Impact of urbanization on creeks of Mumbai, India: a geospatial assessment approach

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Abstract

Creeks are the inherent coastline feature that connects rivers to the sea and plays an important role in the ecological processes and the material transfer. In the present study, an impact of urbanisation on the creeks of Mumbai, India namely Thane, Malad and Manori creeks, has been addressed. Multi-temporal satellite images of Landsat for the years 1972, 1994 and 2016 are considered to perform the changes in the mudflat and growth of the mangrove, as well as the changes in creeks width apart from the Land use Land cover (LULC). Object-based image analysis using multi-spectral resolution confirmed that there is an overall increase in the spatial extent of mangroves and reduction in the width of all the creeks. Mangroves around Thane creek and Manori creek have increased from 50.7 km^2 to 57.6 km^2 and 8.4 km^2 to 25.2 km^2 respectively. However, there is a decrease in mangroves around Malad Creek from 13.3 km^2 to 9.7 km^2 during 1972 to 2016. The relationship between the creek geometry and LULC was also explored, and it has been revealed that the creek width has reduced due to urbanisation. Life expectancy analysis projected a further reduction in the width of the creeks for the years 2025 and 2050. The study suggests that there must be stringent bye-laws for disposal of sewage into the creeks and development activity near the creek areas. Further, upper stretches of the creeks require cleaning and dredging so that the tidal water will be approached up to the upper portion to maintain the creek ecosystem.

Keywords LULC · Mangroves · Creek · Mumbai · OBIA · GIS

Introduction

Creeks are the omnipresent and copious estuarine ecosystems, which are essential in the material transfer and the ecological processes having characteristics of the tidal wave flushing (Athalye et al. 2012). This natural cleansing phenomenon of the creeks makes them a suitable place for the sewage and effluent discharges along with the solid waste of nearby areas

and industrial establishments (Vijay et al. 2014). On the other hand, creeks and wetlands are considered an important part of the ecosystem as they play a crucial role in groundwater recharge, nutrient capture, controlling flood and filtration of sediments (Chaves and Lakshumanan 2008). It is also evident that urbanisation and coastal development are causing danger to natural tidal creeks by reducing its ecological value and increasing impacts. The existences of mangroves along with the mudflats beside the creeks create its self-enriching system (Pomeroy and Kuenzler 1969) and it is most dynamic to all kinds of bio-network (Odum and Barrett 1971). Mangroves forests are very vital ecosystems as they provide support to a complex community assemblage reduce coastal erosion and serve as sinks for macronutrients, micronutrients and heavy metals (Athalye et al. 2012).

India has a coastline length of about 7500 km which passes through rocks and sandy beaches (Rajawat et al. 2015). It supports one-fourth of the population of India within 100 km of the coastline. Due to urbanisation and industrialisation and subsequent increase in quantum of the domestic and industrial sewage, urban authorities started to release sewage into the creeks. Mumbai being the financial capital of Maharashtra is the most populous metropolitan city

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in India (Tirkey et al. 2005). Thane Creek is one of the tidal creeks apart from Manori and Malad creeks located in Mumbai. It has numerous drainage streams coming from Mumbai sub-urban areas. The geometry of the Thane creek is such that it is wider and deeper towards the sea and narrow and shallow towards the Ulhas river which links to the north of the creek. In last few decades, it has been reported with heavy industrial growth along the creek which also led to the urbanisation in the area. This development occurred in the flatlands of the foothills along with the filling of low-lying wetland portions of the creek. Such development on both sides of the Thane creek (i.e., Mumbai and Navi Mumbai) caused considerable siltation, altering the creek profile, especially in the last two decades (Mendiratta and Gedam 2014). Thane Creek is also defined by various stretches of mangrove, salt pans, and acclaimed flamingo sanctuary. Various research studies reported the destruction of the mangroves due to increased urbanisation around the Thane creek. Similar conditions are being faced by Manori and Malad creeks (Mendiratta and Gedam 2014).

Remote Sensing and Geographical Information System (GIS) techniques find a vast application when it comes to monitoring and mapping of natural resources in the coastal regions. Such applications include assessment of erosion/ accretion, shoreline changes, littoral drift, coastal wetlands monitoring, intertidal boundaries (Nayak et al. 1991; Gangadhara Bhat and Subrahmanya 1993; Chen 1998; Sreekala et al. 1998), spatiotemporal changes in Land Use Land Cover (LULC) (Carlson and Sanchez-Azofeifa 1999; Guerschman et al. 2003; Rogan and Chen 2004; Dezso et al. 2005) and to assess the changes in widths of the creek. Based on these, the main objective of the present study is to assess the changes in LULC of Mumbai city with a special focus on mangrove and change in width of the Thane, Malad and Manori creeks using remote sensing analysis. The study also aims to determine the relationship between urbanisation and mangrove growth along with the life expectancy of the creek using regression analysis.

Study area

The present study covers the surroundings of Mumbai, Navi Mumbai and Thane in the state of Maharashtra with geographical extent 18° 53′ 0"N to 19° 19′ 0"N and 72° 46′ 30"E to 73° 02′ 0"E with an area of around 1226 sq. km. The base map of the study area is shown in Fig. 1. The study area comes under low-lying plain and there are two parallel ridges flanked it on the east and west side (web-1). The study area is under tropical climate and receives most of the rainfall during south-west monsoon with an average annual rainfall of 2422 mm. The maximum and minimum average annual temperature in the city is 31.2 °C and 23.7 °C respectively. The area is well

connected through railway, roadways, and airways. Being the financial capital and one of the large commercial sectors, Mumbai is one of the most populous cities of India and most dense urban area across the globe (web-1). Mumbai, the economic hub of India, contribute to factory, industrial, customs duty, foreign trade, information technology sector, etc. kind of job for the people. As mentioned in the introduction, the present study is concerned with the growth of mangroves along the creeks of the Mumbai viz. Thane, Malad, and Manori. Thane Creek has an inlet towards southern part, i.e. to the shoreline of the Arabian Sea, and the northern part of the Thane creek is connected with Ulhas River. Thane creek has rich diversities in terms of mangroves and marine ecosystems. Industrialisation and urbanisation are affecting both sides of the Thane Creek. There are two more creeks in Mumbai viz. Malad and Manori situated in the North-West side of Mumbai. The major drains namely Oshiwara and Dahisar (river) meet into Malad and Manori creek respectively.

Materials & methods

The methodology adopted in the present study is divided into four sections. Section I describes a collection of satellite data, Section II deals with the Object-Based Image Analysis (OBIA), Section III is about Field verification/Ground truthing and Section IV delineates change detection and life expectancy analysis of the creeks. The methodology of the research work is summarised through flowchart (Fig. 2).

Section I data collection

In the present study, three images of Landsat have been collected from United States Geological Survey as it is already ortho-rectified, geocoded and terrain corrected. The spectral bands used for the image analysis are green, red, near-infrared (NIR) and mid-infrared (MIR). The details of the images considered in the study along with the band combinations are presented in Table 1. The band combination denoted is in the order of green, red, NIR and MIR.

Section II image analysis

False Colour Composites (FCC) images are very useful as they allow us to see the finer variations in near infra-red reflectance which is related to photo-synthesizing vegetation (Sujatha et al. 2000; Verma et al. 1994; Rao and Venkataratnam 1991). In this study, three different Landsat images were used i.e., Landsat-1 (MSS), Landsat-5 (TM) and Landsat-8 (OLI) to carry out the LULC analysis. The image analysis tool of ArcGIS 10.3.1 was used for band composition as a pre-processing tool, ESRI as an interactive stretch tool and cubic convolution as a statistical classifier
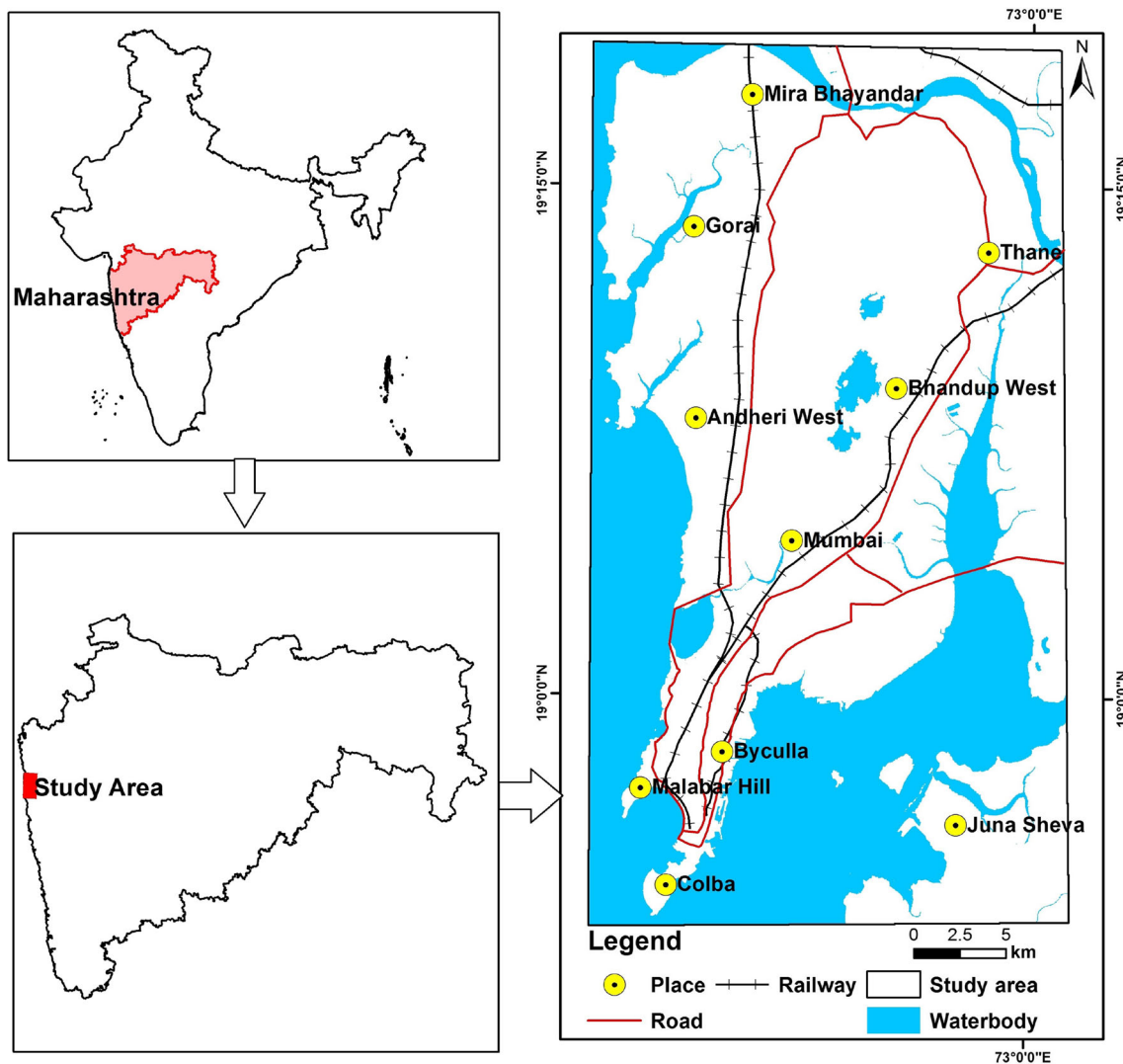
Fig. 1 Base map of the study area

