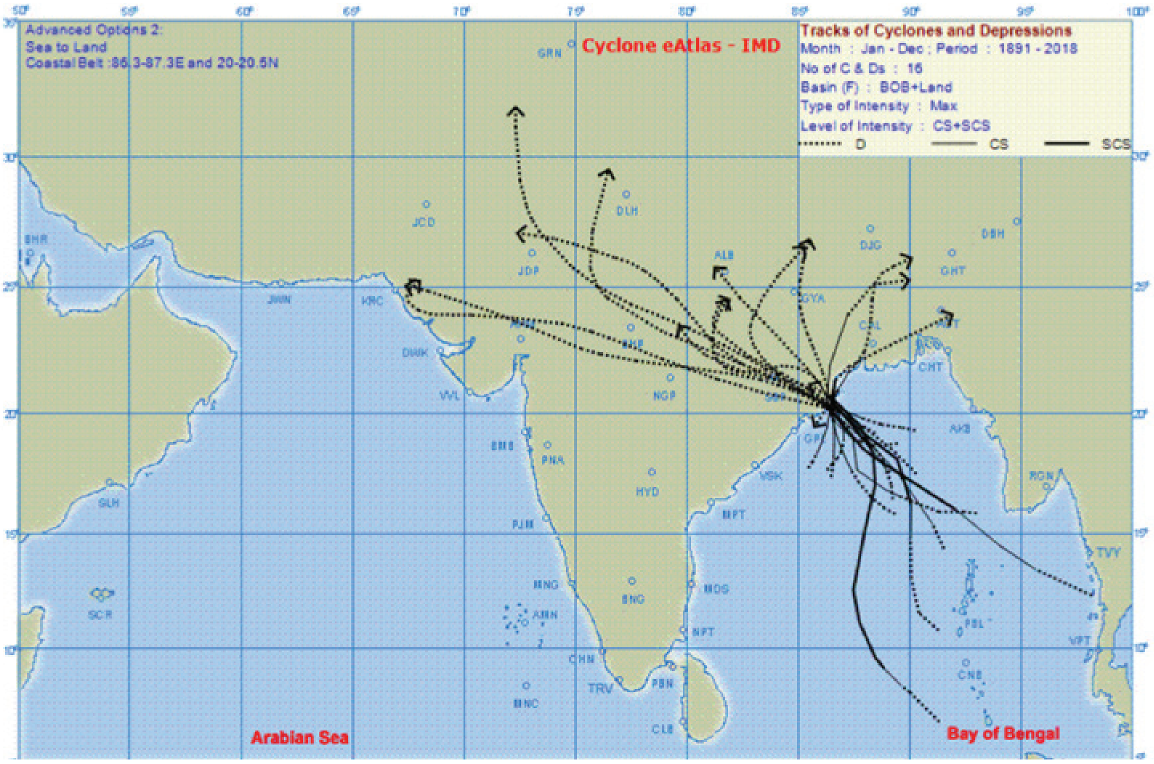


Figure 71 *Map showing the tracks of cyclones near the Bhitarkanika coast from 1891 to 2018 (Source: Cyclone eAtlas-IMD)*

__Table 26__ List of natural disasters in Kendrapara District

Disaster	Year	Consequences
Cyclone	1999 – Super cyclone	The entire Kendrapara district was severely battered by heavy winds and rain, and several villages were inundated by saline water. Mangrove patches near Mahakalpara were destroyed.
	2013 – Phailin	The heavy rainfall induced by this cyclone affected the crop yield.
	2019 – Fani	The heavy rainfall after the landfall affected the people and the agriculture of the entire district.
Flood	1995, 1997, 1999, 2001, 2003, 2006, 2007, 2008, 2009, 2011, 2013	Kendrapara district was badly hit by floods in 2011. The cropped area and houses were mostly affected.

(Source: District Disaster Management Plan Kendrapara, Odisha, 2020)

Figure 72 (a) *Breaching of shoreline embankment on southern side of Pentha during Cyclone Hud Hud, on 12 October 2014 (Source: DoWR, Odisha)*

__Figure 72 (b)__ Breaching of shoreline embankment on southern side of Pentha during Cyclone Hud Hud, on 12 October 2014 (Source: DoWR, Odisha)

10.2 Oceanographic conditions along Bhitarkanika coast

In an estuarine system, the dynamic processes that exist in the nearshore region, such as coastal currents, tides, tidal currents, internal and surface waves, storm surges and tsunamis can alter the estuarine characteristics. Bhitarkanika Sanctuary is located along the east coast of India, where the natural events and nearshore processes most often ravage the coast and cause erosion, coastal flooding and storm surges. This has been evidenced at the Pentha coast many times. Besides, the sea level rise also has negative consequences on the shoreline. Therefore, it assumes importance in the study of oceanographic processes.

10.2.1 Tide

The tide is the major controlling force in estuarine hydrodynamic processes, which advect and disperse the fluvial martial in coastal water bodies and produce crucial changes in the adjacent beaches and the bottom topography of the estuary region.

Tide data of the Dhamra coast were collected from the State Project Management Unit, ICZMP, Bhubaneswar, Odisha for a 12 month period from May 2012 to April 2013, and the seasonal changes in the tidal range are examined in Figure 73. The spring tide range is 3.1–3.7 m, and the neap tide range is 0.6–1.4 m (Figure 73).

The tide along this coast is mostly meso-tidal and semi-diurnal in nature. The tides are responsible for sea water intrusion in the sanctuary, resulting in a brackish salinity regime, which is crucial for the survival of the flora and fauna, including mangroves. The tidal flux is an important factor for the vegetative growth of mangroves and creates conducive habitats for coastal food webs by rejuvenating the nutrients in sediments.

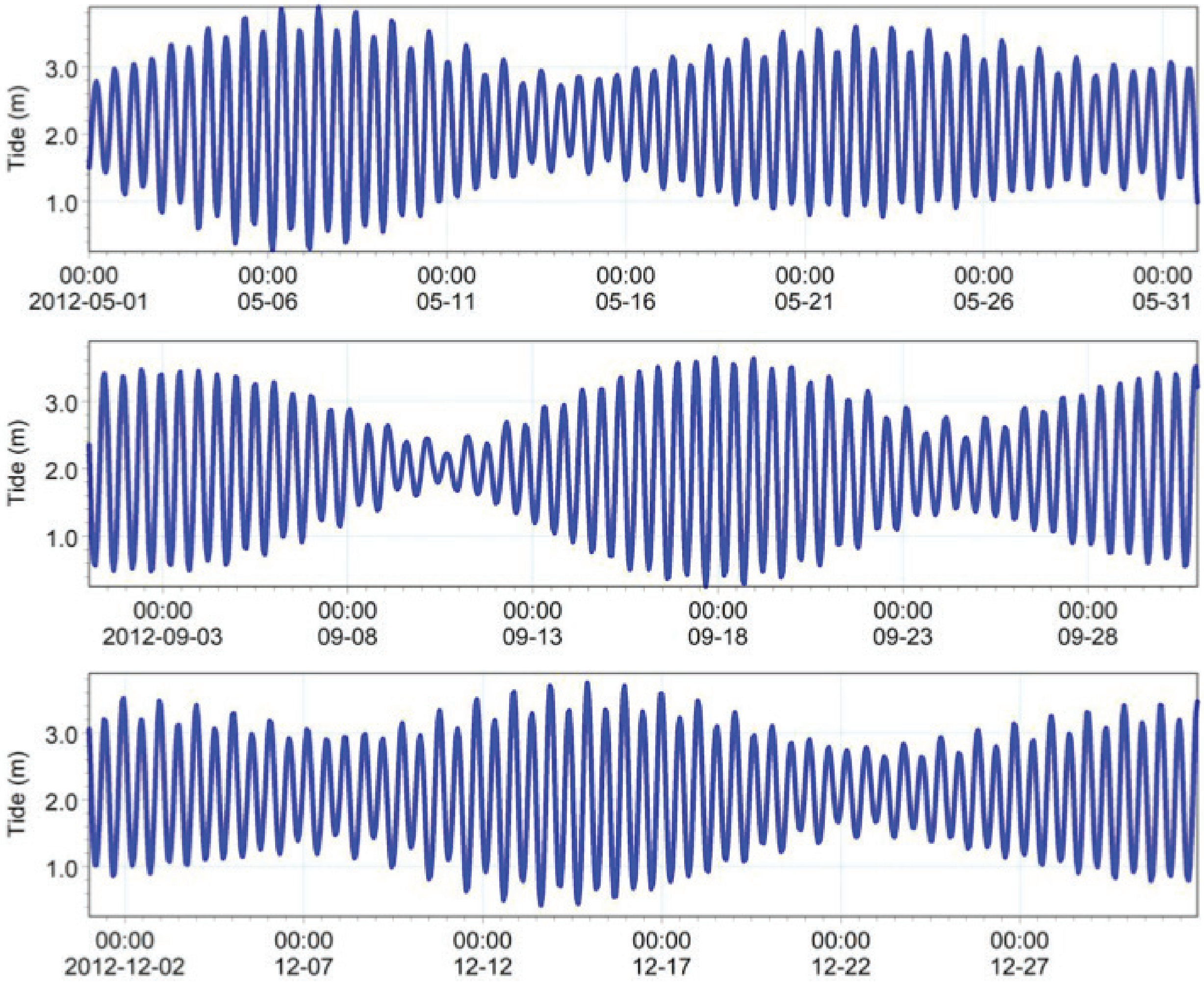


***Figure 73** Tidal variation at Dhamra coast in May, September and December 2012*

10.2.2 Wave

Wave energy is considered to be the primary reason for coastal erosion, and thus it is useful for understanding the patterns of erosion. Wave data off Paradeep were obtained from State Project Management Unit, ICZMP, Bhubaneswar, Odisha (Source: ICZMP, Odisha). The data were analysed to understand the wave characteristics. The wave height varies significantly along the coast, while the direction is consistently along the SE–S direction, even during the NE monsoon (Figure 74).

