

# Chapter 10

## Geomorphology, Land Use/Land Cover and Sedimentary Environments of the Chilika Basin



Rajiv Sinha, R. Chandrasekaran, and Neeraj Awasthi

**Abstract** The Chilika is one of the largest brackish water lagoons in Asia and is well known for its biologic diversity. Designated as one of the Ramsar sites in 1981, Chilika was under serious threat in the late 1990s due to severe physical and ecological degradation. Some of the severe problems included large-scale siltation and reduction in the water level as well as salinity, threatening some of the rare species of fauna in this region. Following a significant intervention in the form of opening a new mouth in 2000, Chilika recovered significantly and is undoubtedly a model example of wetlands restoration. This chapter aims at documenting this success story based on geomorphic studies in and around Chilika using remote sensing images for the period 1980–2015. We have also mapped land use/and cover changes for two different periods 1980–2000 and 2000–2015 to understand the causal factors of the degradation. We conclude that despite the dynamic geomorphic environment around the Chilika, the intervention in 2000 has had a positive effect this far, but needs close monitoring. Anthropogenic impacts in the Chilika Basin are expressed in terms of significant increase in urban settlements at the cost of natural land cover such as scrub forest, agriculture plantation and wastelands. Some improvement in terms of increase in evergreen forest is recorded in the post-intervention period. However, a close vigil on this very sensitive ecosystem is desirable.

**Keywords** Lake geomorphology · Remote sensing · Wetland mapping · Ecosystem · Human impacts

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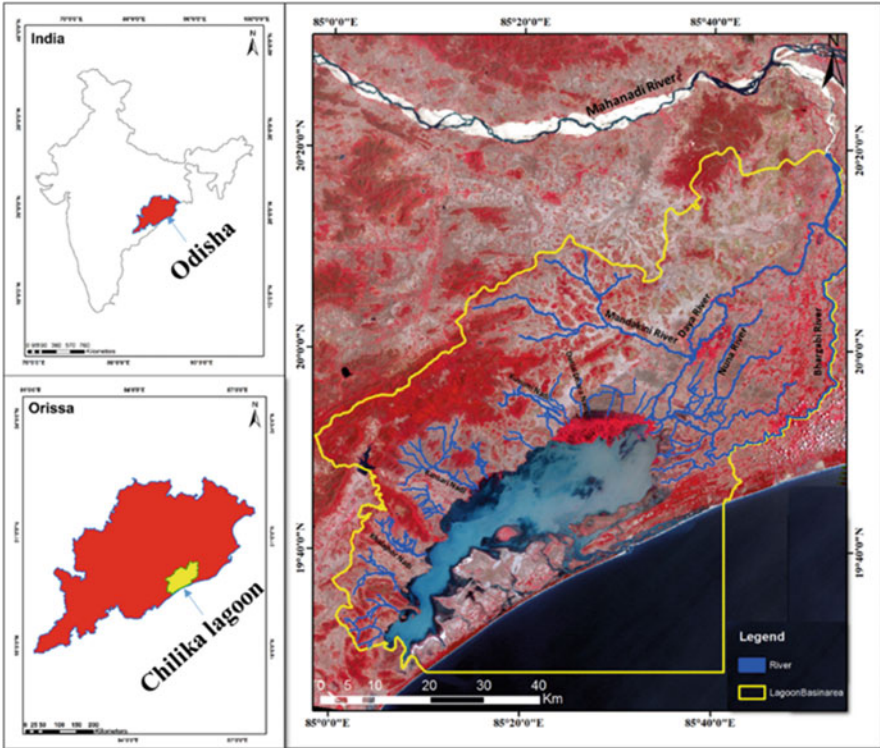
## 10.1 Introduction

India is gifted with innumerable natural resources comprising mineral deposits, forests, vast expanses of fertile land for agricultural activities, rivers, wetlands, and water bodies such as ponds and lakes. Wetlands, either human-made or natural, freshwater or brackish play an imperative role in the terrestrial landscape and in maintaining environmental sustainability. Irrespective of their size, wetlands play a significant role in securing social well-being of people by providing drinking water, livelihood, improving groundwater conditions and controlling floods. These water bodies also play a substantial role in maintaining rich biodiversity. In recent years, along with natural forces, human activities have been identified as the dominant force responsible for adverse impacts on the wetlands ecosystems. Because of human encroachment, sewage disposal, eutrophication, and heavy metal pollution, many wetlands throughout the world (e.g. Okeechobee in Florida, Arre in Denmark, Balaton in Hungary, Biwa in Japan, Baikal in Russia, Victoria in Africa, Great Lakes of North America etc.) are showing varying degree of environmental degradation (Williams 2002). Land use/land cover (LULC) changes brought by a variety of social causes, and human activities have significantly affected the wetland environment and its biodiversity in different parts of the world (Zorrilla-Miras et al. 2014; Valdez et al. 2016).

Chilika ( $19^{\circ}30' - 20^{\circ}30'N$  and  $85^{\circ}00' - 86^{\circ}00'E$ ), situated on the East Coast of India, is one of the largest brackish water tropical lagoons in Asia (Fig. 10.1). The wetland, covering an area of  $1165 \text{ km}^2$  during the peak monsoon season supports the livelihood of more than 1.5 lakhs fishermen living in 132 villages and is also well-known for its unique assemblage of marine, brackish, and freshwater ecosystem with estuarine characters (Kumar and Pattnaik 2012). In the Indian sub-continent, it is also one of the largest wintering grounds for the migratory birds within the Central and East Asian Australasian Flyway. During the peak migratory season, the Chilika hosts around 225 bird species alongwith a highly productive fishery (Kumar and Pattnaik 2012).

Given its rich biodiversity, the wetland was designated as a “Ramsar Site” in 1981 under the Ramsar Convention on Wetlands (Pattnaik 2002; Kumar and Pattnaik 2012). However, the Chilika started facing severe problems since 1990s arising from natural as well as anthropogenic activities (Sarkar et al. 2012). The major problems included (a) decline in the salinity of the lake (b) increased input of nutrients resulting in extensive macrophyte growth, eutrophication and their decomposition leading to anoxia and hypoxia-like conditions (Sahu et al. 2014), (c) changes in the strength and nature of hydrological regimes in the upstream, and (d) pollution from agriculture, aquaculture, and domestic waste.