(Liu et al. 2006). The FCC images of the study area are shown in Fig. 3.

Pixel-based analysis has limited recognition of image as pixel itself and not as a geographical object. The topology of the pixel is limited, spatial photo-interpretive elements like context and shape are neglected. High-resolution imageries

Fig. 2 Methodology adopted in the present study

which itself containing large variability confuses pixel-based software, which ultimately leads to increased inaccuracies in classification (Hay and Castilla 2006). Methods that are generally in use for this practice are either supervised or unsupervised classification or a combination of both (Enderle and Weih 2005). In the present work, Object-Based Image Analysis (OBIA) has been carried out using eCognition Developer 9.0 to overcome the drawbacks of pixel-based analysis (Blaschke 2010). The multi-resolution segmentation algorithm was used to classify similar pixels in objects taking scale parameter as 5, shape value 0.3 and compactness factor of 0.8. The image classification was carried out based on the geospatial indices viz. Normalised Difference Vegetation Index (NDVI), Normalised Difference Water Index (NDWI) and Normalised Difference Built-up Index (NDBI). These geospatial indices make the classification quite easy as discrimination based on numerical values is simple as compared to visual interpretation (Rundquist et al. 2000; Jensen 2009;
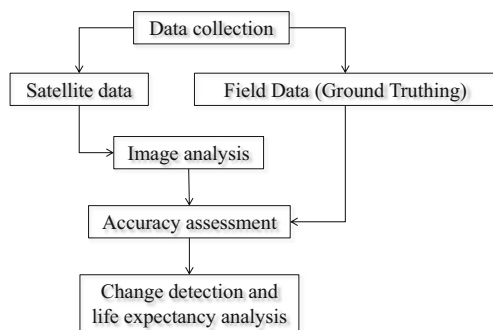
Table 1 Details of the Landsat satellite images

S.no	Satellite	Sensor	Resolution (m)	Date of pass	Bands used for Image analysis
1	Landsat-1	MSS	60	11/10/1972	1,2,3,4
2	Landsat-5	TM	30	30/10/1994	2,3,4,5
3	Landsat-8	OLI	30	26/10/2016	3,4,5,6

Lucas et al. 2008; Jones and Vaughan 2010). The expressions for spectral indices are given below

$$NDVI = \frac{NIR - R}{NIR + R} \qquad (1)$$

$$NDBI = \frac{MIR - NIR}{MIR + NIR} \qquad (2)$$

$$NDWI = \frac{Green - NIR}{Green + NIR} \qquad (3)$$

Where, NIR = Near-Infrared spectral band, R = Red spectral band, MIR = Middle Infrared spectral band and Green denotes green spectral band (Zha et al. 2003). NDVI has a very crucial role in musking out every kind of vegetation from other land use in an efficient manner. Using a different range of NDVI, it is possible to separate the mangrove and other terrestrial vegetation. Similarly, NDWI can easily and quickly separate water bodies and land from an image while

NDBI is a very efficient algorithm for the extraction of the built-up area from other LULC classes. Thus, these indices are very effective and meaningful for LULC analysis. Apart from these indices, brightness and number of pixels an object contains were also considered as a parameter of identification in LULC classes. Brightness refers to the shiny reflectance of a surface in visible light spectrum whereas several pixels denote the size of an object. The larger the object, it will have more number of pixels. OBIA allows identifying the certain range of every feature (LULC class) using 'feature view' tool and 'image object information' display the other information like mean value, compactness, pixel count, brightness. Feature view tool even allows discriminating the range of similar kind of features, example: the different range of NDVI can discriminate among the forest, mangrove, terrestrial vegetation etc. The range of spectral indices used in the present study is explained in Table 2.
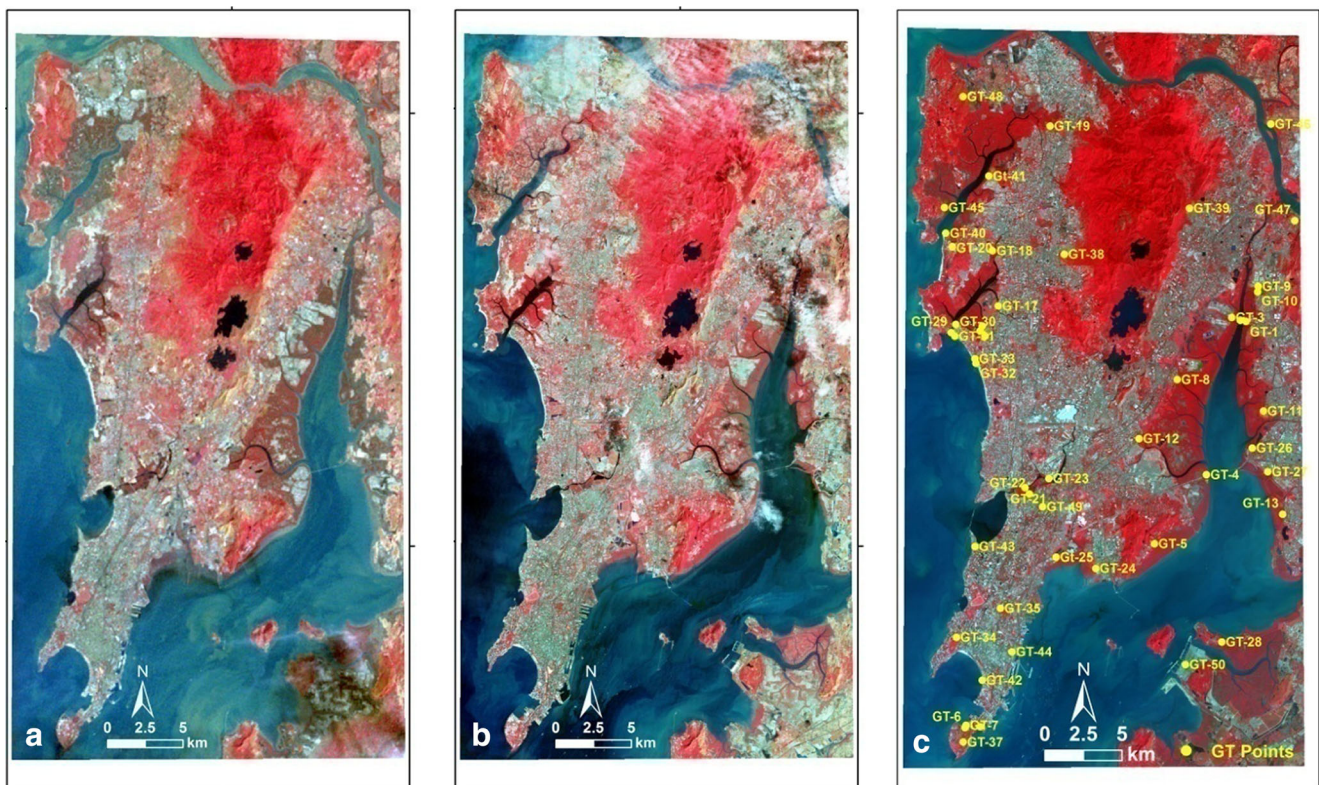

Fig. 3 False colour composites images of the study area **a** October 1972 Landsat-1, **b** October 1994 Landsat-5, **c** October 2016 Landsat-8

Table 2 Class wise range of spectral indices used in the present study

| LULC Class | Year | | | | | |
| | 1972 | | 1994 | | 2016 | |
	Spectral index	Range	Spectral index	Range	Spectral index	Range
Agriculture (Cropland)	Green*	30–34	Green*	34-35	Green*	29-33
Built-up	NDBI	38–143	NDBI	0.02–0.42	NDBI	0.19–0.23
Barren land	Red*	68–69	Red*	36-37	Red*	44-56
Vegetation (Terrestrial)	NDVI	0.15–0.51	NDVI	0.2–0.8	NDVI	0.2–0.52
Mangrove	NDVI	0.50–0.078	NDVI	0.83–0.9	NDVI	0.64–0.87
Mudflat	Green*	53-56	Green*	29-31	Green*	47-62
Saltpan	Green*	75–80.5	MIR*	29-39	Green*	70-83
Sand	Brightness	72-74	Brightness	90–127	Brightness	108–121
Water Body	NDWI	0.13–0.55	NDWI	0–0.6	NDWI	0–0.25

* Mean value of band

Section-III field verification

Field verification allows classified data to relate to reality. Ground truthing is the procedure to train and validate remote sensing analysis. In this study, Garmin GPS was used for collecting the coordinates and photographs were captured for evidence. Based on the ground truth survey, accuracy assessment was carried out for LULC classification.