The waves mainly arrive from the SE, with the exception of 2% of the time, during which they arrive from the NE and E. This same obliqueness on the shore is clearly demonstrated by the wave direction. The variations of significant and maximum wave height (Table 27) suggest that the maximum wave height, is recorded mostly during July–September and in November along the coast.

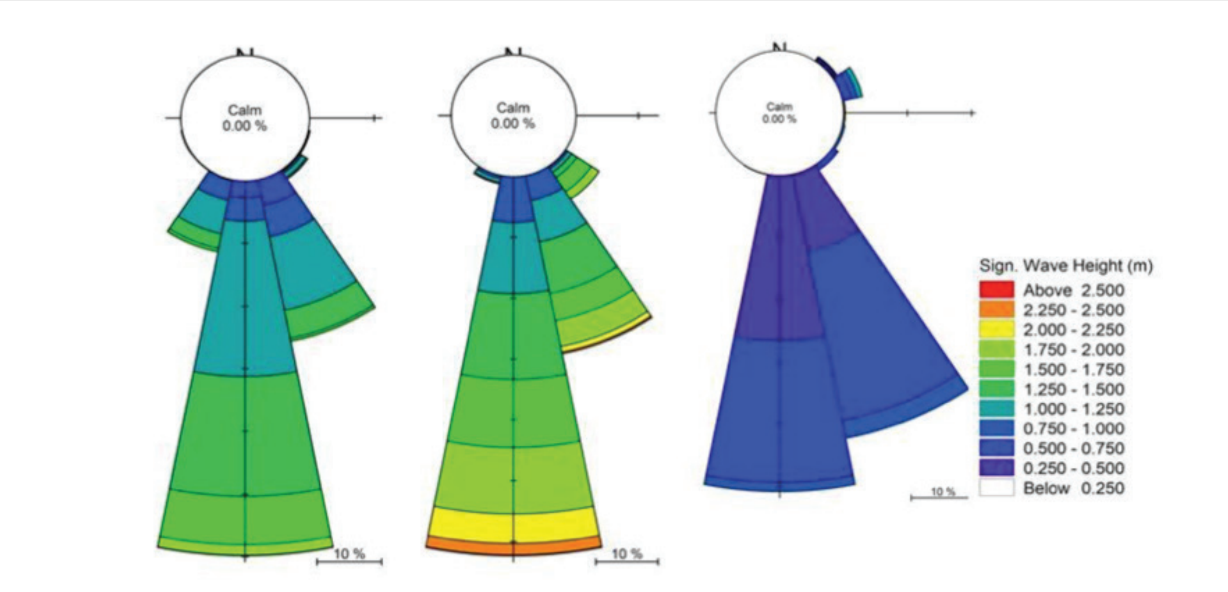


Figure 74 *Wave rose diagram of significant wave height (May, August and December 2012)*

Table 27 *Ranges of significant (Hs) and maximum wave heights (Hmax) during the period from May 2012 to April 2013 off Paradeep*

Month	Hs (m)	Hmax (m)
May 2012	0.61 – 1.76	0.94 – 3.76
August 2012	0.75 – 2.63	1.19 – 4.59
December 2012	0.24 – 1.11	0.37 – 2.58

10.2.3 Longshore sediment transport

Littoral drift, the wave-driven long shore transport of sediment, plays a major role in shoreline dynamics. Human-induced modification of littoral drift is a ubiquitous cause of coastal erosion. Strong littoral drift resulting in sand movement is one of the major reasons for coastal erosion. The longshore sediment transports were estimated at three places (Pentha, Satabhaya and Ekakula Spit) along the Bhitarkanika coast. The net annual longshore sediment transport is towards the north round the year (Figure 75), and it is comparatively higher on the coast of Pentha compared with Satabhaya and the Ekakula spit. This leads to significant erosion on the Pentha coast.

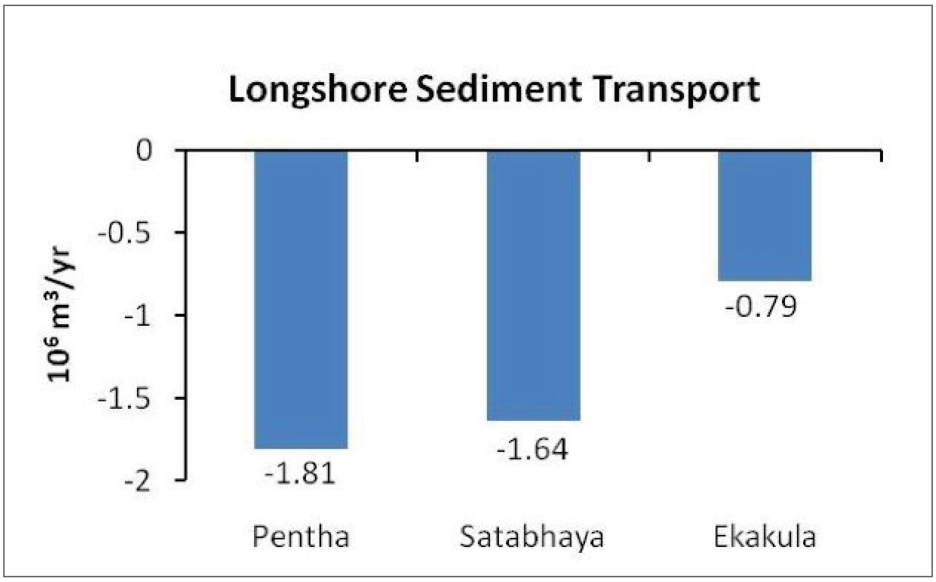


Figure 75 *Annual longshore sediment transport along the Bhitarkanika coast*
*(*A negative value means the transport is northerly)*

10.3 Possible impact of coastal flooding

Storm surges arise on the arrival of strong winds to the coastline, resulting in massive piling of seawater, which can initiate sudden inundation as well as coastal flooding. Storm surges are reported to reach heights of up to 6.1 m at the coasts of Kendrapara and Jagatsinghpur (close to Bhitarkanika). They have a potential to submerge around 2000 km^2 of land (Sahoo & Bhaskaran, 2019). Storm surges and storm tides submerge coastal zones and consequently result in salinity ingress in the groundwater, surface water and soil, thereby reducing agricultural productivity. Coastal flooding normally occurs when dry and low-lying lands are submerged by sea water. Coastal flooding is largely a natural event; however, human influences on the coastal environment can exacerbate coastal flooding. Extraction of water from groundwater reservoirs in the coastal zone can lead to subsidence of the land, thus increasing the risk of flooding. Engineered protection structures along the coast, such as sea walls, alter the natural processes of the beach, often leading to erosion on adjacent stretches of the coast, which also increases the risk of flooding.

The sea level rise and extreme weather events, such as cyclones, will increase the intensity and amount of coastal flooding, affecting hundreds of millions of people. The GMSL has risen by 1.7 (1.5-1.9) mm/year since 1901, and the rate of rise has accelerated to 3.3 mm/year since 1993. The GMSL is very likely to rise by ~26 cm by 2050 and ~53 cm by 2100 for a mid-range mitigation scenario. Extreme sea-level events are projected to occur frequently over the tropical regions (high confidence) and along the Indian coast (medium confidence). They will be associated with an increase in the mean sea level and climate extremes (Swapna et al., 2020).

Considering the sea level rise and surges due to cyclonic storms, modelling analysis was carried out by CDA to understand the extent of coastal flooding along the Bhitarkanika coast (from Hukitola Bay to Dhamra port). The scenario used was surges of different heights (50 cm/1m/2 m/5 m), and the projected area under inundation was analysed on the basis of digital elevation model (SRTM 30m) data (Figure 77, Table 28). It was found that a surge of 50 cm will inundate villages along the shoreline to an extent of 1.23 km^2. Subsequently, the inundation will be greater with an increase in surge height.