The present study aims to map different landforms and LULC in the Chilika basin to evaluate spatial variability and temporal dynamics of geomorphic and anthropogenic processes during the last 35 years. Remote sensing and GIS are important tools to understand the global, regional, and local scale processes that affect the earth, and therefore, have a wide range of applications in the field of geology, agriculture,



**Fig. 10.1** Location map of Chilika Basin on the east coast of India. The Landsat image (False Color Composite) shows the various landscape elements in the region; blue color represent water in and around the Chilika Lake, red color shows the vegetation cover. Major drainage lines feeding the Chilika Lake are also drawn in blue

environment and integrated ecological assessment (Hudak and Wessman 1998; Fung and Ledrew 1987; Yeh and Li 1998; Long et al. 2008). Historical maps and remote sensing data have been used in a GIS framework to document these changes and to understand (a) the level of degradation of the Chilika during 1980s, and (b) the recovery of the Chilika after the implementation of a rehabilitation programme by the Chilika Development Authority (CDA) during late 1993.

## 10.2 Study Area

The Chilika lake runs parallel to the coastline of the Khordha and Ganjam districts of Odisha in northeast to southwest direction. The length and width of the lagoon are about 65 km and 20 km, respectively. To the north, west, and south, the lagoon is bordered by the Eastern Ghat hill ranges whereas to the east, a 60 km long sand bar

separates the Chilika from the Bay of Bengal (Kumar and Pattnaik 2012). The lagoon opens into the Bay of Bengal through a 24 km long narrow outer channel that runs parallel to the coastline (Sarkar et al. 2012). Until September 2000, the Chilika had a major mouth (apart from others) opening in the Bay of Bengal near Arakhakuda. An artificial opening was created near Satapada connecting the Chilika with the Bay of Bengal (Sarkar et al. 2012). At the southern end of the lagoon, the ~18 km long “Palur Canal” connects the Rambha Bay to the mouth of the Rushikulya Estuary. The Chilika along with six other small streams between the Mahanadi and the Rushikulya River forms the part of the Mahanadi Basin. Chilika’s catchment area spans 4406 km<sup>2</sup>, 68% of which is drained by non-perennial rivers and streams from the western catchment and 32% by the distributaries of the Mahanadi River entering into the lagoon from the north-eastern end (Sarkar et al. 2012). On the basis of water salinity, depth, and ecological conditions, the Chilika has been broadly divided into four sectors, namely the northern, central, southern and outer channel.

The Chilika catchment experiences a tropical monsoonal climate with an average annual rainfall of 1300 mm and temperatures between 14 °C and 40 °C (Sarkar et al. 2012). The wind changes its direction under the influence of southwest and northeast monsoons with speed varying from 19 to 58 km/h (Sarkar et al. 2012). The water level in the lagoon fluctuates seasonally and during high and low tides. During rainy season, the Chilika expands to an area of over 1165 km<sup>2</sup> with the water depth varying from 1.8 to 3.7 m whereas in dry season (December–June), the waterspread area reduces to 950 km<sup>2</sup> with water depth varying between 0.9 and 2.6 m (Mohanty et al. 1996; Ghosh and Pattnaik 2005). In winter (November–January), a large portion of the Chilika acts as breeding and nesting grounds for millions of migratory bird species. Severe cyclonic storms and sometimes, super-cyclones frequently hit the region during pre-monsoon months of May–June and end of monsoon/post-monsoon months of October–November. During these storms, the wind speed mounts to more than 200 km/h. Torrential rains with storm often accompany these surges 10–12 m high. These storms pose a serious threat to the environment of the lagoon and the people living around by causing a dramatic change in the population of the biotic communities (e.g. phytoplankton, zooplankton, higher plants, fishes and birds) and by flooding extensive lowland areas.

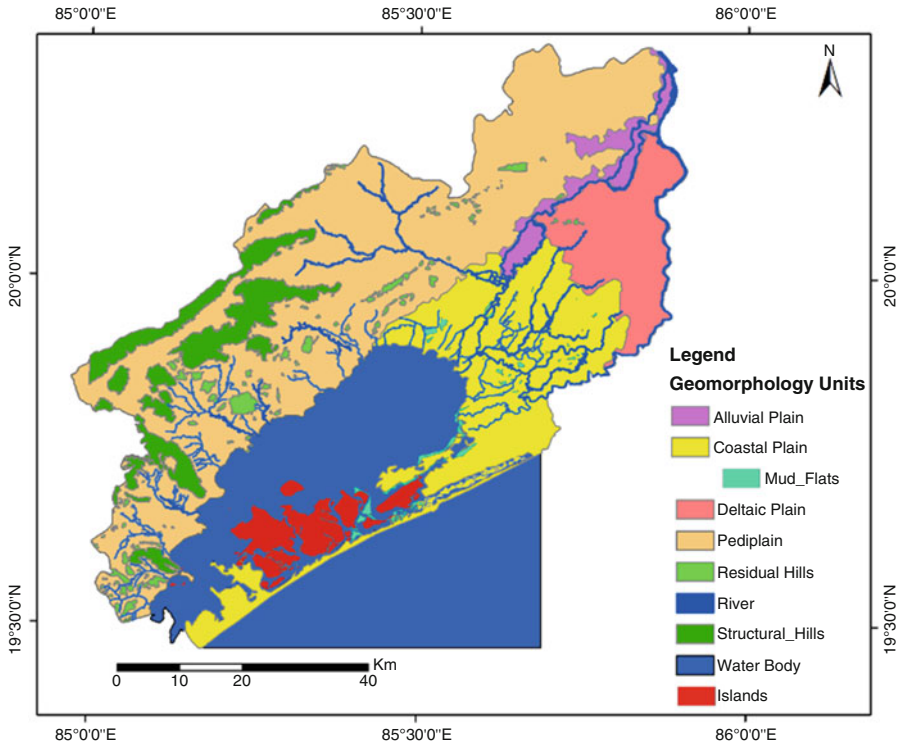
### 10.3 Data and Methods

This study utilised topographic maps and satellite imageries. The topographic maps (73E – 1, 2, 3, 5, 6, 9, 12, 15 and 16) of 1:50000 scales obtained from Survey of India were scanned and converted into digital format. These maps were georeferenced with longitude and latitude using ArcGIS (10.1) to demarcate the Chilika Lagoon boundary. Georeferenced Landsat satellite imageries were downloaded from USGS website (<http://earthexplorer.usgs.gov>) for the years 1980, 1988 (spatial resolution: 79 m), 2000, 2005, 2010, and 2015 (spatial resolution: 30 m). The ERDAS Imagine (2014 version) software was used to create False Color Composites (FCCs) and

ArcGIS (10.1) for extracting the study area. For LULC classification, 90 polygons were identified for different land use/land cover patterns in each imagery in ERDAS Imagine (2014) for a supervised classification using the maximum likelihood algorithm (Wu and Shao 2002; McIver and Friedl 2002). We selected 300 points randomly for accuracy assessment of the LULC classification of the Landsat images corresponding to 1980, 1988, 2000, 2005, 2010 and 2015. Accuracy assessment represents the error matrix, along with the overall accuracy and the Kappa coefficient. The Kappa coefficient is used to infer the superiority of one map production over another, and a value of more than 0.8 indicates a strong agreement or accuracy between classification map and the ground reference map (Jensen 2005). In the accuracy assessment, topographic sheets and Google Earth maps were used for the ground verification for the years of 2015, 2010, 2005, 2000. The geomorphic landforms within the lagoon were visually interpreted and manually digitized utilizing the ArcGIS (10.1).