Section-IV life expectancy analysis

Life expectancy refers to a condition when the creek becomes fully choked, and there is no space for a tidal phenomenon that occurs in a natural creek. The life expectancy of creeks was determined by considering different sections along the length of the creek. All the creeks were divided into three sections viz. lower creek, i.e. point where the creek meets the ocean, upper creek, i.e. point where the creek meets the river and a middle creek, i.e. portion between upper and lower creek. The creeks were further divided into multiple single-line sections to obtain a single value for carrying out the analysis. The length of these sections for Thane, Malad and Manori creeks were determined using the measure tool of ArcGIS® for the years 1972, 1994 and 2016. Regression analysis was then carried out to establish the trend of the changes in the width of the creek. Simple linear regression (SLR) models between the width (dependent variable) and time (independent variable) were developed for each section of the creek and further width of the creek was predicted for the year 2025 and 2050.

Results and discussion

LULC and changes detection analysis of Thane, Malad and Manori creeks are discussed in this section. Further, a relationship is developed between changes in creek width and LULC for life expectancy analysis of the creek.

LULC and change detection analysis

LULC analysis is necessary to understand the present scenario and serves as an important input for the effective planning and management of an area. LULC maps of the study area for 1972, 1994 and 2016 are shown in Fig. 4, and statistics are represented in Fig. 5. LULC classes are categorised into nine classes viz. agriculture (cropland), built-up, barren land, vegetation (terrestrial), mangrove, waterbody, mudflat, salt pan and beach. The change detection analysis reveals the transformation of the study area using image analysis tool and raster calculator tool. The decrease in vegetation, mudflats, waterbody and increasing built-up area reveals that human activities are rapidly growing. As a result, discharge of sewage and siltation is increasing, mudflats and growth of mangroves are taking place into the creek. This degradation may lead to different natural calamities like the escalation of water in an urban area, repetitive floods, clogging of drainage system, loss of property etc.

A major fraction of the study area is occupied by waterbody, built-up and vegetation (terrestrial). Built-up in the study area has increased by 7.1% from 1972 to 2016 while water body is reduced by 1.4%. Vegetation (terrestrial) also decreased by 1.3% from 1972 to 2016. The decrease in vegetation may be attributed to the increase in built-up in the study area. Mangroves in the study area are increased by 1.75% from 1972 to 2016 while mudflats are decreased by 3.5%. Although, there was a decrease in spatial coverage of the mangroves from 1972 to 1994 which may be attributed to geomorphological processes in the creek ecosystem or may be due to the destruction caused by developmental activities. Further, a decrease in mudflats is evidential for the growth
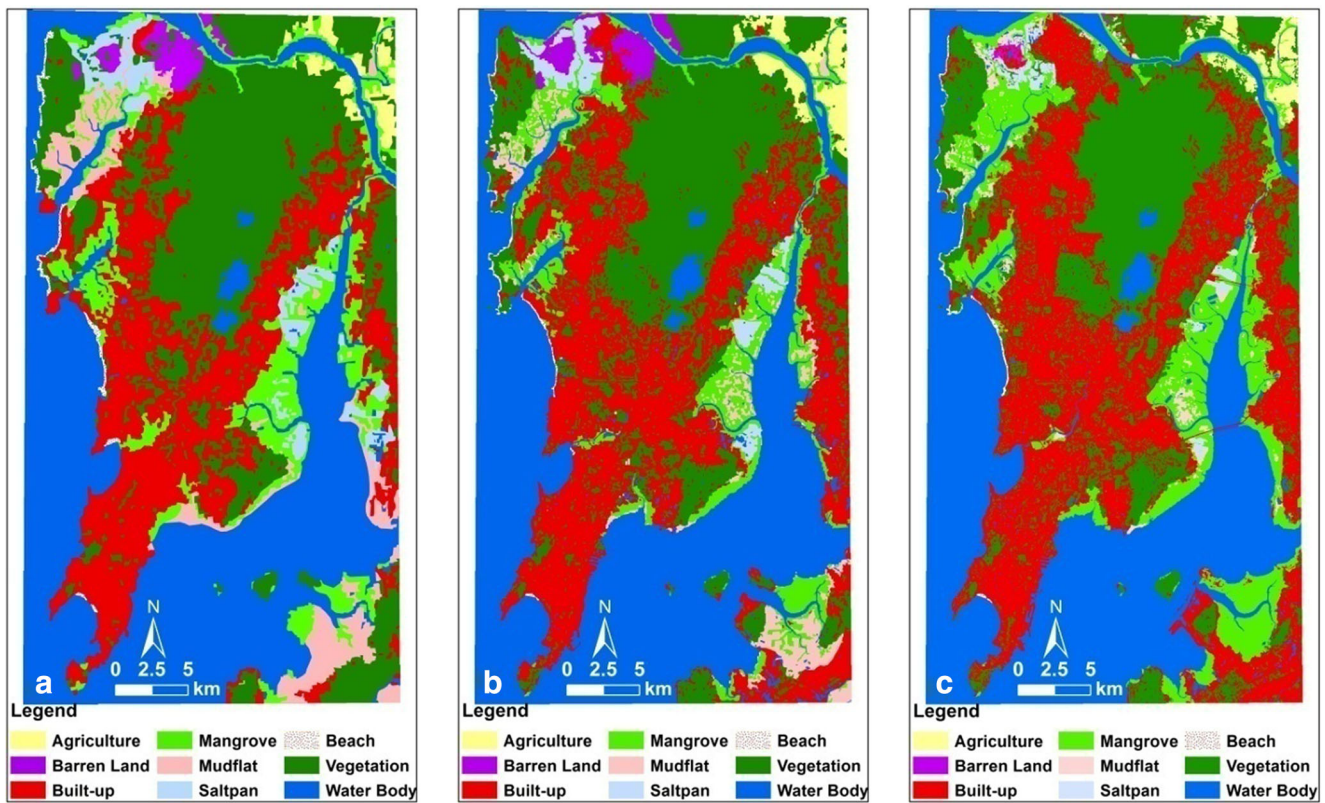
Fig. 4 LU/LC of the study area **a** October 1972 Landsat-1, **b** October 1994 Landsat-5, **c** October 2016 Landsat-8

of mangroves as soft and fertile mudflats are good nutrient capturing strips and provide a favourable condition for the growth of the mangroves. The mudflats are formed by oceanographic and tidal currents as well as domestic and industrial waste disposal into the creeks which further propagates the extension of mudflats in the inner periphery of the creeks (Sasamal et al. 2007). The mangrove root system also provides stability to mudflats as it holds the silt particles around its periphery which further increases the density of mangroves. Besides the above classes, other LULC classes exist in the study area are agriculture (cropland), salt pan, barren land and sea beach. There is no significant change from 1972 to 2016 except salt pans in the study area decreased by 1.7% which may also be attributed to built-up. LULC analysis of October 2016 image is used for post-classification accuracy as current practices of area usage and coverage as recorded

during the ground-truth survey. Based on the spatial extent of classes and variability of distribution across the study area, a suitable sample size of 50 was used for the accuracy assessment. Detail of ground-truthing is presented in Table 3 and ground-truthing (GT) locations are displayed on FCC (Fig. 3c) as well as field photographs are shown in Fig. 6. Accordingly, an error matrix was generated to assess the overall accuracy, which is found to be 86.5%.

Thane creek

Thane Creek is one of the largest creeks in Mumbai. There are three cities viz. Mumbai, Thane and Navi Mumbai which are geographically connected by Thane creek. The total length of the Thanecreek is around 40 km. Figure 7 shows the status of the Thane creek from 1972 to 2016.