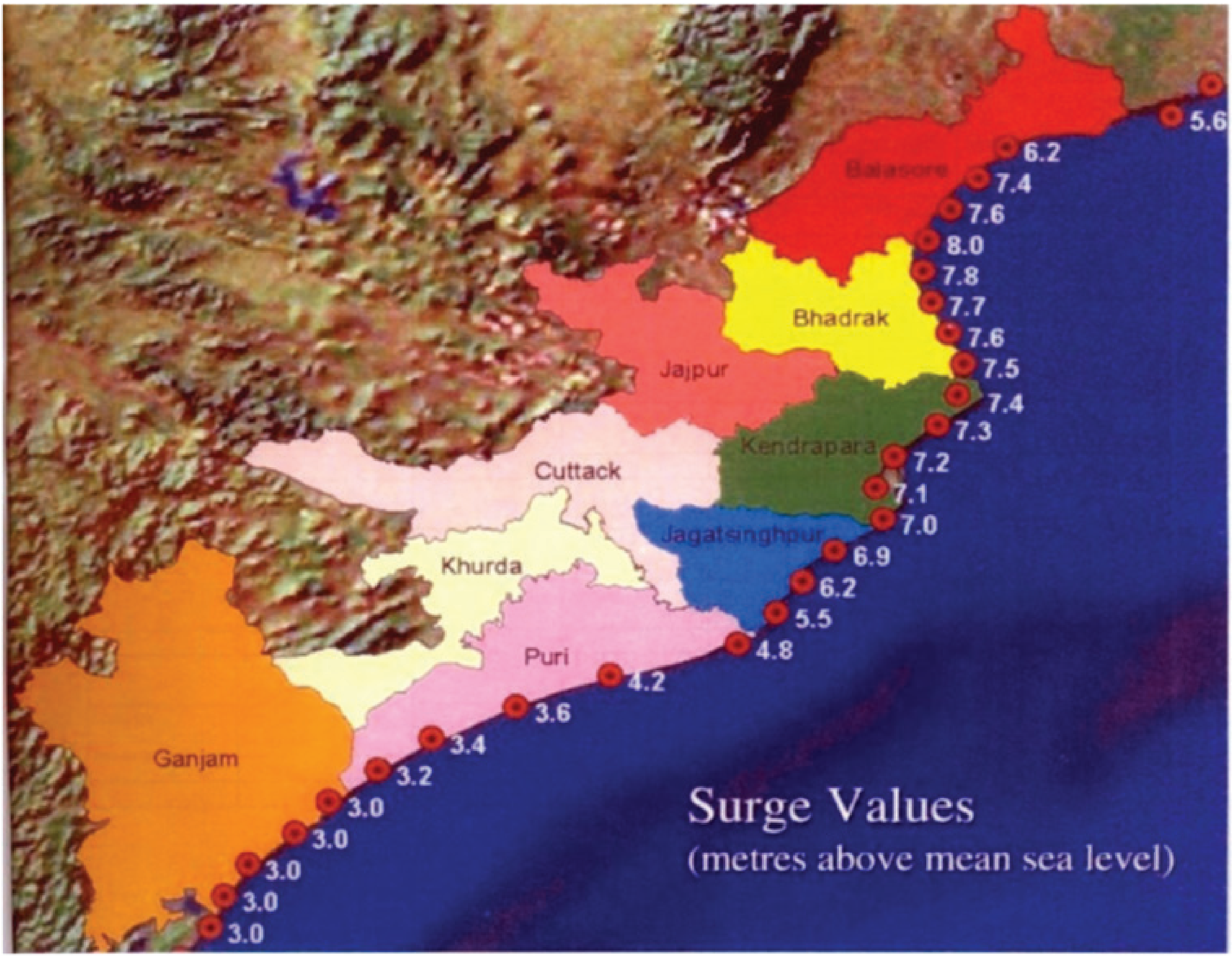


Figure 76 *The sea level rise along with the surge values*
(Source: DoWR, Odisha)

Table 28 *Extent of inundation and villages by coastal flooding due to various surge heights in Bhitarkanika coast*

Surge height (m)	Predicted area (km^2) under inundation	No. of villages under inundation
0.5	1.23	30 (bordered at river shoreline)
1.0	17.22	36
2.0	241.52	155
3.0	738.68	467

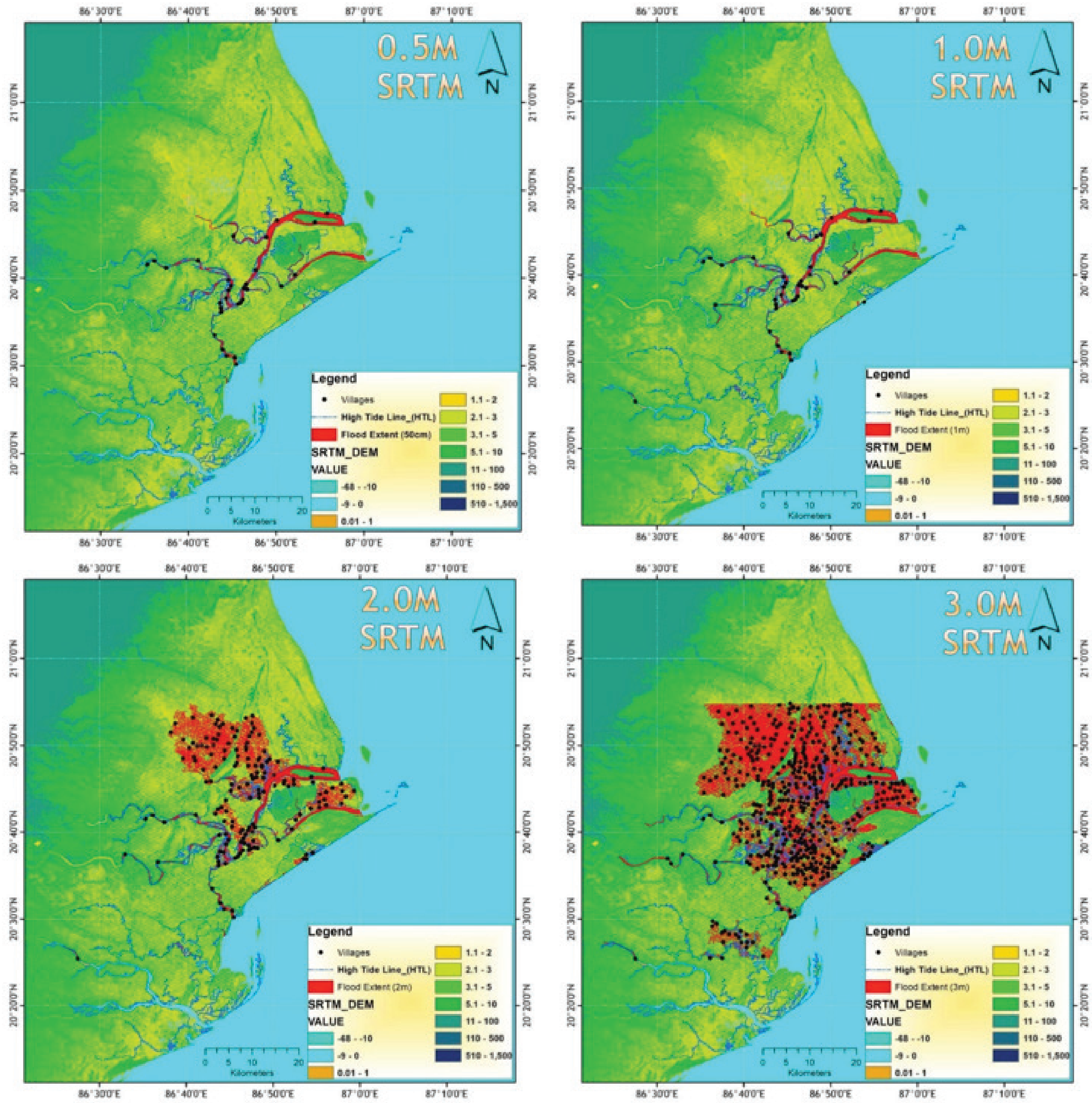


Figure 77 Flood extents of different surge heights on the Bhitarkanika coast (Source: CDA, Bhubaneswar, Odisha 2020)

10.4 Management recommendations to mitigate coastal erosion and coastal flooding

To mitigate and minimise the vulnerability, plantation of mangroves and Casuarina and sand dune creation could be carried out to provide a barrier and buffer against the coastal flooding and heavy wind of the Bhitarkanika Sanctuary coastline. The following are some of the possible management interventions that could reduce the coastal erosion and coastal flooding:

10.4.1 Beach nourishment (beach fill)

Beach nourishment is the placement of large quantities of sand on an eroding beach to advance the shoreline seaward of its present location. This approach does not involve construction of permanent structures and is the most common method of erosion mitigation. The materials for beach nourishment are obtained from an offshore borrow area.

Beach nourishment is used to accomplish goals such as (i) building additional recreational areas, (ii) offering storm protection and (iii) providing in some cases, a habitat for endangered species. Sand recycling along with beach replenishment offers potential advantages to the long-term sustainability of coast protection. Dunes are also re-established through beach replenishment. Beach nourishment (beach fill) is a process to rebuild the dune field and to minimise the coastal erosion. This method has been adopted earlier at Gopalpur coast near Gopalpur Port (south Odisha coast) in 2009 (Kar et al., 2017) and has had positive impacts.

These processes can be implemented at the coasts of Pentha, Satabhaya and Habelikhati, where the maximum erosion has been noted in the shoreline change analysis. Gopalpur Ports Limited (GPL) and the Department of Water Resources, Government of Odisha could be the implementing agency and could provide technical resources for this intervention. The funding could be acquired from these agencies.

10.4.2 Sand dune development and plantation

Encroachment on the sea with man-made development has often led to the loss of sand dunes. Large dune areas have been levelled to make way for real estate developments or have been lowered to permit easy access to the beach area. Dune planting with appropriate grasses and shrubs reduces landward wind-born losses and helps preserve dunes.

10.4.3 Mangrove plantation

Mangroves play a vital role in mitigating coastal erosion as barriers agains tidal action and storm surges associated with tropical cyclones. The mangrove vegetation along the Odisha coast is especially important because the coast is highly vulnerable to cyclones and is subjected to strong littoral drift. Realising the importance of mangrove vegetation along the Odisha coast, the technical expert committee formed for Odisha cyclone (Govt. Of Odisha, 1974) recommended plantation and restoration of mangroves along the coast over a width of 1 km.