#### **10.4 Geomorphology of the Chilika Basin and Lagoon Based on Remote Sensing Data**

The various geomorphic units in the Chilika Basin are shown in Fig. 10.2. The northern and western parts of the Lagoon are surrounded by structural hills, residual hills and pediplain whereas deltaic, alluvial, and coastal plains are present in the north-eastern and eastern parts. There is very little information available on the geomorphic evolution of the Chilika, particularly its origin. Pascoe (1964) suggested that it was a shallow brackish water inshore lake connected to the Bay of Bengal during the later stages of the Pleistocene period. However, a more recent study by Khandelwal et al. (2008) recovered a 8 m long sediment core from Chilika for a detailed sedimentological and pollen studies and argued that the Chilika was a part of a river or a river delta with fresh water vegetation about 13,500 years BP when the sea level was lower. It was only after ~9500 years BP, with the rise in sea level, it became an estuary and mangrove vegetation dominated the area. The fall in sea level after about 2000 cal years BP changed the morphology of the coast by forming barrier spits and sand ridges. Consequently, a large lagoon was formed replacing the marine species by fresh water species (Khandelwal et al. 2008). The discharge of sediments by the tributaries of the Mahanadi River might have added to the formation of the spit bars (Krishnan 1968). The longshore drift and tidal currents and probably strong winds shifted sands to the shore resulting in the growth of the barrier spits and sand ridges. The barrier beach protected the Chilika from any direct influence of the Bay of Bengal and gradually transformed the lake into a shallow lagoon. The presence of a number of shoals, sand spits, sand bars and openings of shallow depth helps in maintaining lake's estuarine character by considerably reducing the tidal flow in and out of the lake.



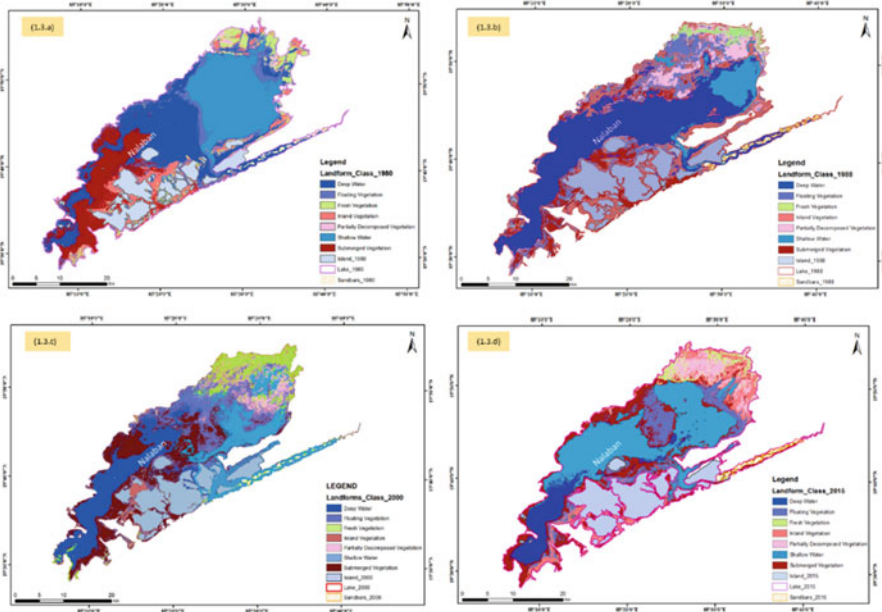
**Fig. 10.2** Regional geomorphology of the Chilika Basin prepared from satellite images (this work)

### 10.4.1 Geomorphic Landform Changes

To assess the landform changes within and around the Chilika, we have prepared geomorphic maps of the lagoon using satellite images corresponding to the months of April and May of 1980, 1988, 2000, 2005, 2010 and 2015 enabling a systematic assessment of changes in the landforms. The emphasis of geomorphic mapping was on (a) lagoon boundary, (b) barrier islands, and (c) sand bars (Fig. 10.3). We discuss the landform changes for two different periods namely (a) 1980–2000 (pre-intervention period) and (b) 2000–2015 (post-intervention period) to highlight the impact of the restoration program, particularly the opening of a mouth adjoining Satapada.

Table 10.1 documents some of the significant changes in landforms within the lagoon for the period 1980–2000 and 2000–2015. The lagoon area increased from 865.42 km<sup>2</sup> to 932.62 during 1980–1988 and decreased to 909.28 during 1988–2000 and then increased to 876.10 km<sup>2</sup> between 2000 and 2015. On the other hand, both island area, as well as sand bars, decreased during the period 1980–2000. The period 2000–2015, however, shows a slightly different trend. During this period, the island area kept on declining, but sand bars increased drastically from 4.78 km<sup>2</sup> to





**Fig. 10.3** Geomorphic maps of the Chilika for (a) 1980, (b) 1988, (c) 2000 and (d) 2015 documenting major landform changes during the period 1980–2015 prepared from repetitive satellite images (this work)

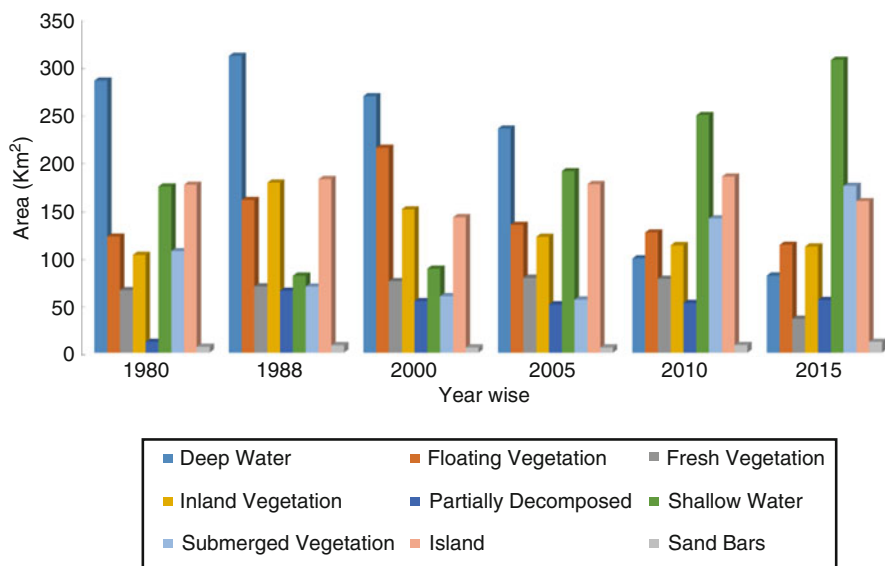
11.33 km<sup>2</sup>. It appears that the elevations of the islands are only slightly higher than the lagoon resulting in their submergence as the water level increases. While some of the sand bars were also submerged during the pre-intervention period, a drastic increase in their area in the post-intervention period suggests a much higher sediment flux through the new opening in September 2000.