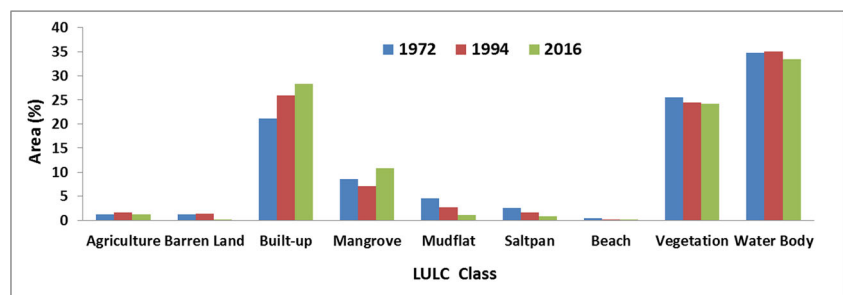**Fig. 5** LU/LC inventory showing changes in land use over the time

Table 3   Details of ground truthing

Sr No	Location Code	Latitude N	Longitude E	Description
1	GT-1	19° 9′ 0.298″	72° 59′ 1.242″	Mangrove
2	GT-2	19° 9′ 2.400″	72° 58′ 48.622″	Thane Creek
3	GT-3	19° 9′ 8.101″	72° 58′ 29.542″	Saltpan
4	GT-4	19° 3′ 36.234″	72° 57′ 37.562″	Mangrove
5	GT-5	19° 1′ 9.250″	72° 55′ 43.963″	Mangrove
6	GT-6	18° 54′ 37.585″	72° 48′ 49.032″	Mangrove
7	GT-7	18° 54′ 42.635″	72° 48′ 51.102″	Mangrove
8	GT-8	19° 6′ 55.840″	72° 56′ 30.351″	Mangrove
9	GT-9	19° 10′ 14.540″	72° 59′ 27.574″	Mangrove
10	GT-10	19° 10′ 2.942″	72° 59′ 26.339″	Mangrove
11	GT-11	19° 5′ 52.264″	72° 59′ 42.152″	Mangrove
12	GT-12	19° 4′ 50.763″	72° 55′ 7.136″	Mangrove
13	GT-13	19° 2′ 14.654″	73° 0′ 27.431″	Mangrove
14	GT-14	19° 8′ 22.548″	72° 49′ 23.108″	Mangrove
15	GT-15	19° 8′ 33.447″	72° 49′ 11.483″	Mangrove
16	GT-16	19° 8′ 43.923″	72° 49′ 16.410″	Mangrove
17	GT-17	19° 9′ 26.534″	72° 49′ 51.334″	Mangrove
18	GT-18	19° 11′ 22.933″	72° 49′ 37.042″	Mangrove
19	GT-19	19° 15′ 46.966″	72° 51′ 41.307″	Mangrove
20	GT-20	19° 11′ 29.865″	72° 48′ 7.809″	Mangrove
21	GT-21	19° 3′ 4.221″	72° 50′ 55.684″	Mangrove
22	GT-22	19° 2′ 51.126″	72° 51′ 5.434″	Mangrove
23	GT-23	19° 3′ 24.383″	72° 51′ 48.310″	Mangrove
24	GT-24	19° 0′ 16.436″	72° 53′ 34.562″	Mangrove
25	Gt-25	19° 0′ 38.522″	72° 52′ 6.304″	Mangrove
26	GT-26	19° 4′ 33.730″	72° 59′ 18.379″	Mangrove
27	GT-27	19° 3′ 43.936″	72° 59′ 53.467″	Mangrove
28	GT-28	18° 57′ 44.332″	72° 58′ 15.824″	Mangrove
29	GT-29	19° 8′ 29.087″	72° 48′ 7.530″	Malad creek (Waterbody)
30	GT-30	19° 8′ 46.586″	72° 48′ 17.558″	Malad Creek (Waterbody)
31	GT-31	19° 8′ 21.689″	72° 48′ 15.963″	Beach
32	GT-32	19° 7′ 24.927″	72° 49′ 3.364″	Beach
33	GT-33	19° 7′ 34.498″	72° 49′ 1.126″	Mangrove
34	GT-34	18° 57′ 47.284″	72° 48′ 27.577″	Terrestrial Vegetation
35	GT-35	18° 58′ 49.857″	72° 50′ 4.325″	Terrestrial Vegetation
36	GT-36	18° 54′ 39.977″	72° 49′ 22.516″	Terrestrial Vegetation
37	GT-37	18° 54′ 7.318″	72° 48′ 45.465″	Terrestrial Vegetation
38	GT-38	19° 11′ 17.377″	72° 52′ 16.328″	Terrestrial Vegetation
39	GT-39	19° 12′ 57.013″	72° 56′ 52.951″	Terrestrial Vegetation
40	GT-40	19° 11′ 58.070″	72° 47′ 52.807″	Manori creek (Waterbody)
41	Gt-41	19° 13′ 59.837″	72° 49′ 26.710″	Mangrove
42	GT-42	18° 56′ 17.519″	72° 49′ 26.115″	Waterbody
43	GT-43	19° 0′ 58.883″	72° 49′ 6.299″	Built-up
44	GT-44	18° 57′ 18.190″	72° 50′ 31.221″	Built-up
45	GT-45	19° 12′ 52.182″	72° 47′ 48.924″	Mudflats
46	GT-46	19° 15′ 56.669″	72° 59′ 51.413″	Agriculture
47	GT-47	19° 12′ 33.355″	73° 0′ 47.048″	Agriculture
48	GT-48	19° 16′ 46.762″	72° 48′ 27.453″	Barren Land
49	GT-49	19° 2′ 24.383″	72° 51′ 35.016″	Built-up
50	GT-50	18° 56′ 55.703″	72° 56′ 55.729″	Built-up

As per LULC and change detection in Thane creek, the spatial coverage of mangrove and alteration in creek width are shown in Fig. 8a–c respectively. The area around Thane creek is characterised by heavy built-up followed by waterbody,

Fig. 6 Field photographs of creeks

mangrove, salt pan and mudflat. The mangrove around Thane creek has increased from 50.7 km² in 1972, 52.0 km² in 1994 and 57.6 km² in 2016. Thane creek receives domestic, industrial and port-based waste which contributes to the degradation of water quality of creek along with heavy siltation. The wastewater is pumped through various stations to treatment plants and then discharged into the creek (Vyas and Vyas 2007).

The average width of the creek in the lower portion was 6991 m in 1972, which was reduced by 3.85% in 1994 and by 13.2% in 2016. The average width of the middle portion was 3082 m in 1972 which was reduced by 7.4% in 1994 and by 20% in 2016. Similarly in the upper portion, the average width has been reduced by 18.6% in 1994 and by 46% in 2016 which was 594 m in 1972. The highest percentage reduction has been observed in an upper portion of the creek which shows that there is more siltation as compared to the middle and lower portion. The reduction in creek width is a function of several factors viz. siltation due to oceanic current, inflow of domestic and industrial wastewater, ambient condition, development activity etc.

In all portions of the Thane creek, there was a decrease in mangroves from 1972 to 1994 and increased from 1994 to 2016. Although looking at the changes in the width of the creek, it constantly decreased in each portion from 1972 to 2016. One of the noticeable factors in this change is the reduction of mudflats and saltpans along the creek. The mudflats are reduced because of the growth of mangroves on it and as evidential from LULC analysis. Reduction in saltpans

indicates the anthropogenic activity occurring near the creek which ultimately contributed to the reduction of creek width. The maximum coverage of mangrove existed in the middle portion of the creek (25–30 Km²) followed by lower (13–17 Km²) and upper (6–8 Km²) portions. It is also revealed that the upper portion has experienced an overall decrease in the growth of mangroves contradictory to the other two portions. This addresses considerable natural and anthropogenic activities in the upper portion of the creek.

Malad creek

Malad suburban patch is situated in North-West of Mumbai and has a population of 2.6 million (Kamble and Vijay 2011). The creek situated in this zone is famously known as Malad creek running with a length of about 8 km and characterised by rich patches of mangrove. The spatial changes in Malad creek in the last three decades are shown in Fig. 9. As per LULC and changes analysis in the Malad creek, the spatial coverage of mangrove and alteration in creek width are shown in Fig. 10a–c respectively.