Mangrove vegetation restricts and slows down the erosion process and act as a shield against cyclones and tsunamis. The trees are well equipped with branched root systems (Hentala plants), pneumataphores or breathing roots (Sundari, *Heritiera* sp., etc.) or stilt root systems (*Rhizophora* sp., *Kandelia* sp.), and the grasses (Nalia, *Myriostachya* sp.) reduce the tidal current action. The plantation of mangrove species in Bhitarkanika Sanctuary has been actively pursued by the Rajnagar Wildlife division, with the support of the Integrated Coastal Zone Management Programme (ICZMP).

10.4.4 Geo-synthetic tubes

Geo-synthetic tubes filled with sand can be placed perpendicular to the shoreline or parallel to the shoreline to dissipate the wave energy. In order to protect the coastline at Pentha from vulnerable erosion, the Department of Water Resources, Government of Odisha has taken up the up-to-date method of soft engineering technology under the Integrated Coastal Zone Management Programme (ICZMP), which includes construction of a geo-textile tube embankment (Figure 78).

Figure 78 *Accretion of sand has started in front of the geo-tube*
(Source: Department of Water Resources, Odisha)

10.5. Recommendation for hydrological monitoring

Several field observations are recommended for obtaining a better understanding of the water balance, tidal influx, extent of saline water propagation, sedimentation and tidal variation.

- **Where does it need to be done?**
  - ~ Long-term observation of the discharge upstream of Bhitarkanika Sanctuary (Pattamundai, Aul and Chandbali) could give a more realistic view of the freshwater supply to the sanctuary. Similarly, long-term observation of the discharge to the sea (tidal prism) at Hansua, Maipura and the Dhamra river estuary could substantiate the water balance at Bhitarkanika Sanctuary after subtracting the discharge at the estuary from the upstream discharge (Figure 74).
  - ~ Long-term observation of tide near Dhamra Port, Dangamala and Gupti could help understand the tidal hydrodynamics of the sanctuary (Figure 74).
  - ~ Seasonal simultaneous longitudinal observations of the salinity (through each river from the estuary upstream) could help understand the extent of saline water propagation.
  - ~ Long-term observation of meteorological parameters at Dangamala through a permanent weather station
  - ~ Periodic bathymetric surveys of entire rivers of Bhitarkanika Sanctuary to measure the rate of sedimentation
- **What parameters?**
  - ~ Discharge, tidal prism, salinity, tide, weather parameters (wind speed and direction, temperature, rainfall, relative humidity, solar radiation), depth
- **When and what frequency?**
  - ~ Discharge – Daily time scale
  - ~ Tidal prism – River mouth cross-section and velocity measurement at each estuary during both ebb and flood phases, on a monthly basis
  - ~ Salinity – Seasonal
  - ~ Tide – Hourly
  - ~ Weather parameters – hourly
  - ~ Bathymetry – At 5 year intervals in winter
- **What resources are required?**
  - ~ Velocity measurement unit
  - ~ Establishment of water level mark/tide pole at each location with respect to the M.S.L.
  - ~ Water quality probe for salinity measurement/manual titration method.
  - ~ Automatic weather station unit
  - ~ Echo-sounder integrated with GPS and software for surveying and analysis
  - ~ Several national research and educational institutes across India (i.e., NCCR, NCSCM, Water Resource Department, IITs universities, etc.) have expertise in the above-mentioned aspects and should be consulted by the site manager for a detailed assessment.

11 STATUS AND TRENDS IN COMPONENTS, PROCESSES AND SERVICES

Ecological character is the description of components, processes and ecosystem services. Ecological character is an indicator of the health of a wetland ecosystem. Changes to the ecological character of the wetlands outside the natural variation may signal that uses of the site are unsustainable and may lead to the breakdown of the ecological, biological and hydrological functioning of the wetland system. The status and trends in components, processes and services, derived from evaluation of features is discussed in this section.

11.1 Ecological components

Ecological Components	Current / Latest Status	Data Assess-ment Year & Source	Status at the Time of Ramsar Site Designation (2002) Baseline	Data Assessment Year and Source	Trend
Physical form					
a) Wetland area	The sanctuary area has been rationalised, and the new area of the sanctuary is 673 km^2. Longitudes 87° 02′ 30” E to 86° 40′ 30” E, latitudes 20° 17’ 30” to 20° 47’ 30”. There were 410 villages in the sanctuary as per the 2011 census. However, with the new proposed map for the sanctuary, 52 villages will be excluded, leading to a total of 358 villages being retained inside the sanctuary.	Management Plan of Bhitarkanika Sanctuary and National Park, for 2020–21 to 2029–30	672 km^2 area declared as Bhitarkanika Sanctuary in 1975 as per Government of Odisha notification in 1975. The Bhitarkanika Ramsar site designated area is 650 km^2. 145 km^2 areas declared as national park inside the sanctuary in 1998. 410 villages were located within the sanctuary	Bhitarkanika Wildlife Sanctuary (Vide Govt. of Odisha, Department Forest, Fisheries & A.H. Department Notification No. 8F (WL) 6958/BBSR Dt. 22.4.1975) MoEFCC 2020, Ramsar sites of India, Factsheet) Management plan Bhitarkanika Sanctuary and National Park Period 2020-21 - 2029-30	No human induced reduction in wetland area. Ramsar site designated area remains same. The area of wetland indicated as indicated at time of designation needs to be maintained as per commitment under Ramsar Convention.

Ecological Components	Current / Latest Status	Data Assessment Year & Source	Status at the Time of Ramsar Site Designation (2002) Baseline	Data Assessment Year and Source	Trend
Physical form					
b) Wetland types in the complex	LULC analysis during 2020 showed that the sanctuary landscape is composed of agricultural land (46.3%), dense mangroves (15.1%), water bodies (11.2%), open mangroves (7.4%), intertidal zone (3.4%), mud flats/swamps (7.2%), plantations/other vegetation (5.5 %), sand (1%) and aquaculture units (2.9%).	CDA Final Report, July 2021	LULC analysis during 2000 showed that sanctuary landscape was composed of agriculture (52.0%), Dense Mangroves (18.2 %), Water body (11.9%), Open Mangroves (4.4%), Inter Tidal Zone (2.4%), Mud Flats/ Swamps (5.0%), Plantation/Other Vegetation (5.1 %), Sand (0.9%), Aquaculture(0.1%).	CDA Final Report July 2021	There is net decline in area under agriculture and dense mangroves. The open mangroves and intertidal zone showed a significant increase in area. The area under aquaculture showed a sharp increase.
Wetland sediment					
a) Sediment texture	**Sanctuary:** During the monsoon and winter, sand dominated the sediments (87.40% to 87.84%), whereas silt/clay constituted 12.60% to 12.14% of the sediments. **Major rivers:** During the monsoon and in winter, sand dominated the river sediments, i.e., 94.10% to 91.02%, whereas silt/clay constituted 5.90% to 8.99% of the sediments.	CDA Final Report, July 2021	No data available for year 2002 for the sanctuary and rivers.		No long term data is available on sediment texture for trend analysis either from sanctuary or from rivers.

Ecological Components	Current / Latest Status	Data Assessment Year & Source	Status at the Time of Ramsar Site Designation (2002) Baseline	Data Assessment Year and Source	Trend
Wetland sediment					
b) Total organic carbon (TOC	**Sanctuary:** The average TOC content in the sediments varied between 1.725% and 2.295% during the monsoon and in winter. **Major rivers:** The average TOC content varied between 1.790% and 2.061% during the monsoon and in winter.	CDA Final Report, July 2021	No data available for year 2002 for the sanctuary and rivers.	CDA Final Report July 2021	Not enough data available for trend analysis. No previous assessments from river sediments are available.
c) Available nitrogen (AN)	**Sanctuary:** The average AN content varied between 0.022% and 0.01% in the sediments of the sanctuary during the monsoon and in winter. **Major rivers:** The average AN content varied between 0.012% and 0.01% in the river sediments.	CDA Final Report, July 2021	No data available for year 2002 for the sanctuary and rivers.		Not enough data available for trend analysis. No previous assessments are there from rivers.
d) Trace metals (µg/g) in sediments	Cu, 0.69; Mn, 6.28; Pb, 0.25; Fe, 293; Zn, 6.29;Cd, 3.02.	CDA Final Report, July 2021	No data available for year 2002 for the sanctuary and rivers.		No systematic assessments from the sanctuary and river sediments are available.

Ecological Components	Current / Latest Status	Data Assessment Year & Source	Status at the Time of Ramsar Site Designation (2002) Baseline	Data Assessment Year and Source	Trend
Physico-chemical water					
a) Transparency (m)	**Sanctuary:** Monsoon, 0.160; winter, 3.9; average, 0.27. **Major rivers:** Monsoon, 0.20; winter, 2.75; average, 0.24.	CDA Final Report, July 2021	No data available for year 2002 for the sanctuary and rivers.		Not enough data available from both the sanctuary and rivers for trend analysis.
b) pH	**Sanctuary:** Monsoon, 7.37; winter, 7.55; average, 7.45. **Major rivers:** Monsoon, 7.536; winter, 7.56; average, 7.55.	CDA Final Report, July 2021	No data available for year 2002 for the sanctuary. In year 2002, the pH was reported 7.98 and 7.81 from Baitarani and Brahmani rivers, respectively. Analysis of the long term pH data from SPCB (2002-2019) showed pH varied between 7.20 - 8.03 in Baitarani and Brahmani rivers.	SPCB River monitoring data 2002-2019	Not enough data available from both the sanctuary and rivers for trend analysis. No specific trend was observed from SPCB data.
c) Salinity (PSU)	Sanctuary: Monsoon, 3.106; winter, 6.46; average, 4.74. Major rivers: Monsoon, 0.409; winter, 0.80; average, 0.53.	CDA Final Report, July 2021	No data available for year 2002 for the sanctuary and rivers.		Not enough data available from both the sanctuary and rivers for trend analysis.
d) Dissolved oxygen (mg/l)	**Sanctuary:** Monsoon, 5.97; winter, 8.60; average, 7.24. **Major rivers:** Monsoon - 5.62, Winter - 8.15, average - 6.88	CDA Final Report, July 2021	No data available for year 2002 for the sanctuary. In the year 2002, the DO was reported 7.75 and 7.83 from Baitarani and Brahmani Rivers, respectively.	SPCB River monitoring data 2002-2019	Not enough data available from both the sanctuary and rivers for trend analysis.