Probing further, some of the most remarkable changes within the lagoon include a significant variation in various geomorphic elements (Table 10.1). During the period 1980–2000, all vegetation related elements (viz. floating vegetation, fresh vegetation, inland vegetation, and partially decomposed vegetation) show an increase whereas the submerged vegetation decreased drastically (Figs. 10.3, 10.4, and 10.5). This change may be the manifestation of decreased salinity, depth and degradation of the overall ecological condition of the lagoon.

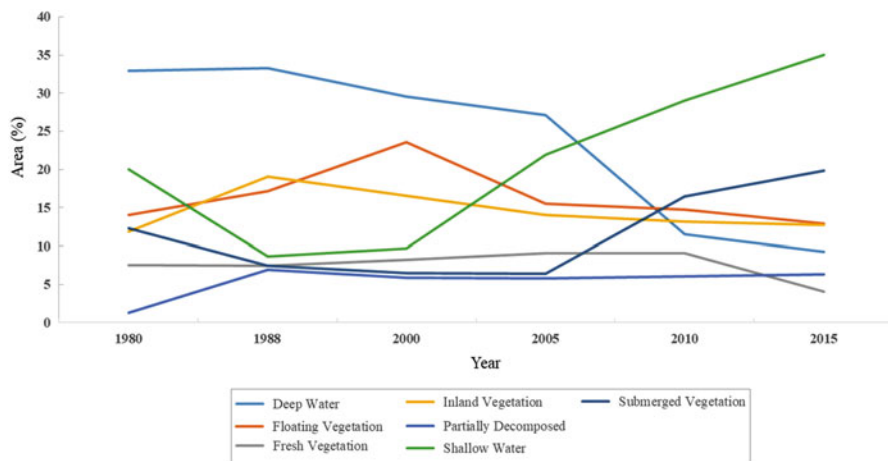
Interestingly, these trends seem to have reversed in the post-intervention period (November 2000–2015), and most vegetation related elements, except for partially decomposed vegetation, show a decrease. The area under submerged vegetation was observed to increase significantly during the latter period, which may be attributed to the revival of the conducive salinity regime. Although the deep water areas decreased drastically during this period, the shallow water areas showed a remarkable increase. We interpret this as a manifestation of increased sediment flux and siltation in the Chilika after the opening of the new mouth. An added factor is

**Table 10.1** Landform changes within the Chilika lake between 1980 and 2015

Type of Landform	1980	2000	2015	Remarks and Inference (after the implementation of programme)
	Area (Km <sup>2</sup> )	Area (Km <sup>2</sup> )	Area (Km <sup>2</sup> )	
Lagoon	865.42	871.80	876.10	Continuous increase; sedimentation rate increased, depth decreased causing submergence of island and increase in inundation
Island	175.49	167.44	158.90	
Sand bars	6.14	4.78	11.33	Decrease and then abrupt increase; passage to old mouth closed
Deep water	284.80	234.44	80.84	Deepwater continuously decreased but shallow water decreased and then abruptly increased; sedimentation rate increased, depth of the lake decreased
Shallow water	273.66	92.48	306.26	
Floating vegetation	144.69	245.37	112.94	Increase and then abrupt decrease; the salinity influx increased, fresh, floating and inland vegetation decreased
Fresh vegetation	65.39	79.71	23.12	
Inland vegetation	102.49	147.05	111.37	
Partially decomposed	11.04	45.06	55.08	Continuous increase; salinity influx increased, decomposed vegetation increased
Submerged vegetation	186.48	54.42	174.12	Decrease and then abrupt increase; salinity influx increased, submerged vegetation increased

**Fig. 10.4** Landform changes in Chilika Basin during the years 1980, 1988, 2000, 2005, 2010 and 2015





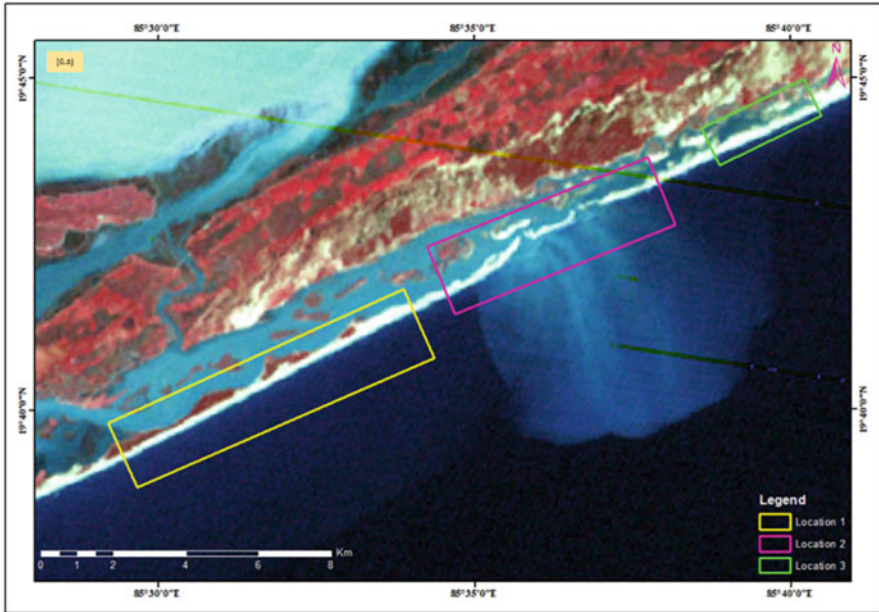
**Fig. 10.5** Landform as well as aquatic vegetation changes in Chilika Basin during the years 1980, 1988, 2000, 2005, 2010 and 2015

**Table 10.2** Tidal inlet changes in between 1980 and 2015

Type of landform	1980 (m)	2000 (m)	Mouth drift (1980–2000) (m)	2010 (m)	Mouth drift (2000–2010) (m)	2010 (m)	Mouth drift (2000–2015) (m)
Old mouth	264.50	160.00	7113.53	Closed	–	Closed	–
Artificial new mouth	–	232.00	–	320.00	1184.80	431.00	2269.46
Rate of mouth drifting/ year			355.68		118.48		151.29

possibly increased flux from the tributaries of the Mahanadi River. Another notable change is the increase in the aerial extent of the Chilika lagoon, mainly due to a decrease in water depth because of high sediment input from the Mahanadi and its tributaries (Figs. 10.3, 10.4, and 10.5). We suggest that the storage capacity of the lagoon decreased due to sedimentation and therefore water spilled to the shore areas thereby increasing the lagoon area.