The area around Malad creek is identified with thick patches of mangroves followed by built-up, waterbody, seabeach and mudflats. Spatial coverage of mangroves around Malad creek in 1972 was 13.44 km², 8.97 km² in 1994 and 9.7 km² in 2016. This reverse change in mangrove area may be due to the development (as highlighted with a yellow circle in Fig. 8) occurred during the year 1972 to 1994 and increased
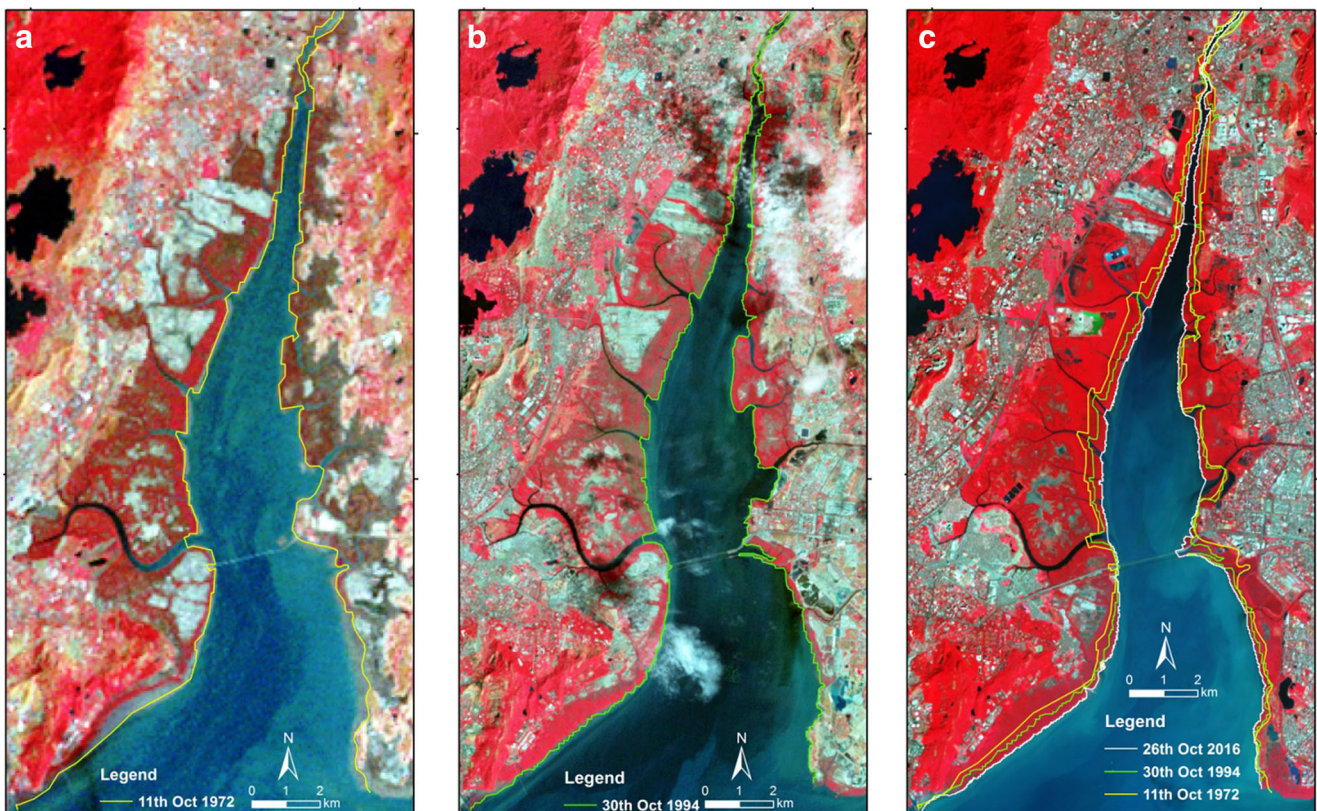
Fig. 7 Changes in width of the Thane creek **a** October 1972 Landsat-1, **b** October 1994 Landsat-5, **c** October 2016 Landsat-8

in mangroves during 1994 to 2016 is because of the growth of the mangroves along the mudflats of the creek. The average width of the Malad creek in the lower portion was 490 m which were reduced by 21% in 1994 and by 33% in 2016. The average width of the middle portion was 514 m in 1972 which was reduced by 13% in 1994 and by 20% in 2016. In the upper portion, the average width has been reduced by 19.4% in 1994 and by 22.7% in 2016 which was 259 m in 1972. The maximum reduction in the width of the creek is observed in the lower portion of the creek. This may be attributed to the fact that Malad receives treated wastewater from Malad and Versova treatment plants along with the untreated sewage from various non-point sources (Mukherji 2002) which ultimately degrades the water quality and causes siltation. This siltation ultimately leads to the formation of mudflats and growth of mangroves.

In Malad creek, mangroves were constantly decreased from 1972 to 1994 and slightly increased from 1994 to 2016. The creek width was decreased from 1972 to 2016. Among the three creeks considered in the study, Malad creek is the one having a reduction in mangroves and creek width simultaneously. This shows the growth of mangroves at the same pace as built-up which occurred along the creek. In all three portions of the creek, a significant reduction in average creek width has been observed during 1972 to 2016. This is because of the formation of mudflats along the creek. There were almost no mudflats in 1972 which was around 1 km^2 in 1994; this is the reason why the highest reduction in creek width occurred during this period. But from 1994 onwards, the width of the mudflats goes on reducing as mangrove started to grow on the mudflats. It does not imply that the formation of mudflats has stopped after 1994 but due to the
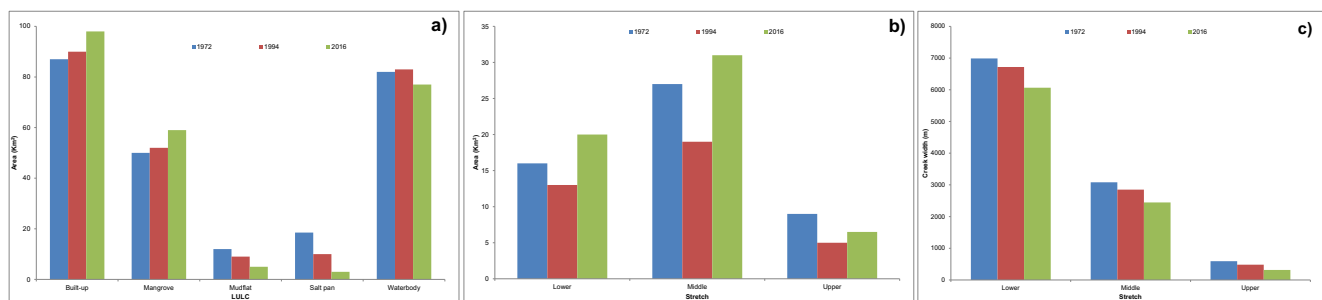

Fig. 8 Statistics of Thane creek **a** LULC, **b** changes in mangroves, **c** Creek width
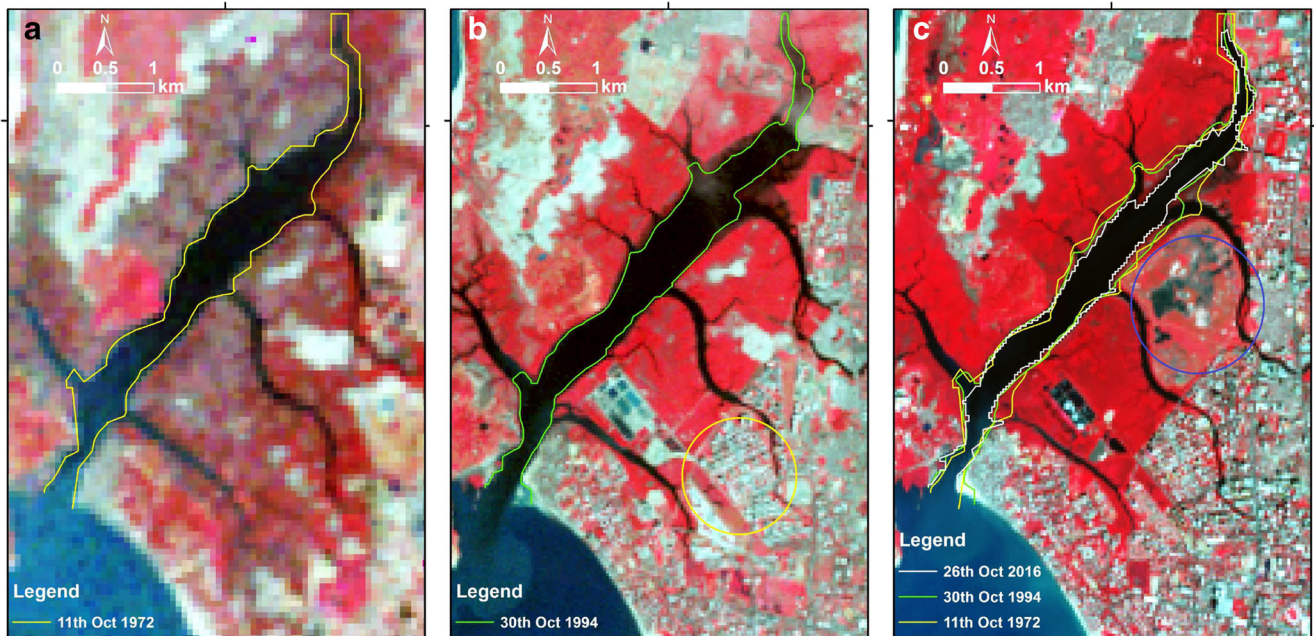
Fig. 9 Changes in width of the Malad creek **a** October 1972 Landsat-1, **b** October 1994 Landsat-5, **c** October 2016 Landsat-8

rate of growth of mangroves is more than the rate of formation of mudflats in the creek. It is also revealed that whatever amount of mudflats reduced along the creek is mainly in the upper portion of the creek as there is not much reduction in the width of the creek during 1994 to 2016. It may be due to natural and anthropogenic activities in the upper portion of the creek. The maximum coverage of mangroves existed in the upper portion of the creek (5–6 Km^2) in 1972 which now only covers to be less than 1 km^2 which implies considerable settlements in the upper portion of the creek.

Manori creek

The ManoriCreek is situated on the North-West side of Mumbai and has a good coverage of mangrove, low lying marshy areas and mudflats. The upper portions of the creek are not fully developed and have a natural beach (Kulkarni et al. 2010). The approximate length of the creek is around 10 km. As per LULC analysis, the areas around Manori creek are characterised by built-up followed by mangrove, waterbody, salt pan, mudflats, barren land and beach. The spatial changes in Manori creek are

represented in Fig. 11. The changes in LULC around Manori creek, spatial coverage of mangroves and alteration in creek width are shown in Fig. 12a–c respectively.