Ecological Components	Current / Latest Status	Data Assessment Year & Source	Status at the Time of Ramsar Site Designation (2002) Baseline	Data Assessment Year and Source	Trend
Physico-chemical water					
			Analysis of the long term DO data from SPCB (2002-2019) showed it varied between 6.5-8.45 mg/L in Baitarani and Brahmani rivers.		
e) Total alkalinity (mmol/l)	**Sanctuary:** Monsoon, 1.55; winter, 1.45; average, 1.50. **Major rivers:** Monsoon, 3.07; winter, 1.79; average, 2.43.	CDA Final Report, July 2021	No data available for year 2002 for the sanctuary and rivers.		Not enough data available from the sanctuary and rivers for trend analysis.
f) Chlorophyll -a (mg/m3)	**Sanctuary:** Monsoon, 0.666; winter, 0.241; average, 0.454. **Major Rivers:** Monsoon, 0.341; winter, 0.227; average, 0.284	CDA Final Report, July 2021	No data available for year 2002 for the sanctuary and rivers.		Not enough data available to observe trend, present data showed lower concentration as compared to earlier records.
g) BOD (mg/l)	**Sanctuary:** Monsoon, 1.28; winter, 1.78; average, 1.53. **Major rivers:** Monsoon, 1.54; winter, 1.56; average, 1.56.	CDA Final Report, July 2021	No data available for year 2002 for the sanctuary. In year 2002, the BOD was reported 4 and 2.25 mg/L from Baitarani and Brahmani rivers. Analysis of the long term BOD data from SPCB (2002-2019) showed it varied between 0.6-2.25 mg/L in Baitarani and Brahmani rivers.	SPCB River monitoring data 2002-2019	Not enough data available from the sanctuary for trend analysis. As per SPCB data (2002-2019) Baitarani and Brahmani rivers are showing declining trend in BOD.

Ecological Components	Current / Latest Status	Data Assessment Year & Source	Status at the Time of Ramsar Site Designation (2002) Baseline	Data Assessment Year and Source	Trend
Physico-chemical water					
h) Nitrite (µM))	**Sanctuary:** Monsoon, 2.6; winter, 0.55; average, 1.60. **Major rivers:** Monsoon - 1.4, Winter - 1.15	CDA Final Report, July 2021	No data available for year 2002 for the sanctuary and rivers.		Not enough data available from both the sanctuary and rivers for trend analysis.
i) Nitrate (µM)	**Sanctuary:** Monsoon, 22.4; winter, 25.81; average, 24.04. **Major rivers:** Monsoon, 9.5; winter, 8.29,	CDA Final Report, July 2021	No data available for year 2002 for the sanctuary and rivers. Analysis of the long term nitrate data from SPCB (2006-2015) showed it varied between 3.12-17.2 µM in Brahmani river.	SPCB River monitoring data 2002-2019	Not enough data available from the sanctuary for trend analysis. No discernible trend observed from rivers.
j) Ammonia (µM)	**Sanctuary:** Monsoon, 3.9; winter, 3.44; average, 3.69. **Major rivers:** Monsoon, 0.5; winter, 0.5.	CDA Final Report, July 2021	No data available for year 2002 for the sanctuary and rivers. Analysis of the long term ammonia data from ENVIS (2006-2015) showed it varied between 0.86-7.3 µM in Brahmani river.	ENVIS River monitoring data (2006-2015)	Not enough data available from both the sanctuary and rivers for trend analysis. No discernible trend observed from rivers.
k) Phosphate (µM)	**Sanctuary:** Monsoon, 0.4; winter, 0.28; average, 0.17. **Major Rivers:** Monsoon, 0.3; winter, 0.42.	CDA Final Report, July 2021	No data available for year 2002 for the sanctuary and rivers.		Not enough data available from both the sanctuary and rivers for trend analysis.

Ecological Components	Current / Latest Status	Data Assessment Year & Source	Status at the Time of Ramsar Site Designation (2002) Baseline	Data Assessment Year and Source	Trend
Physico-chemical water					
l) Silicate (µM)	**Sanctuary:** Monsoon, 36; winter, 133; average, 35. **Major Rivers:** Monsoon, 161; winter, 147.12.	CDA Final Report, July 2021	No data available for year 2002 for the sanctuary and rivers.		Not enough data available from both the sanctuary and rivers for trend analysis.
m) Faecal coliform count (MPN/100 ml)	**Sanctuary:** Water samples from the sanctuary had mean faecal coliform counts ranging between 6 and 327 MPN/100 ml during the monsoon and in winter. **Major Rivers:** Water samples from the rivers had mean faecal coliform counts ranging between 2 and 61 MPN/100 ml during the monsoon and in winter.	CDA Final Report, July 2021	No data available for year 2002 for the sanctuary. Analysis of the long term data from SPCB (2002-2019) showed fecal coliforms varied between 898 - 40627 MPN/100 ml in Baitarani and Brahmani rivers.	SPCB River monitoring data 2002-2019	No previous data is available from sanctuary for comparison. Both Baitarani and Brahmani River showed an increasing trend with respect to annual mean fecal coliform data.
Biota (flora and fauna)					
a) Mangrove diversity and the distribution of mangroves	A total of 38 species (26 true mangrove species and 12 mangrove associates) were recorded from the sanctuary.	CDA Final Report, July 2021	A total of 64 species of plants were recorded from Bhitarkanika Mangrove Protected Area, which included 28 true mangroves, 4 mangrove associates were reported in year 2002.	Badola & Hussain, 2003	The species composition of mangroves inferred from satellite imagery was compared by Das (2017) for different years (1989, 2000 and 2015) and it was found that over the

Ecological Components	Current / Latest Status	Data Assessment Year & Source	Status at the Time of Ramsar Site Designation (2002) Baseline	Data Assessment Year and Source	Trend
Biota (flora and fauna)					
					years only *Avicennia* sp. have witnessed a decline and species such as *Heritiera fomes, Lumnitzera* sp. and *Sueada* sp. have increased significantly.
b) Crocodile	As per the latest Annual Crocodile Census, held on 3 January 2020, the total number of crocodiles in Bhitarkanika was 1757.	Crocodile Census (2020), Wildlife Organization, Odisha	Reptile Census of 2002 reported a total of 1308 estuarine crocodiles in the sanctuary.	Crocodile Census (2002); Wildlife Organization, Odisha	The populations of crocodiles are showing the increasing trend in Bhitarkanika Sanctuary.
c) Phytoplankton	A total of 107 species belonging to 57 genera were recorded. Diatoms and dinoflagellates were the major groups. Two algal blooms were recorded in Bhitarkanika in October in 2018 and 2019. These were blooms of the diatom *Skeletonema costatum* and a bloom of the cyanophyte *Microcystis aeruginosa* during the post-monsoon season.	NCSCM Annual Report, (2018 – 2019 survey)	No data available for year 2002 for the sanctuary.	ENVIS River monitoring data (2006-2015)	Not enough data available from both the sanctuary and rivers for trend analysis. No discernible trend observed from rivers.

Ecological Components	Current / Latest Status	Data Assessment Year & Source	Status at the Time of Ramsar Site Designation (2002) Baseline	Data Assessment Year and Source	Trend
Biota (flora and fauna)					
d) Zooplankton	A variety of mesozooplankton taxa including 32 copepod species were reported from the 2018–2019 survey.	NCSCM Annual Report (2018–2019 survey).	No data available for year 2002 for the sanctuary.		
e) Macrobenthos and meiobenthos	A total of nine phyla, namely, Cnidaria, Annelida, Nemertea, Platyhelminthes, Sipuncula, Arthropoda, Echinodermata, Mollusca and Chordata, are represented by 18 major groups belonging to 95 families of the macrobenthos from Bhitarkanika. The meiobenthos of the Bhitarkanika mangroves is represented by a total of eight phyla, namely, Amoebozoa, Ciliophora, Foraminifera, Myzozoa, Nematoda, Ochrophyta, Rotifera and Arthropoda. A total of 22 major groups belonging to 37 families were observed, with a total of 21 identified up to species level and 24 up to the generic level.	NCSCM Annual Report, (2018-2019 survey).	No data available for year 2002 for the sanctuary.		