We have also investigated the morphological changes around the tidal inlets during the period of observation. The natural mouth of the lagoon was 264.50 m wide in 1980 and situated in the NE part of the lake (Table 10.2, Figs. 10.6a and 10.6c). But in the year 2000, the natural mouth opening reduced to a width of 160 m and further shifted in NE direction approximately by 7 km (Fig. 10.6f and g). The drifting rate calculated was around 355.68 m per year that was much higher than the rate observed in the last 35 years.

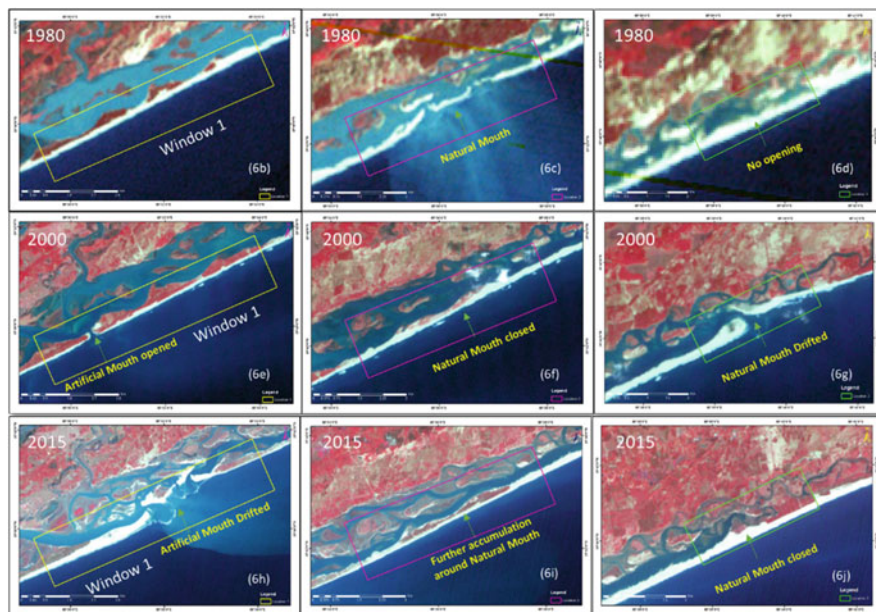


**Fig. 10.6 (a)** Landsat image of the area around the tidal inlet of Chilika. Rectangles mark the windows in which the detailed investigations were carried out

The reducing width of the old mouth severely threatened the Chilika due to problems such as shrinkage of water spread area, a decrease in depth due to siltation, salinity reduction, macrophyte infestation, eutrophication, and loss of biodiversity.

After a series of assessments on the wetland environment on changes in salinity, sedimentation rates, and freshwater macrophytes, the CDA decided to open a new mouth to improve the salinity and the biodiversity in and around the lagoon. In September 2000, a 232 m wide new artificial mouth was opened (Fig. 10.6e). The opening of new lagoon mouth and desiltation of the channel to the sea through the barrier beach at Satapada restored the natural flows of water and sediment by reducing the distance of outflow from the lake by 18 km. This opening vastly improved the lagoon-sea connection and helped to minimise the problems of sedimentation and invasive macrophytes (Ghosh et al. 2006).

The immediate positive impact was the stark and rapid recovery of the fishery along with the considerable improvement in salinity flux. Using the satellite measurements, we observed that by the year 2010, this artificial mouth shifted  $\sim 1$  km towards the northeast with an opening of 320 m and a drift rate of  $118.48 \text{ m year}^{-1}$ . The natural mouth had closed by that time and further accumulation occurred around this by 2015 (Fig. 10.6i). The artificial mouth with a width of 431 m drifted further to a distance of 2269.46 m by 2015 (Fig. 10.6h) with a drift rate of  $151.29 \text{ m year}^{-1}$ . The reconstruction of spit growth and its dynamics indicate that as the width of the mouth increased, so did the rate of drift. The drift was mainly due to large



**Fig. 10.6** (b–j) Changes in tidal inlets and opening of new artificial mouth in the three windows during the period 1980–2015

northerly littoral sediment transport that continuously shifted the inlet mouth towards the north, resulting in elongation of the channel and reduction in channel cross section (Ghosh et al. 2006).

## 10.5 LULC Classification

The term land cover refers to the kind and state of vegetation and subsequent usage such as human structures, soil type, biodiversity and water (Mayer et al. 1995). On the basis of National Remote Sensing Center (NRSC) land use classification system (NRSA 2008), there are nine LULC patterns that were identified in the study area (Table 10.3). These include: (1) settlements (2) agriculture, plantation (3) agriculture, fallow (4) forest, evergreen (5) forest, scrub forest (6) lagoon (7) inland wetland (8) barren/wasteland, and (9) water bodies. In the accuracy assessment, the overall accuracy of the classified image ranged from 80% to 84% and the Kappa coefficient was found to vary between 0.76 and 0.81 which is considered to be acceptable.

Figures 10.7 and 10.8 show the LULC maps of the study area for the period 1980–2015. Tabulations and area calculations provide a comprehensive data set in terms of the overall landform changes, the type, and extent of changes that occurred (Table 10.4). In the year between 1980 and 1988, the spatial pattern of LULC in the