Spatial coverage of mangrove in the creek is determined as 8.45 km^2 in 1972, 16.1 km^2 in 1994 and 25.2 km^2 in 2016. It shows a constant growth of mangroves in Manori creek from 1972 to 2016. Although no considerable industrial units exist nearby the Manori creek, there have been reported several point sources of sewage disposal which might lead to siltation and provides the required nutrients for the growth of mangrove. The average width of Manori creek in the lower portion was 899 m which was reduced by 5% in 1994 and by 13% in 2016. The average width of the middle portion was 659 m in 1972 and subsequently reduced by 8.2% in 1994 and by 39% in 2016. In the case of the upper portion, the average width has been reduced by 24% in 1994 and by 36% in 2016 which was 110 m in 1972. The maximum reduction in creek width has been observed in an upper portion of the creek. This may be because less water is available for dilution even in the case of high tides and there are more chances of settling of silt in the upper portion.
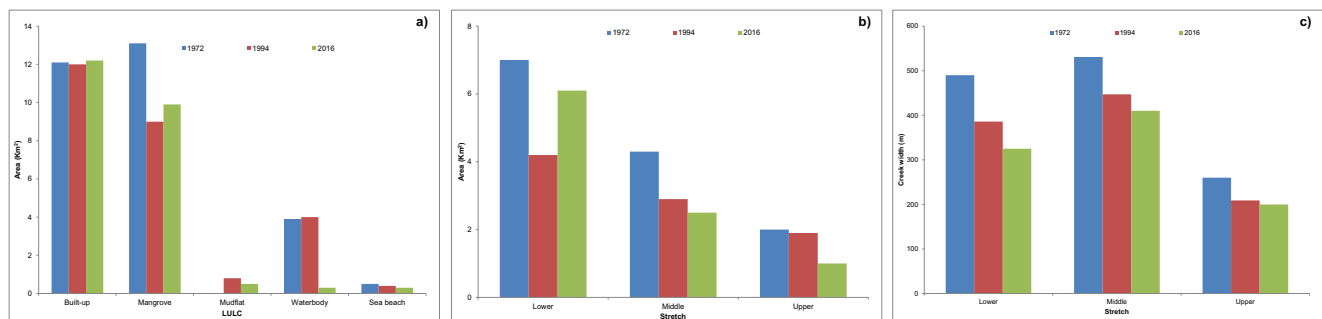

Fig. 10 Statistics of Malad creek **a** LULC, **b** changes in mangroves, **c** Creek width
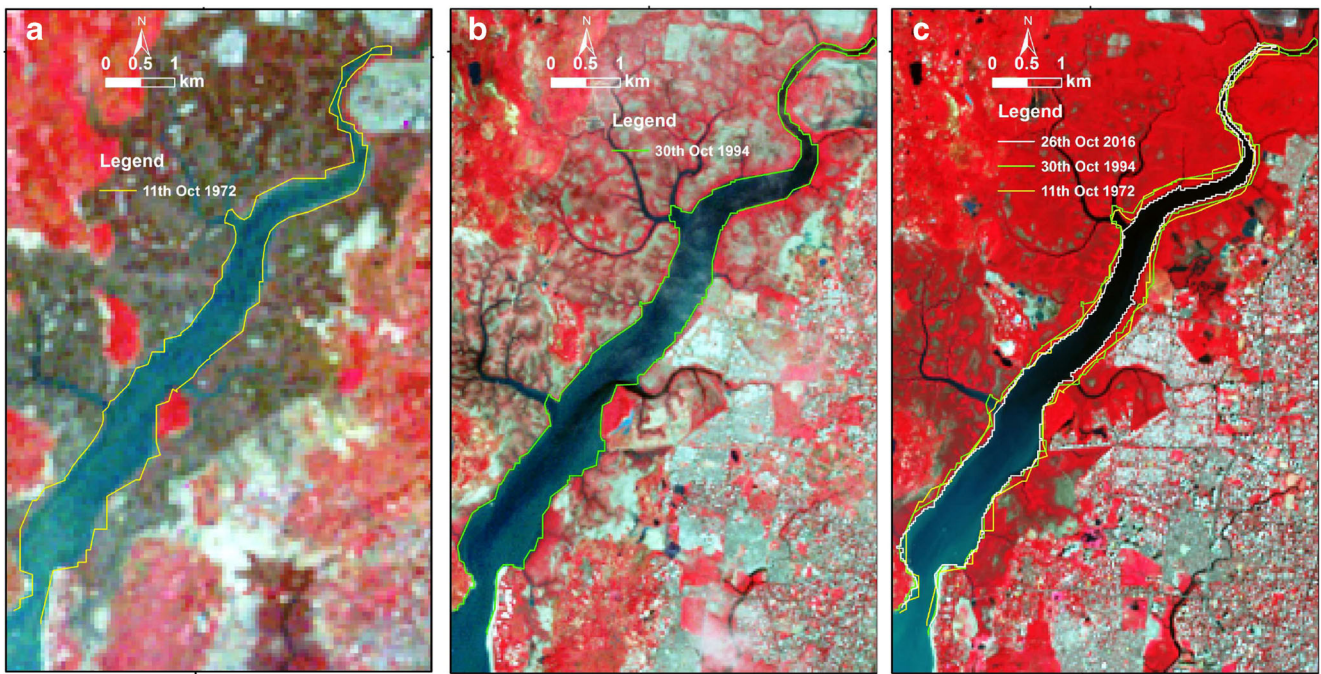
Fig. 11 Changes in width of the Manori creek **a** October 1972 Landsat-1, **b** October 1994 Landsat-5, **c** October 2016 Landsat-8

The coverage of mangrove in all the portions of the Manori creek has increased significantly from 1972 to 2016as contradictory to Thane and Malad creeks. This is also evidential from the overall LULC analysis of the Manori Creek (Fig. 12a). The average width of the creek in all portions has also decreased constantly from 1972 to 2016. The mudflats and saltpans are reduced considerably during 1972 to 2016. As per LULC analysis, salt pans are reduced as a result of developmental activity around the creek and mudflats are reduced as a result of the growth of mangroves on it. The maximum coverage of mangroves was observed in the upper portion followed by middle and lower portions. Conversely, the largest average width of the creek was in lower portion followed by the middle and upper portion. This shows if the spatial extent of mangroves at a particular stretch is high and it will tend to reduce the width of the creek at that stretch. This is because mangroves provide stability to the mudflats and further propagates the formation of mudflats. Mudflats around Manori creek was around 20 km^{2}in 1972, which was reduced to around 5 km^2 in 2016 which is imperative as mangroves during this course of time have increased from

8 km^2 in 1972 to 25 km^2 in 2016. It is also revealed that there was not much sign of growth of mangroves from 1972 to 1994 but from 1994 to 2016 considerable extension in mangrove area has been observed. This may be attributed to the fact that industrialisation and urbanisation around the Manori Creek have picked the pace after 1994 and the wastewater from the community started to put it in the creek, thereby creating a favourable condition for the growth of mangroves regarding nutrients and mudflats formation. It is also evidential from the viewpoint of the increase of built-up as there was not a significant increase in built-up from 1972 to 1994, but it was from 1994 to 2016.

Life expectancy analysis

For life expectancy analysis, various stretches of Thane, Malad and Manori creeks are considered as per image analysis of 1972, 1994 and 2016. Trend analysis of the data is performed using simple linear regression for the prediction of the creek widths in year 2025 and 2050.
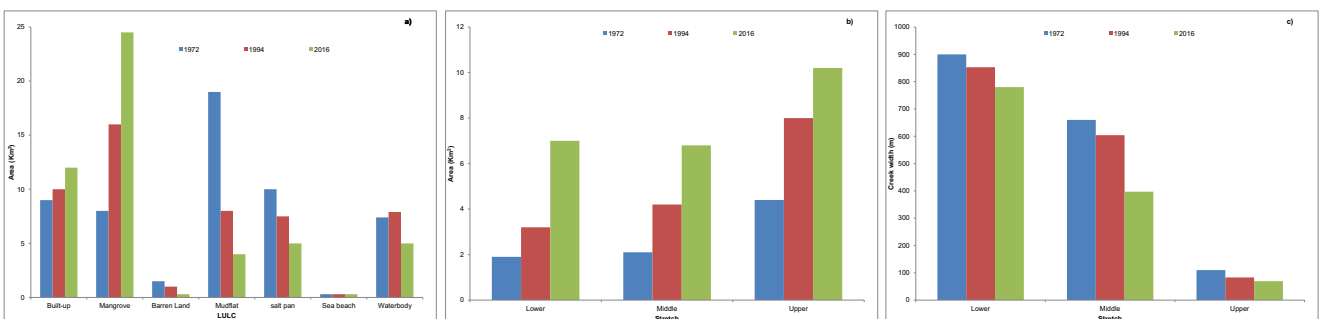

Fig. 12 Statistics of Manori creek **a** LULC, **b** changes in mangrove, **c** Creek width

Thane creek

The minimum and maximum width observed in Thane creek in 2016 are 93 m and 8871 m respectively with a standard deviation of 2633 m. Various profiles viz. *A, B, C, D, E, F, G, H, I, J, K* where widths have been measured as shown in Fig. 13a and changes in the width of the creek at these profiles are graphically presented in Fig. 13b. The regression equations developed for these profiles along with the coefficient of determination and predicted width for the year 2025 and 2050 is presented in Table 4**.** It is estimated that the width of the creek would be decreased considerably in the upcoming years. It is estimated that the average width of the creek in the lower portion will be reduced by 2% in 2025 and by around 10% in 2050 as compared to width in 2016. In the middle portion, the predicted reduction in width is estimated to be 4% and 18% by the year 2025 and 2050, whereas in the upper portion, 14% and 64% reduction of width is estimated by the year 2025 and 2050 respectively. It can be noticed that the higher percentage of reduction in width is estimated in the upper portion of the creek which was also subjected to drastic developmental activities and is also evidential from analysis discussed before. The predicted widths of reduction are lowest in lower portions of the creek which is near to mouth and is characterised by low developmental activity and subjects to tidal flushing phenomenon more intensely than upper portions. Therefore, there are fewer chances of full siltation and

clogging of the creek in this portion. However, by the time the upper portion of the creek gets clogged, it will reduce the length of the creek and will make the remaining portion more prone to siltation and subsequent clogging.