Ecological Components	Current / Latest Status	Data Assessment Year & Source	Status at the Time of Ramsar Site Designation (2002) Baseline	Data Assessment Year and Source	Trend
Catchment climate					
a) Precipitation (mm)	About 80% of the annual normal rainfall occurs during the four months of the south-west monsoon (June to September). Nearly 90% of the basin receives an average annual rainfall of about 1400–1600 mm. The average annual rainfall in the basin is 1442.53 mm. However, during 2019, the mean annual rainfall in the Kendrapara district was 1714.64 mm.	1988-2019, Indian Meteorological Department (IMD) block-level rainfall data.	During 2002, the mean annual rainfall in the Kendrapara district was 1426.37 mm.	1988 - 2019, Indian Meteorological Department (IMD) Block level rainfall data.	The inter-annual variation of rainfall from 1988-2012 over the Brahmani and Baitarani basin indicates that the mean annual rainfall is 1427 mm with a decreasing trend (i.e. - 3.4 mm per year). The inter-annual variation of rainfall from 1988-2019 over the Kendrapara district indicates that the mean annual rainfall is 1558.9 mm and is decreasing at -3.26 mm/year. The basin is predicted to receive comparatively higher rainfall in future and a corresponding increase in evaopo-transpiration and water yield.
b) Air temperature (°C)	During 2019, the mean annual air temperature at the Chandbali IMD station, located in the coastal plains of Baitarani basin was 27^{0}C, with minimum and maximum temperature of 22-31^{0}C in winter and summer months.	2001-2019, Indian Meteorological Department (IMD)	During 2003, the mean annual air temperature at Chandbali station was 27 ^{0}C , with minimum and maximum temperature of 20-32 ^{0}C in winter and summer months.	2001 – 2019, Indian Meteorological Department (IMD)	The inter-annual variation of air temperature from 2001-2019 from Chandbali indicates a non-significant increasing trend in the Baitarani basin.

Ecological Components	Current / Latest Status	Data Assessment Year & Source	Status at the Time of Ramsar Site Designation (2002) Baseline	Data Assessment Year and Source	Trend
Catchment climate					
c) Water sources	The mean annual freshwater runoff in 2017 at the Jenapur gauge station, located in the direct catchment of Bhitarkanika, was 15,142 MCM. The total annual freshwater discharge at the Akhuapada and Khanditar gauge stations of the Baitarani river in 2019 was 2,47,305.78 MCM. Detailed assessments of the hydrological regime contribution from the sea need to be carried out.	Brahmani Basin Vol-II CWC 2018	The mean annual freshwater runoff in year 2002 at Jenapur gauge station located in the direct catchment of Bhitarkanika was 10792 MCM. The total annual freshwater discharge at Akhuapada and Khanditar gauge stations of Baitarani River during 2019 was 147629.17 MCM.	Brahmani Basin Vol-II CWC 2018	Analysis of long term dataset showed a declining trend for both annual freshwater runoff and sediment load at Jenapur which is located at the beginning of Brahmani river delta. The annual freshwater discharge of Baitarani River at Akhuapada and Khanditar were over the period of 2000-2019 indicated a non-significant increasing trend.
d) Groundwater resources	The groundwater availability is assessed as 5170.66 MCM in the Brahmani - Baitarani basin.	GOI Ministry of Water Resources, Brahmani and Baitarani Basin, March 2014	No data available for year 2002.		No previous assessments available
e) Basin soil	Soil is the main natural resource in the basin. 42.92% of the basin area comes under fine textured soil, followed by 38.39% under medium textured soil. 26.62% of the basin suffers severe erosion, which is prominent in the central table land.	GOI Ministry of Water Resources, Brahmani and Baitarani Basin, March 2014	No data available for year 2002.		No previous assessments available

Ecological Components	Current / Latest Status	Data Assessment Year & Source	Status at the Time of Ramsar Site Designation (2002) Baseline	Data Assessment Year and Source	Trend
Catchment climate					
f) Sedimentation	The mean annual sediment load in 2017 at the Jenapur gauge station, located in the direct catchment of Bhitarkanika, was 2,92,8561 MT.	Brahmani Basin Vol-II CWC 2018	The mean annual sediment load in 2002 at Jenapur gauge station was 1880732 MT.	Brahmani Basin-Vol-II CWC 2018	The mean annual sediment load over the period 1980-2017 at Jenapur gauge station located in the direct catchment of Bhitarkanika was 5446292 MT. The sediment load is showing declining trend over 1980-2017.
g) Hydraulic structures	The Rengali, Salandi and Mandira reservoirs are the largest water bodies in the Brahmani–Baitarani basin. The reservoir area of Rangali is 44,940 ha. As per the available data in India-WRIS, Rengali is the largest reservoir in the basin in terms of storing capacity. No. of water resource structures: Dams = 61; Barrages = 5; Weirs = 4; Anicuts =1; Lifts = 0; Power Houses = 1. No. of water resource projects: Irrigation projects - major = 8; medium = 35; extension, renovation and modernisation = 4; Hydroelectric = 1.	GOI Ministry of Water Resource Brahmani and Baitarani Basin, March 2014	Data for the year 2002 is not available.		Rengali Dam constructed on Brahmani river, is the reservoir which control freshwater flow into Brahmani basin in Odisha. The dam is located in Angul District, Odisha. The Water Resources Department, Government of Odisha, have been very active to create new projects with specific purposes of irrigation, flood control to possible extent and hydro-power generation in Brahmani and Baitarani basin. Odisha has planned to utilise some more water resources in the second phase of

Ecological Components	Current / Latest Status	Data Assessment Year & Source	Status at the Time of Ramsar Site Designation (2002) Baseline	Data Assessment Year and Source	Trend
Catchment climate					
					Rengali Irrigation Project, a barrage scheme constructed across Brahmani river at Samal in Angul district, 35 km downstream of Rengali dam project. The Mega Drinking Water Project at Nuahat under
					Chandabali Assembly segment of Bhadrak on Bhadrak-Kendrapara Border for supply of drinking water to Bhadrak and Balasore districts aims for extracting water from Kharasrota River that flows between Aul and Rajkanika blocks situated in the Kendrapara district of Odisha. The project will also adversely affect the entire Bhitarkanika Sanctuary as it is dependent for its survival on this river.

Ecological Components	Current / Latest Status	Data Assessment Year & Source	Status at the Time of Ramsar Site Designation (2002) Baseline	Data Assessment Year and Source	Trend
Catchment climate					
h) LULC - in direct catchment	LULC analysis of year 2020: Mixed Forest (2.6%), Crop Land (76.1%), Built up Land (7.7%), Scrub Land (1.5%), Fallow Land (3.5), Water bodies (5.7%), Plantations (0.3%) and Mangroves (2.5%).	CDA Final Report, July 2021	LULC analysis of the year 2005 showed that Mixed Forest (2.7%), Crop Land (82.7%), Built up Land (4.5%), Scrub Land (1.5%), Fallow Land (0.9%); Water bodies (5%); Plantations (0.2%) and Mangroves (2.5%).	CDA Final Report July 2021	Change pattern analysis between year 2005 and 2020 showed a net decline in cropland area whereas built-up land and fallow land showed a significant increase in area.
i) Coastline erosion	During 2010–2020, the maximum accretion was 144.72 m, while the maximum erosion was 264.62 m in the Bhitarkanika coast.	CDA Final Report, July 2021	During 1989-2000, max accretion was 222.23 m while max erosion was 221.20 m in the Bhitarkanika coast.	CDA Final Report July 2021	The shoreline changes in last 45 years (1975-2020) were analysed to understand the erosion and accretion pattern. The coastal stretch between Pentha and Banspani River is experiencing significant erosion phenomena at a higher rate with maximum erosion rate of 17.16 m/yr. A small stretch near north of the Hansua River mouth shows accretion during 1975-2020 at maximum rate of 12.43 m/yr while the remaining part of the Bhitarkanika coast is experiencing erosion.

Ecological Components	Current / Latest Status	Data Assessment Year & Source	Status at the Time of Ramsar Site Designation (2002) Baseline	Data Assessment Year and Source	Trend
Catchment climate					
j) Salt water intrusion	No assessments have been carried out.		No data available for year 2002.		No historical records/assessments available for trend analysis.
Sanctuary hydrology					
a) Hydrolo gical connectivity	The sanctuary is influenced by freshwater inputs from three rivers (Brahmani, Baitarani and Dhamra). The outflow to the sea as well as the saline water ingress during high tides occurs through the Dhamra, Maipura and Hansua estuary mouths.	CDA Final Report, July 2021	During 2002, also the major freshwater inlets were Brahmani, Kharsua and Baitarani. The outlets to BoB were Dhamra, Maipura and Hansua estuary mouths.	Satellite imagery 2000	As per current status, hydrological connectivity is maintained but there is reduction in freshwater flow and sediment load.
b) Water balance	The average annual total flow of freshwater during 2002–2012 was 23,551.3 million cubic metres (MCM). Of this 19,924.4 MCM (85%) and 3625.6 MCM (15%) flowed during the monsoon and the non-monsoon season, respectively. Full water balances including marine flows have not been attempted. No assessments have been carried out.	Das, 2017	No historical records available.		Overall, the supply of water at Bhitarkanika Sanctuary is expected to decrease to 46.12% (in the year 2051) from 74.64% (in the year 2001) after consumption of water in both the basin.