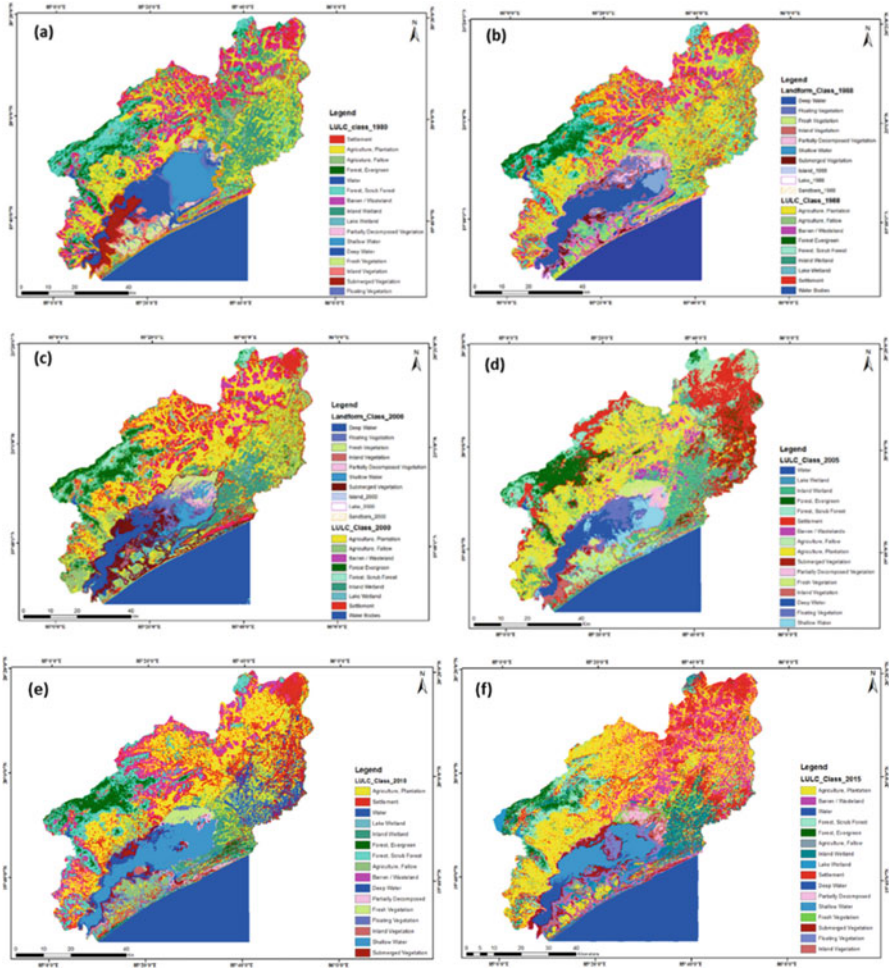
**Table 10.3** Description of LULC classes identified in the study area

Land use/Land cover types	Description
Settlement	Area of human habitation developed due to non-agricultural use and that has a cover of buildings, transport & communication, utilities associated with water, vegetation and vacant lands
Agriculture, plantation	Areas under agricultural tree crops adopting certain agricultural management techniques. It includes crops which are normally grown in the hilly regions (tea, coffee, rubber etc.,) and closely associated with forest cover
Agriculture, fallow	Lands taken up for cultivation but temporarily allowed to rest, uncropped for one or more seasons, but not less than 1 year
Forest, Evergreen	Areas that comprise of the thick and dense canopy of tall trees which predominately remain green throughout the year. It includes both coniferous and tropical leaved evergreen species
Forest, scrub forest	Forest areas where the crown density is less than 10% of the canopy cover, generally seen at the fringes of the dense forest cover and settlements where there is biotic and abiotic interference
Lake wetland	Water logged areas (seasonal and perennial) in and around the lake
Inland wetland	Areas that include ox bowlakes, cut off meanders, playas, swamp marsh etc.
Barren/wasteland	Areas where rock exposure of varying lithology, often barren and devoid of soil and vegetation cover is present. They occur amidst hill forests as opening or an isolated exposures on plateaus and plains
Water bodies	Areas with surface water either impounded in the form of ponds, lakes, reservoirs, or flowing streams, rivers, canals etc.

Source: National LULC mapping using multi-temporal AWiFs data, NRSA/LULC/1:250K/2008-3, 2008

Chilika Lake exhibits water, agriculture plantation, inland wetland and settlement as the most extensive types of LULC. This LULC pattern accounted for about 29–30%, 21–22%, 13–14%, and 10–11% respectively of the total study area (Table 10.4). But in the years between 2000 and 2015, the most extensive type of LULC constituted of water, agriculture plantation, settlement, and inland wetland in the study area and they represented about 26–32%, 17–20% 14–18% and 12–15% respectively of the total area (Table 10.4). The doubling of settlement area from a mere 9.74% in 1980 to 18.30% in 2015 reflects a significant human impact on the system during the last 3–4 decades.

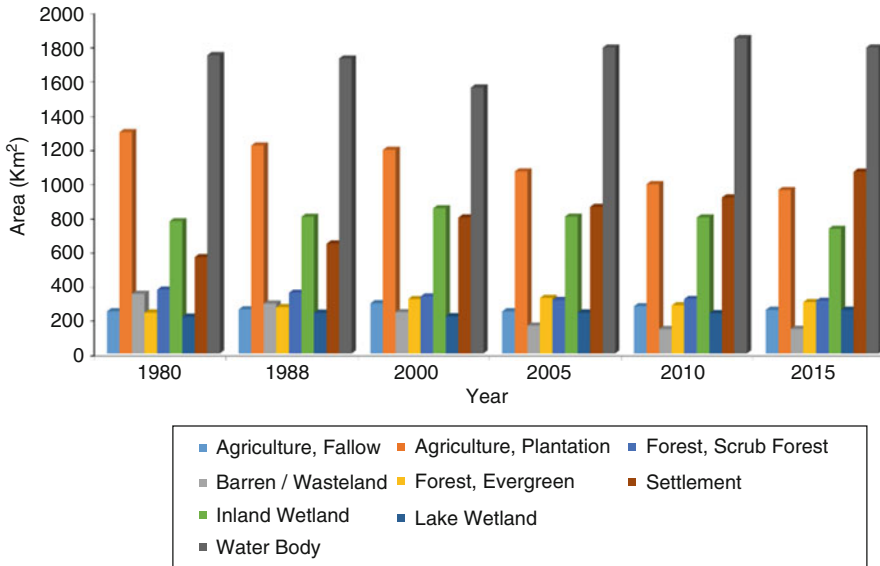
The increase has been particularly steep during 1980–2000, and it slowed down remarkably in the post-2000 period. It also appears that agriculture (plantation) and scrub forest suffered the maximum loss as both these classes show a continuous decrease during the entire period of 1980–2000. We interpret that most of the agriculture and scrub forest classes have been converted to settlements over time. Interestingly, the evergreen forest shows some increase between 1980 and 2000 but then got stabilised in the post-2000 period. The lake area shows a decrease between 1980 and 2000 but then has been increasing thereafter with minor variations, a clear manifestation of the opening of the new mouth.



**Fig. 10.7** Land use/land cover maps of Chilika Basin for (a) 1980, (b) 1988, (c) 2000, (d) 2005, (e) 2010 and (f) 2015 prepared from repetitive satellite images (this work)

During the period 1980–2015, significant changes were observed in the settlement, agriculture plantation and barren/wasteland areas while other classes do not show many differences. Between 1980 and 2015 (Table 10.4), the area of agriculture plantation (338.7 km<sup>2</sup>) and barren landform (204.9 km<sup>2</sup>) decreased and settlements (496.6 km<sup>2</sup>) increased. A two-fold increase in the settlement class is observed between 1980–2000 and 2010–2015 due to the increase in urban population. Similarly, Lake Wetland (40.53 km<sup>2</sup>) and water bodies (45.0 km<sup>2</sup>) increased due to new mouth opening in the year 2000. The scrub forest areas (65.16 km<sup>2</sup>) decreased and evergreen forest areas (62.57 km<sup>2</sup>) increased. This change implies





**Fig. 10.8** Land use/land cover changes in Chilika Basin during the period 1980–2015

that these scrub forest areas converted into evergreen forest due to high dense vegetation cover. Interestingly, overall agriculture fallow land does not show much variation between 1980 and 2015 (Fig. 10.9).