Malad creek

The minimum and maximum widths observed in Malad creek in 2016 are 200 m and 434 m respectively with a standard deviation of 85 m. Several profiles viz. *A, B, C, D, E, F,* where widths have been measured is shown in Fig. 14a and is represented graphically in Fig. 14b. The regression equations developed for these profiles, along with the coefficient of determination and predicted width for the year 2025 and 2050 are presented in Table 5. It is estimated that the average width of the creek in the lower portion would be reduced by 12.6% in 2025 and by around 41% in 2050 as compared to width in 2016. In the middle portion, the predicted reduction in width is estimated to be 6.4% and 21% by the year 2025 and 2050. In the case of the upper portion, 9% and 26% reduction of width is estimated by the year 2025 and 2050 respectively. It could be noticed that a higher percentage of reduction in width is estimated in the lower portion of the creek which is the reverse of Thane creek. Due to geographical conditions, Malad creek has a lower width towards the seaside, i.e. at the mouth of the creek which makes it more vulnerable for siltation as compared to the upper portion. This is the reason why the highest reduction in

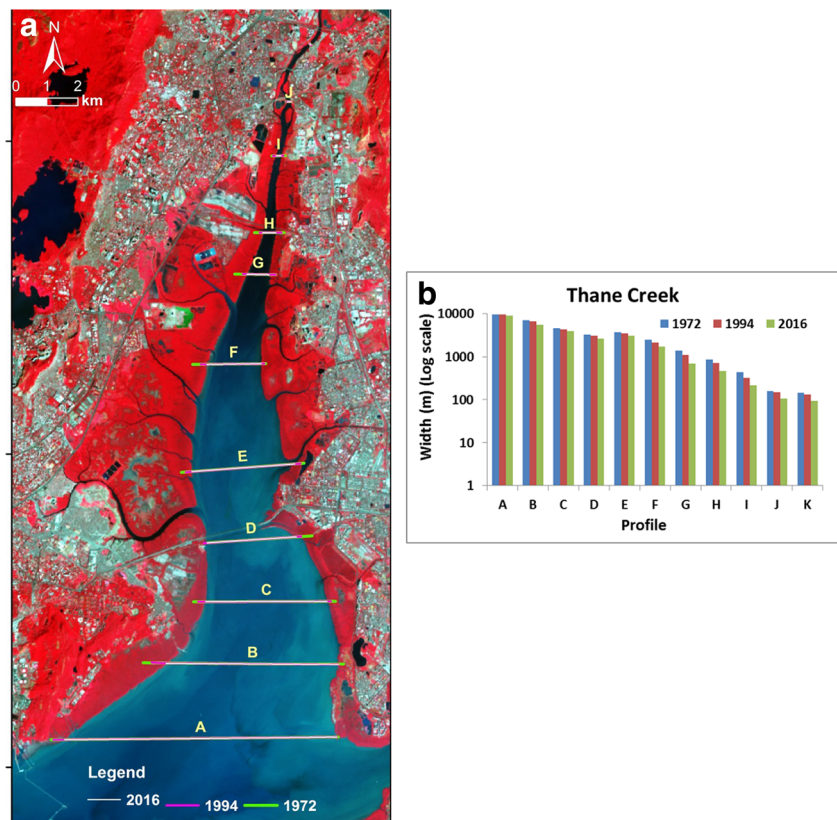**Fig. 13 a** Various profiles on Thane creek **b** Variation in width of the creek

Table 4 Regression equations and prediction of creek width for Thane creek

Profile	Derived Equation	R^2	Channel width m (Existing)	Predicted Chanel width m (2025)	Predicted Chanel width m (2050)
A	$y = -10.90x + 30,835$	$R^2 = 0.914$	8871.8	8762.5	8490
B	$y = -20.43x + 46,799$	$R^2 = 0.999$	5450.5	5428.2	4917.5
C	$y = -14.99x + 34,181$	$R^2 = 0.993$	3876.5	3826.2	3451.5
D	$y = -11.54x + 26,174$	$R^2 = 0.999$	2593.4	2805.5	49,831
E	$y = -14.45x + 32,507$	$R^2 = 0.987$	3047.7	3245.7	2884.5
F	$y = -13.53x + 29,051$	$R^2 = 0.999$	1698.7	1652.7	1314.5
G	$y = -13.98x + 28,924$	$R^2 = 0.992$	699.4	614.5	265
H	$y = -11.89x + 24,417$	$R^2 = 0.999$	467.2	339.7	42.5
I	$y = -5.363x + 11,022$	$R^2 = 0.981$	214.6	161.9	27.85
J	$y = -0.614x + 1365.$	$R^2 = 0.750$	104.7	111.8	106.3
K	$y = -1.182x + 2456$	$R^2 = 0.792$	93.6	62.4	32.9

creek width is observed in this portion. It is also clearly seen from LULC analysis that the right side portion of the creek at the mouth has a high degree of developmental activity and so the sewage discharges from the drain. Besides wastewater from built-up, it also receives treated wastewater from Versova treatment plant and creates a favourable condition for the formation of mudflats and thereby reducing the width of the creek. In the case of Malad creek, the reduction of width is lowest in the middle portion of the creek, which is obvious as there is not much development as compared to upper and lower portions.

Manori creek

The minimum and maximum width observed in Manori creek in 2016 are 69 m and 882 m respectively with a standard deviation of 266 m. Several profiles viz. *A, B, C, D, E, F,* where widths have been measured is shown in Fig. 15a, and changes in the width of the creek at these profiles is graphically presented in Fig. 15b. The regression equations developed for these profiles along with the coefficient of determination and predicted width for the year 2025 and 2050 is presented in Table 6. It is estimated that the average width of the creek in the lower portion will be reduced by 2.6% in 2025 and by around 11.2% in 2050 as compared to width in 2016. In the middle portion, the predicted reduction in width is estimated to be 9.3% and 47% by the year 2025 and 2050. In the case of the upper portion, 14.5% and 47.8% reduction of width is estimated by the year 2025 and 2050 respectively. The maximum reduction in width is estimated in the upper portion of the creek. In 1994, there were so many patches of

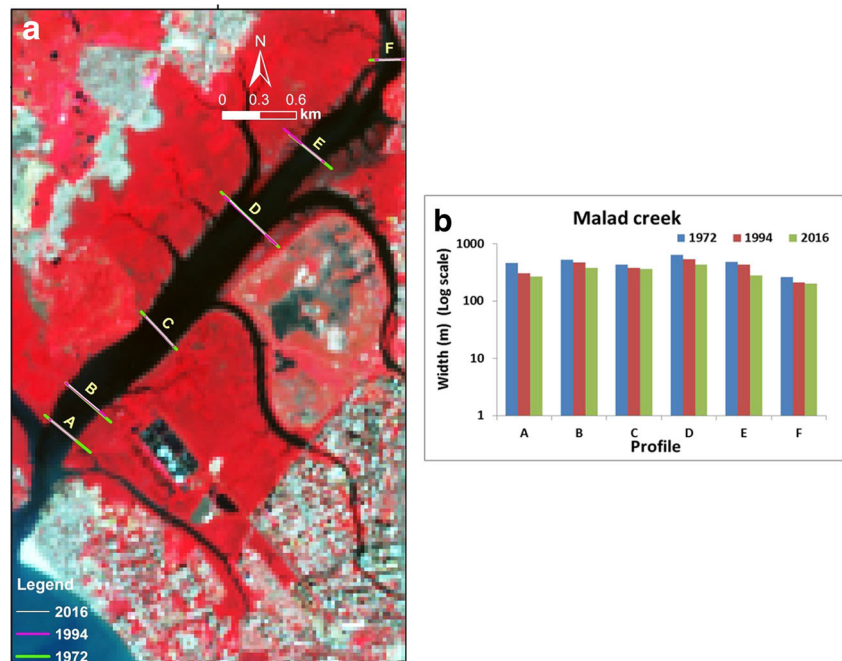**Fig. 14 a** Various profiles on Malad creek **b** Variation in width of the creek

Table 5 Regression equations and prediction of creek width for Malad creek

Profile	Derived Equation	R^2	Channel width m (Existing)	Predicted Chanel width m (2025)	Predicted Chanel width m (2050)
A	$y = -5.134x + 10,569$	$R^2 = 0.813$	268.4	172.6	44.3
B	$y = -3.876x + 8137$	$R^2 = 0.978$	381.6	288.1	191.2
C	$y = -2.349x + 5040$	$R^2 = 0.855$	359.6	283.2	224.55
D	$y = -6.499x + 13,507$	$R^2 = 0.970$	434.4	346.5	184.05
E	$y = -5.550x + 11,424$	$R^2 = 0.796$	279.1	185.2	46.5
F	$y = -3.068x + 6365$	$R^2 = 0.962$	200.3	152.3	75.6

open land and mudflats in the upper portion of the creek which occupied mangrove in 2016. This is the reason for a drastic increase in mangroves from 1994 to 2016, and therefore significant reduction in the width of the creek in the upper portion.