Ecological Components	Current / Latest Status	Data Assessment Year & Source	Status at the Time of Ramsar Site Designation (2002) Baseline	Data Assessment Year and Source	Trend
Sanctuary hydrology					
c) Groundwater infiltration and seepage	No assessments have been carried out.		No data available for year 2002.		No historical records/assessments available for trend analysis.
d) Tidal inflow/outflow/stream variation	No assessments have been carried out.		No data available for year 2002.		No historical records/assessments available for trend analysis.
e) Surface – groundwater connectivity	No assessments have been carried out.		No data available for year 2002.		No historical records/assessments available for trend analysis.
f) Aquifer depth	No assessments have been carried out.		No data available for year 2002.		No historical records/assessments available for trend analysis.
g) Tidal regime	The tide data of Dhamra coast were analysed for a 12 month period from May 2012 to April 2013. The river flow in the sanctuary is influenced twice daily by high and low tides at approximately 6-hourly intervals.	CDA Final Report, July 2021. Source data: State Project Management Unit, ICZMP, Odisha	No data available for year 2002.		The spring tidal range is 3.1 - 3.7 m and the neap tidal range is 0.6 - 1.4 m. The tide along this coast is mostly meso-tidal and semidiurnal in nature.
Energy-nutrient dynamics					
(a) Primary production	Mean GPP for winter was found to be 5.9 g C m^{-2} day^{-1} (with maximum of 11 g C m^{-2} day^{-1}). Summer mean of GPP was least among all	Lele et al., 2021	No data available for year 2002.		No historical records/ assessments available.

Ecological Components	Current / Latest Status	Data Assessment Year & Source	Status at the Time of Ramsar Site Designation (2002) Baseline	Data Assessment Year and Source	Trend
Energy-nutrient dynamics					
	seasons (1.2 with maximum of 5.9 g C m^{-2} day^{-1}), while the post-monsoon season was intermediate (mean GPP of 1.7 and maximum of 5.2 g C m^{-2} day^{-1}) in Bhitarkanika National Park.				
b) Nutrient cycling (carbon, nitrogen)	No assessments have been carried out.		No data available for year 2002.		No historical records/ assessments available.
Ecological processes					
(a) Fish recruitment and migration	No assessments have been carried out.		No data available for year 2002.		No historical records/ assessments available.
(b) Mangrove species succession	No assessments have been carried out.		No data available for year 2002.		No historical records/ assessments available.
(c) Rate of sedimentation	No assessments have been carried out.		No data available for year 2002.		No historical records/ assessments available.
(d) Rate of erosion	No assessments have been carried out.		No data available for year 2002.		No historical records/ assessments available.
e) Tidal inundation regime	No assessments have been carried out. Tide gauge stations are not installed within the sanctuary.		No data available for year 2002.		No historical records/ assessments available.

Ecological Components	Current / Latest Status	Data Assessment Year & Source	Status at the Time of Ramsar Site Designation (2002) Baseline	Data Assessment Year and Source	Trend
Ecosystem services					
(a) Provisioning services	The total fish catch from Bhitarkanika Sanctuary was 3.77 kg/h having a market price of US$2.25. It was also found that mangrove sites had considerably high fish yields, 123.34 kg/h (earning US$ 44.62/h) compared with sites without mangroves, where the yield was 17.89 kg/h (earning US$2.62/h).	Hussain and Badola, 2010	The estimated value of fish catch per hour was Rs. 89.91 for 3.77 kg.	Study period March-July 2002 (Badola and Hussain, 2003)	No historical records /assessments available for trend analysis.
(b) Cultural services	It includes religious as well as touristic values, which are important contributions to livelihood capitals. Bhitarkanika National Park witnessed an increase in the flow of visitors for its rich scenic beauty.	Mangrove Forest Division WL, Rajnagar. Source data 2008 - 2013	No data available for year 2002.		Trends on tourist data and revenue collected indicate increasing touristic activity in Bhitarkanika. (Mangrove Forest Division WL, Rajnagar Source data 2008-2013).
(c) Regulating services	Latest assessments are not available.		The value of nitrogen, phosphorus and potassium in one hectare of mangrove soil was found to be Rs 29070/ kg, Rs 433.74/kg and Rs 11092.66/kg respectively, while it was Rs 20576.70/kg, 309.83/kg and Rs 8667.24/kg, respectively, in 1 ha of non-mangrove soil in Bhitarkanika mangrove forest.	Study period 2001-2002 (Badola and Hussain, 2003)	No historical records/ assessments available for trend analysis.

11.2 Threats to Ecological Character

Based on the analysis of wetland features and status and trends of components, processes and services, threats to ecological character have been identified. The threats have been further linked to the likely influence on the ecological character and the likelihood of change ranked as high, medium or low.

Major threats to ecological character	Cause of the threat	Likely biotic response	Likely impact on ecosystem services	Degree of impact (low, medium, high)	Current management /practice recommendations
a) Rising surface air	Rising greenhouse gas emissions due to anthropogenic activities	The increase in surface air temperatures in Brahmani-Baitarani basin will impact various mangrove species. Increases in temperature as projected in Brahmani and Baitarani basins can disrupt physiological processes including reduction in photo-synthetic rates that decrease leaf formation, which affects the net productivity. High surface temperatures also increase evapotrans-piration, thus rendering water more saline. Warming results in ice-melting and oceanic expansion, thus triggering a sea-level rise that in turn alters mangrove distribution by shifting the species upwards inland.	Loss of mangrove species will lead to loss of ecological functions (hydrological flux, biological productivity, carbon sequestration, sediment retention and pollutant sequestration and land accretion, shoreline protection, flood control, reduction in saline water intrusion).	High	Restoration and plantation of mangroves, mangrove associates, capacity building of forest staff for raising nursery and taking up mangrove plantation through different modules.

Major threats to ecological character	Cause of the threat	Likely biotic response	Likely impact on ecosystem services	Degree of impact (low, medium, high)	Current management /practice recommendations
		species upwards inland. Furthermore, changes in the species composition and flowering and fruiting periods are the other responses to increased temperatures.			
b) Rising sea level	Rising surface air temperature and other factors	The key consequence from increasing sea levels will be to increase the flooding of deltaic regions, which adds to the misery of local communities, with frequent floods. This could also lead to a decline in the freshwater supply, increase the coastal erosion and salt water intrusion and reduce productive deltas. The eroding beaches also pose a threat of seawater intrusion into the agricultural fields adjacent to the coast.	This will impact the agricultural land making them more saline unfit for cropping. Loss of mangroves will happen in erosion prone area. Loss of nesting and breeding ground of the endangered Olive Ridley sea turtles.	High	Coastal protection structures at Bhitarkanika coast. Laying of geosynthetic tubes in the seabed. Coastal aforestation as the next layer from the present beach towards the land to stabilise the beach and to act as a second line of defense. Construction of the embankment in the landward side as a last line of defense against sea water intrusion into the agriculture fields.
c) Natural disasters such as floods, cyclones, tsunamis and droughts	Rising surface air temperature, sea level rise and other factors.	The coastal part of the Brahmani and Baitarini basins is severely impacted by cyclonic storms. These influence the sanctuary, its	Loss of mangrove species and loss of carbon sequestration capacity of mudflats, loss of shoreline will lead to loss of nesting and breeding ground of the	High	The areas along the many of the tidal rivers and creeks in the area which are non-forest lands are presently devoid of mangroves. It is,

Major threats to ecological character	Cause of the threat	Likely biotic response	Likely impact on ecosystem services	Degree of impact (low, medium, high)	Current management /practice recommendations
		shoreline and salinity regime due to saline water intrusion. Cyclones cause physical damage to mangroves, which affects the overall ecology of the sanctuary. Storm surges associated with cyclonic storms also cause serious damage to the coastal structures and are responsible for landward movement of the shoreline and coastal erosion. IPCC (2007) also stated that an increased sea surface temperature has been demonstrated to increase the number and frequency of hurricanes since the 1970s.	endangered Olive Ridley sea turtles.		therefore, proposed to take up plantation of mangroves /mangrove associates in the above areas which in the long run will act as a natural cyclone shelter belt. The above will also help in stabilisation of tidal river banks, prevent soil erosion and act as a buffer zone.
d) Anthropogenic activities in the sanctuary	Encroachment of forest land for agriculture /prawn culture, chemical discharges form prawn gherries, increasing demand on the forest for firewood, small timber, fodder and other forest products. In and around the site, a large	Destruction or degradation of mangrove patches.	Loss of mangrove associated ecosystem services.	Moderate	Intensive patrolling in the sanctuary (Marine Protection squad) and in peripheral villages is essential to keep a check on the environment degrading anthropogenic activities by the local villagers. Regulating coastal aquaculture to

Major threats to ecological character	Cause of the threat	Likely biotic response	Likely impact on ecosystem services	Degree of impact (low, medium, high)	Current management /practice recommendations
	chunk of the agriculture land adjacent to rivers and creeks has been converted to prawn farms. Increasing pressure of tourists, illegal fishing and over-fishing in rivers and creeks. There are known pollution-causing industries such as Oswal and Paradeep Phosphate Limited around Bhitarkanika that could affect the ecological soundness. The use of chemicals and pesticides in agricultural fields and effluents coming from the large number of prawn gherries has an impact on the wildlife, depending on the aquatic habitat.				ensure sustained increase in aquaculture products while protecting environment. Creating awareness of environmental protection among local coastal communities for protection of mangroves and sustainable aquaculture practices and other eco-development initiatives.
e) Industrial activity in the basin	The sanctuary has been facing an increasing threat of water pollution from different industrial developmental activities, especially	Destruction or degradation of mangrove patches.	Loss of mangrove -associated ecosystem services.	High	The environmental quality monitoring mechanism should be included in the Management Action Plans (MAPs) for conservation and management of

Major threats to ecological character	Cause of the threat	Likely biotic response	Likely impact on ecosystem services	Degree of impact (low, medium, high)	Current management /practice recommendations
	from the Angul- Talcher region of the basin.				mangroves by establishing a dedicated laboratory facility for long term research and monitoring. Carrying capacity study is essential before any new mine or industry comes up in Brahmani and Baitarani basin. The water requirement by proposed infrastructure should be analysed for their impact on dependent ecosystems such as Bhitarkanika.
f) Reduction in freshwater flow and sedimentation	Increasing number of water resource development projects diverting water for human and agriculture use.	Changes in mangrove species composition and spatial distribution. Loss of oligohaline mangrove species.	Changes in salinity regime will affect the mangrove ecology and fish stock of the sanctuary as the sanctuary is the nursery and spawning ground of several species of fish and prawn.	High	Maintenance of water accounts, in terms of withdrawals, consumption and returns, separately for individual sectors (water for agriculture, people and nature) need to be assessed and integrated in order to understand the real impacts of land and water use and management policies.