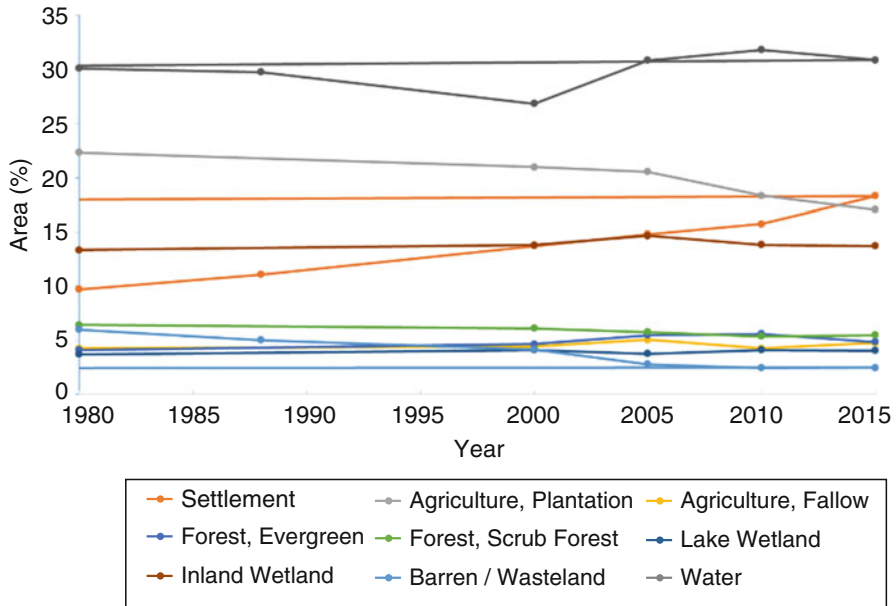
## 10.6 Sedimentary Environment of Chilika

Three hydrological subsystems influence the hydrology of the Chilika Lagoon namely, (a) the Mahanadi River system on the northern side, (b) small river channels on the western side, and (c) the Bay of Bengal on the eastern side (Kumar and Pattnaik 2012). The distributaries of the Mahanadi River namely, Daya, Nuna, Bhargavi and Makara drain directly into the Chilika (Fig. 10.1). These distributaries of the Mahanadi though controlled by the Naraj barrage upstream contribute maximum silt load and fresh water into the Chilika (Pattnaik 2002). Ghosh et al. (2006) and Khandelwal et al. (2008) estimated that 1.5 million tons of silt load are discharged every year by the Mahanadi distributaries along with 51% of the total freshwater inflow into the lake. As many as 52 small rivers and rivulets from western catchment (e.g. Kansari, Kusumi, Janjira, Tarimi) account for 0.3 million tons of sediments supply annually along with the total freshwater input of 39% (Ghosh et al. 2006). The longshore sediment transport (littoral drift) of the Bay of Bengal also contribute about 0.1 million tons of sediments annually (Sarkar et al. 2012). The discharge by the rivers to the Chilika is high during peak flood seasons of the Southwest monsoons (June–September) and very low during rest of the year. The

**Table 10.4** LULC classification for 1980, 2000, 2005, 2010 and 2015 images

Land cover type	1980		2000		2005		2010		2015		Remarks
	Area (Km <sup>2</sup> )	Area (%)	Area (Km <sup>2</sup> )	Area (%)	Area (Km <sup>2</sup> )	Area (%)	Area (Km <sup>2</sup> )	Area (%)	Area (Km <sup>2</sup> )	Area (%)	
Settlement	564.38	9.74	812.78	14.02	858.84	14.82	913.50	15.76	1060.98	18.30	Continuous increase, significant
Agriculture, plantation	1292.52	22.30	1171.29	20.21	1062.76	18.34	987.97	17.05	953.82	16.46	Continuous decrease
Agriculture, fallow	246.35	4.25	264.22	4.56	246.60	4.25	276.57	4.77	255.44	4.41	No change
Forest, Evergreen	238.42	4.11	327.59	5.65	324.52	5.60	281.09	4.85	300.99	5.19	Some increase between 1980–2000 and then no change
Forest, scrub forest	372.95	6.43	328.07	5.66	312.38	5.39	318.71	5.49	307.79	5.31	Continuous decrease, minor
Lake wetland	214.74	3.71	174.36	3.01	238.67	4.12	235.59	4.06	255.27	4.40	Decrease between 1980–2000 and then increase
Inland wetland	774.54	13.36	708.09	12.22	801.68	13.83	796.40	13.74	729.51	12.59	No major change
Barren/wasteland	348.27	6.01	211.69	3.65	162.46	2.80	142.44	2.46	143.37	2.47	Significant decrease throughout
Water bodies	1743.63	30.08	1797.72	31.02	1787.89	30.85	1843.53	31.81	1788.63	30.86	No change





**Fig. 10.9** Trend analysis of land use/land cover in Chilika between 1980 and 2015

lagoon receives 10% of freshwater input from direct precipitation (Khandelwal et al. 2008). Due to high sediment supply by the Mahanadi distributaries, the sedimentation rate is comparatively higher in northern ( $7.6 \text{ mm year}^{-1}$ ) and central sectors ( $8 \text{ mm year}^{-1}$ ) and low in the southern sector ( $2.8 \text{ mm year}^{-1}$ ) (Sarkar et al. 2012).

Sediments to the Chilika are mostly derived from the denudation of hills and plateaus of the Eastern Ghats exposed on the northern, western and southern borders of the lake. The sediments are mostly of silt-clay size with biogenic debris and occasional intercalated lenses of sand (Zachmann et al. 2009). Sand predominates on the eastern and western shores of the central and southern sectors, at the bottom of the outer channel and spits and bars. Because of long-distance transport, the Mahanadi distributaries supply fine-grained sediments of mud size whereas the small rivers/rivulets originating from the nearby hills mostly carry coarser sediments. A seaward decrease in mud has been observed with an increase in sand content towards the mouth of the outer channel (Rao et al. 2000). The sediments show a predominance of quartz along with minor admixtures of feldspar (microcline), muscovite, and clay minerals. The clay minerals are composed of hydro-muscovite, illite, and kaolinite (Zachmann et al. 2009). The heavy metals exhibit slightly decreasing concentrations from northeast to southwest, thus indicating the supply of contaminants from the Mahanadi River. The organic matters within the sediments of the lagoon are from the decomposition of macrophytes and supplies by the rivers. The organic matter content is highest in the northern sector (1.29%) that decreases seaward (Pattnaik 1987; Rao et al. 2000).