11.3. Knowledge gaps and monitoring needs

	Ecological components / precesses and services	Criticality for management plan monitoring	Info available in literature / secondary data	Knowledge gaps	Monitoring need
1.	Wetland soil - Texture - Nutrient cycling	Medium (Biogeochemical processes will be helpful to understand the nutrient cycling in sanctuary)	No systematic data available.	Trends in biogeochemical properties of sediments and water.	Seasonal monitoring of biogeochemical properties
2.	Rate of sedimentation	High	No data available	Trends in sedimentation	Periodic Bathymetric survey of rivers under Bhitarkanika Sanctuary is required to study the sedimentation.
3.	Physico-chemical water (temperature, pH, salinity, DO, transparency, nutrients, cations and anions)	High (Salinity, nutrients, particularly in the context of sustenance of mangrove species)	No systematic data available.	Long term trends and criticality of parameters observed in the context of management objectives.	Monthly monitoring and trends analysis is proposed to be covered under Ecosystem Health Assessment.
4.	Energy Nutrient dynamics; primary production (nutrient cycling, carbon cycling)	Medium	No systematic data available.	Trends in primary production, carbon and nutrient cycling and their relationship with mangroves.	Seasonal assessments of primary productivity and nutrient cycles.
5.	Physical form - Area - Bathymetry - Shape	High	Bathymetric information is not available for rivers. Shoreline change pattern available.	Trends in bathymetry are critical for sediment load.	Bathymetry (for every five years) Shoreline changes (at least decadal).
6.	Biota - Wetland plants - Vertebrate fauna (fish, reptiles and water birds) - Phytoplankton	Medium	Studies are available on mangroves, fishes and birds.	Limited information is available on sediment and water microbial communities, phytoplankton and benthic	Comprehensive survey of microbial communities, phyto -plankton is lacking. At least, seasonal surveys should be done especially from mudflats and water

	Ecological components / precesses and services	Criticality for management plan monitoring	Info available in literature / secondary data	Knowledge gaps	Monitoring need
	- Microbial communities (benthic and pelagic) - Aquatic macro-invertebrates			fauna, species invasion risk and conducive factors.	as they are crucial for recycling of nutrients, carbon storage and productivity of the lagoon.
7.	Climate - Precipitation - Air temperature - Evaporation - Wind - Humidity	High	Covered in IMD monitoring system.	Long term climate trends and impacts on hydrological regimes, physico-chemical properties of water and biota.	Climate change modeling for Bhitarkanika Sanctuary and basin, linking scenarios with changes in ecological character.
8.	Geomorphology - Topography - Connectivity to surface waters - Water sources - Soil - Erosion	High	Connectivity with rivers, surface waters assessed through hydrological modeling by only a few studies.	Regional patterns in geomorphology (covering Brahmani and Baitarani basin and the Bay of Bengal systems) and linking to changes to hydrological regimes, sedimentation patterns and biota.	Regional studies on geomorphology and linkages with Sanctuary basin and sub basin changes.
9.	Hydrology - Water balance - Groundwater infiltration and seepage - Surface groundwater interactions - Tidal regimes - Inundation regimes	High	Assessment of water inflows and outflows is done by CWC gauge stations. Tide monitoring stations are lacking for assessing tidal observations.	Water balance, with overall contribution of freshwater and marine sources, surface-groundwater abstractions (highly relevant to assessment impacts on salinity regime and mangrove ecology).	Long-term observation of discharge at upstream of Bhitarkanika Sanctuary (Pattamundai, Aul and Chandbali) could give more realistic view of freshwater supply to the sanctuary. Similarly, the long-term observation of discharge to sea (Tidal prism) at Hansua, Maipura and Dhamra river estuary could substantiate the water. Long-term observation of tide near Dhamra port,

	Ecological components / precesses and services	Criticality for management plan monitoring	Info available in literature / secondary data	Knowledge gaps	Monitoring need
					Dangamala and Gupti could help to understand the tidal hydro-dynamics.Seasonal simultaneous longitudinal observation of salinity (through each river from estuary to upstream) could help to know the extent of saline water propagation. Long-term observation of weather parameter at Dangamala.
10.	Processes that maintain animal & plant populations - Mangrove diversity - Fish migration - Crocodile population	High	Limited information is available on the impact of hydrological regime (quantity and quality), salinity changes and pollutants on mangrove ecology and diversity.	Likely impacts of climate change.	Need to continue assessments and link to changes in physico-chemical water parameters.
11.	Wetland soil - Texture - Nutrient cycling	Medium (Biogeochemical processes will be helpful for understand the nutrient cycling in the sanctuary)	No systematic data available.	Trends in biogeochemical properties of sediments and water.	Seasonal monitoring of biogeochemical properties.
12.	Rate of sedimentation	High	No data available	Trends in sedimentation	Periodic Bathymetric survey of rivers under Bhitarkanika Sanctuary is required to study the sedimentation.

	Ecological components / precesses and services	Criticality for management plan monitoring	Info available in literature / secondary data	Knowledge gaps	Monitoring need
13.	Physico-chemical water (temperature, pH, salinity, DO, transparency, nutrients, cations and anions)	High (Salinity, nutrients, particularly in the context of sustenance of mangrove sp.)	No systematic data available.	Trends in primary production, carbon and nutrient cycling and their relationship with mangroves.	Seasonal assessments of primary productivity and nutrient cycles.
14.	Energy nutrient dynamics; primary production (nutrient cycling, carbon cycling)	Medium	No systematic data available.	Trends in primary production, carbon and nutrient cycling and their relationship with mangroves.	Seasonal assessments of primary productivity and nutrient cycles.
15.	Physical form - Area - Bathymetry - Shape	High	Bathymetric information is not available for rivers. Shoreline changes pattern available.	Trends in bathymetry are critical for sediment load.	Bathymetry (for every five years) Shoreline changes (at least decadal).
16.	Biota - Wetland plants - Vertebrate fauna (Fish, Reptiles and Water birds) - Phytoplankton - Microbial communities (benthic and pelagic) - Aquatic macro-invertebrates	Medium	Studies have been conducted on mangroves, fishes and birds.	Limited information is available on sediment and water microbial communities, phytoplankton and benthic fauna, species invasion risk and conducive factors.	Comprehensive survey of microbial communities, phytoplankton is lacking. At least, seasonal surveys should be done especially from mudflats and water as they are crucial for recycling of nutrients, carbon storage and productivity of the lagoon.
17.	Climate - Precipitation - Air temperature - Evaporation - Wind - Humidity	High	Covered in IMD monitoring system.	Long term climate trends and impacts on hydrological regimes, physico-chemical properties of water and biota.	Climate change modeling for Bhitarkanika Sanctuary and basin, linking scenarios with changes in ecological character.

	Ecological components / precesses and services	Criticality for management plan monitoring	Info available in literature / secondary data	Knowledge gaps	Monitoring need
18.	Geomorphology -Topography - Connectivity to surface waters - Water sources - Soil - Erosion	High	Connectivity with rivers, surface waters assessed through hydrological modeling by only few studies.	Regional patterns in geomorphology (covering Brahmani and Baitarani basin and the Bay of Bengal systems) and linking to changes to hydrological regimes, sedimentation patterns and biota.	Regional studies on geomorphology and linkages with Sanctuary basin and sub basin changes.
19.	Hydrology - Water balance - Groundwater infiltration and seepage - Surface groundwater interactions - Tidal regimes - Inundation regimes	High	Assessment of water inflows and outflows is done by CWC gauge stations. Tide monitoring stations are lacking for assessing tidal observations.	Water balance, with overall contribution of freshwater and marine sources, surface-groundwater abstractions (highly relevant to assessment impacts on salinity regime and mangrove ecology).	Long-term observation of discharge at upstream of Bhitarkanika Sanctuary (Pattamundai, Aul and Chandbali) could give more realistic view of freshwater supply to the sanctuary. Similarly, the long-term observation of discharge to sea (Tidal prism) at Hansua, Maipura and Dhamra river estuary could substantiate the water. Long-term observation of tide near Dhamra port, Dangamala and Gupti could help to understand the tidal hydrodynamics.Seasonal simultaneous longitudinal observation of salinity (through each river from estuary to upstream) could help to know the extent of saline water propagation. Long-term observation of weather parameter at Dangamala.

	Ecological components / precesses and services	Criticality for management plan monitoring	Info available in literature / secondary data	Knowledge gaps	Monitoring need
20.	Processes that maintain animal and plant population - Mangrove diversity - Fish migration - Crocodile population	High	Limited information is available on the impact of hydrological regime (quantity and quality) salinity changes, pollutants on mangrove ecology and diversity.	Likely impacts of climate change.	Need to continue assessments and link to changes in physico-chemical water parameters.

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