The monsoon rains strongly influence the hydrography of the lagoon. Sediment and water supplies from the catchments upstream as well as oceanic longshore transport are maximum during monsoon months, and the lake consequently experiences massive flooding during these months. Due to the influence of both tides and perennial freshwater inflow from the rivers, the lake salinity ranges from seawater strength to freshwater. The salinity decreases during the monsoon due to the substantial influx of freshwater from the northern and central sectors. The southern sector is the least affected even during monsoon and maintains its brackish-water conditions. During the summer, the water level of the lagoon is at its lowest, and this facilitates the influx of saline water from the outer channel into the lake and salinity of the lake increases. The winds also play an essential role in regulating salinity of the lake by mixing water from different sectors.

The Chilika lagoon environment is suitable for the survival of freshwater, brackish, and marine water organisms (Siddiqi and Rao 1995). The population of these organisms varies both spatially as well as seasonally where the salinity plays an important role. Biodiversity is severely affected by the spatial and temporal salinity gradients caused by freshwater inflows from the river systems, seawater intrusion under the tidal influence and weak circulation (Ghosh et al. 2006; Sahu et al. 2014). The outer channel is more prone to these changes where polyhaline and mesohaline organisms get gradually replaced by oligohaline organisms with a decrease in salinity. However, siltation of the lagoon is identified as a major source for salinity decrease and a threat to the ecosystem (Kumar and Pattnaik 2012).

Our work on the LULC changes suggests that in last few decades, the change in the land use pattern in the direct catchments of Chilika Lagoon has led to an overall decline of agriculture plantation (5.84%) and barren lands (3.54%) (Figs. 10.6 and Table 10.4). Probably increased rates of erosion upstream have ultimately increased the sediment load considerably although there are no measured rates of erosion available from this region. Moreover, the river inflows to the lagoon are being regulated upstream through a series of hydraulic structures influencing water availability for maintenance of ecosystem processes and functions of the wetland downstream (Ghosh et al. 2006). Since 2000, the increased tidal influence the lagoon probably acted as a sink for terrestrial material, and as a result, the average depth of the lake decreased (Fig. 10.3). However, this observation needs to be supplemented by detailed bathymetric surveys of the lake. The accumulation of sediments causes gradual choking of outer channel restricting the outflux of silt-laden freshwater. Siltation often results in shifting and blockage of the outer channel and mouth, preventing the smooth exchange of water and sediment between the lake and the sea (Chandramohan and Nayak 1994). Siltation of the outer channel and disturbed tidal flux has also resulted in shrinkage of the lagoon area and with a massive addition of suspended sediments transparency of the lake has been significantly affected. Though seasonal and episodic, storm surges, cyclones, monsoonal floods and longshore drift change coastal geomorphic features and add to the problems of salinity and siltation.

Apart from siltation, the Chilika environment is being degraded by several natural and human factors taking place within the Mahanadi River Basin as well as the coastal processes within the Bay of Bengal. The extensive habitation surrounding the lake and in the catchment basin is a serious threat to the lagoon because increased agricultural practices, disposal of untreated domestic garbage and wastewater has resulted in increased inputs of nutrients and pollutants to the lake through the various river and tributary systems. Nutrient enrichment has led to massive macrophyte growth, and their decomposition has created anoxia and hypoxia-like conditions in the lake (Sahu et al. 2014). Increase in freshwater weeds have considerably reduced the breeding of fish and led to a decrease in fishing activity.

## 10.7 Concluding Remarks and Future Perspectives

The land is a natural resource for supporting the life system. This chapter has highlighted that the water bodies, agricultural plantation, and settlement are the predominant LULC in the study area. These LULC classes form an essential ecosystem in Chilika. The lagoon is facing a significant problem of siltation mainly due to improper utilisation of LULC. Agriculture plantation and barren lands are more vulnerable due to urbanisation such as engineering construction, settlements, and transport. Changes in the island landforms within the lake are mainly due to the river as well as sea input into the lake. Sandbar area fluctuations reflect that depends upon the sedimentation input as well as the opening of the mouth. After the opening of the new mouth, there is an increase in the number of small sand bodies in the form of islands in the northern part of the lake. Sedimentation in the Chilika remains a serious concern, and there is no reasonable estimate of annual sediment flux into the basin. The tidal inlet was drifting in the NE direction due to the influence of long-shore currents at a higher rate in the pre-hydrological invention, and the rate of drift has been quite significant in the artificial mouth as well after the hydrological invention. It is necessary to monitor the rate of tidal inlet changes because it is the primary factor for salinity changes in the lake. This chapter has also demonstrated the effective use of remote sensing data in a GIS framework to understand the LULC change and its causal factors. However, there is a strong need for generating high-resolution time series using satellite images of intermediate periods and detailed field investigations to confirm some of the changes to evolve a sustainable management strategy.

The hydrology of the Chilika Lagoon is influenced significantly by the river systems in the northern and western catchment and by the Bay of Bengal. The Mahanadi distributaries are responsible for significant freshwater, and silt load into the lagoon whereas the longshore sediment transport of the Bay of Bengal is mostly restricted to the coast and outer channel. The wetland environment is under serious threat because of the changes in salinity values controlled by freshwater inflow from the rivers and the tidal exchange between the lagoon and sea. Natural factors like storm surges, cyclones, monsoonal floods, sediment deposition by longshore drift

(tidal inlet changes) and human-induced factors like change in land use pattern upstream to the lagoon, increased agricultural practices, disposal of untreated domestic garbage and wastewater are degrading the lagoon environment which is needed to be monitored and managed adequately.

A detailed work focusing on deep sediment cores from different parts of the lagoon may be extremely rewarding to reconstruct the temporal as well as spatial evolution of the Chilika. No geochemical data is available on the Chilika sediments to understand the nutrient cycling and geochemical evolution of the lagoon through geological time. In addition, detailed geochemistry of stratigraphically controlled core samples should answer several aspects of the lagoon evolution and the paleoclimate of the area. Lagoons are the appropriate sites for the reconstruction of relative sea level and paleosalinity changes. Sea level change with time and the relative contribution of the saline water into the lagoon can be studied by reconstructing the salinity variations using various proxies such as evaporate concentration, the  $^{87}\text{Sr}/^{86}\text{Sr}$ , Sr/Ca ratios along with  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  of the biogenic carbonates. These isotopic and elemental ratios are ideal proxies for paleosalinity because of the typically different values in the fresh and sea waters. Also, biogenic carbonates incorporate Sr isotopes in their crystal lattice during precipitation with no important effect, recording the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of the waters in which they grew. A consistent trend is expected between the above proxies as a result of mixing between fresh and seawater. Furthermore, the seawater contribution can be quantified with the help of available paleo salinity data from the Bay of Bengal (Indian Ocean).

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