Conclusions

The objective of the study was to assess the impact of urbanisation on the creeks of Mumbai viz. Thane, Malad and Manori creeks. LULC and change detection analysis was performed around the creeks from 1972 to 2016 to assess the changes in mangroves and width of the creeks. From change detection analysis, it is revealed that there is an overall increase in the spatial extent of mangrove and a significant reduction in the width of the creeks. Possible reasons behind the increase in mangrove growth would be the formation of mudflats in the inner periphery of the creeks. This may be due to

oceanographic phenomenon or the discharge of untreated sewage from drains, dumping of unauthorised solid waste in the creeks and dumping of dismantled/excavated material during construction. The study suggests that this increase should not be taken on a positive note as mangrove is increasing in the creek-ward side and not on the landward side. This will further increase towards the creek-ward side, and a stage will be reached when there will be limited space for free movement of the tidal water in the creek. This has been confirmed with life expectancy analysis of creeks and observed that there would be a further reduction of creek width up to 2025 and 2050. Overall, it could be said that urbanisation is the root cause of this detrimental effect on creek ecosystem.

The study suggests that solid and liquid waste should not be disposed into the creeks without proper treatment and monitoring. The other important factor which is detrimental to the creek ecosystem is the developmental activities along the creeks. This haphazard developmental activity exerts pressure on the creek-ward side of the creek and hence making it more

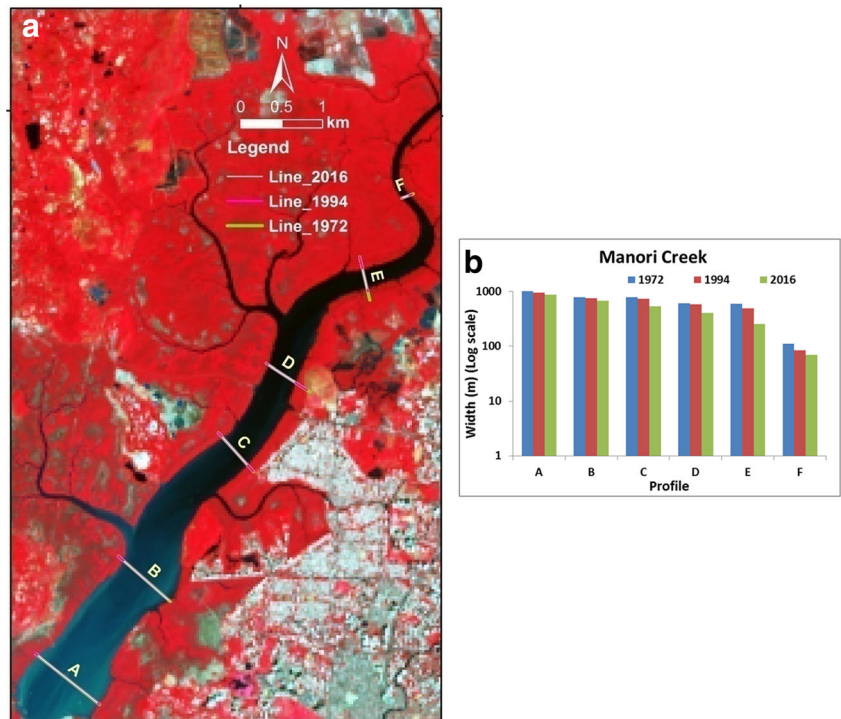**Fig. 15** **a** Various profiles on Manori creek **b** Variation in width of the creek

Table 6 Regression equations and prediction of creek width for Manori creek

Profile	Derived Equation	R^2	Channel width m (Existing)	Predicted Chanel width m (2025)	Predicted Chanel width m (2050)
A	$y = -2.064x + 5095$	$R^2 = 0.767$	882.5	915.4	863.8
B	$y = -2.862x + 6500$	$R^2 = 0.916$	677.9	704.4	632.9
C	$y = -4.313x + 9178$	$R^2 = 0.785$	531.2	444.1	336.3
D	$y = -6.022x + 12,546$	$R^2 = 0.872$	403.2	351.4	200.9
E	$y = -6.921x + 14,207$	$R^2 = 0.970$	256.5	191.9	18.95
F	$y = -1.739x + 3591$	$R^2 = 0.934$	77.5	69.5	26.05

stable for the formation of mudflats and reducing the width of the creek. Hence, proper planning and control should be implemented to monitor the development activities near creeks as they play a crucial role in ecosystem services. Upper stretches of Thane, Malad and Manori creeks are more vulnerable based on life expectancy analysis and require immediate measures in terms of cleaning and dredging so that upper stretches get tidal water to maintain the creek ecosystem.

References

Athalye RP, Quadros G, Gokhale KS (2012) Environmental management strategies for creeks and estuaries: a case study of Thane Creek India. Bionano Front

Blaschke T (2010) Object based image analysis for remote sensing, ISPRS Journal of Photogrammetry and Remote Sensing 65(1):2–16

Carlson TN, Sanchez-Azofeifa GA (1999) Satellite remote sensing of land-use changes in and around San Jose, Costa Rica. Remote Sens Environ 70(3):247–256

Chaves AB, Lakshumanan C (2008) Remote sensing and GIS-based integrated study and analysis for MangroveWetland Restoration in Ennore Creek, Chennai, South India. In: Proceeding of Taal2007: The 12th World Lake Conference, p 685

Chen LC (1998) Detection of shoreline changes for tideland areas using multi-temporal satellite images. Int J Remote Sens 19(17):3383–3397

Dezso Z, Bartholy J, Pongracz R, Barcza Z (2005) Analysis of land-use/land-cover change in the Carpathian region based on remote sensing techniques. Physics and Chemistry of the Earth, Parts A/B/C, 30(1–3), 109–115

Enderle DI, Weih RC Jr (2005) Integrating supervised and unsupervised classification methods to develop a more accurate land cover classification. J Ark Acad Sci 59(1):65–73

Gangadhara Bhat H, Subrahmanya KR (1993) Paleoshorelines and coastal processes in Dakshina Kannada, Karnataka, India: a study based on remotely-sensed data. Int J Remote Sens 14(17):3311–3316

Guerschman JP, Paruelo JM, Bella CD, Giallorenzi MC, Pacin F (2003) Land cover classification in the Argentine Pampas using multi-temporal Landsat TM data. Int J Remote Sens 24(17):3381–3402

Hay GJ, Castilla G (2006) Object-Based Image Analysis: Strengths, Weaknesses, Opportunities and Threats (SWOT). International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXVI-4/C42

Web 1: https://www.britannica.com/place/Mumbai#ref1012661

Jensen JR (2009) Remote sensing of the environment: an earth resource perspective 2/e. Pearson Education India

Jones HG, Vaughan RA (2010) Remote sensing of vegetation: principles, techniques, and applications. Oxford university press, Oxford/New York

Kamble SR, Vijay R (2011) Assessment of water quality using cluster analysis in the coastal region of Mumbai, India. Environ Monit Assess 178(1):321–332

Kulkarni VA, Jagtap TG, Mhalsekar NM, Naik AN (2010) Biological and environmental characteristics of mangrove habitats from Manori creek, West Coast, India. Environ Monit Assess 168(1):587–596

Liu Y, Li M, Mao L, Xu F, Huang S (2006) Review of remotely sensed imagery classification patterns based on object-oriented image analysis. Chin Geogr Sci 16(3):282–288

Lucas R, Mitchell A, Bunting P (2008) Hyperspectral data for assessing carbon dynamics and biodiversity of forests. Taylor & Francis Group, New York, pp 47–86

Mendiratta P, Gedam S (2014) The Dynamic Land form - Thane creek and its profile, ISPRS Proceeding Papers of Sort Interactive Session ISPRS TC VIII International Symposium on "Operational Remote Sensing Applications: Opportunities, Progess and Challenges" 9(12), Hyderabad, India

Mukherji D (2002) Degradation of creeks and mangroves and its impact on urban environment- a case study of Mumbai. In: Proceedings of the national seminar on Creeks, Estuaries and Mangroves- Pollution and Conservation, 28 th to 30 th November, 2002, Thane, pp 331–333

Nayak S, Bahuguna A, Shaikh MG, Rao RS (1991) Manual for mapping of coastal wetlands, landforms and shoreline changes using satellite data. Technical note. 63-64

Odum EP, Barrett GW (1971) Fundamentals of ecology, vol 3. Saunders, Philadelphia

Pomeroy LR, Kuenzler EJ (1969) PHOSPHORUS TURNOVER BY CORAL REEF ANIMALS (No.CONF-670503–). Georgia Univ., Athens. Dept. of Zoology; North Carolina Univ., Chapel Hill. Dept. of Environmental Sciences and Engineering

Rajawat AS, Chauhan HB, Ratheesh R, Rode S, Bhanderi RJ, Mahapatra M, Kumar M, Yadav R, Abraham SP, Singh SS, Keshri KN, Ajai (2015) Assessment of coastal erosion along the Indian coast on 1 : 25,000 scale using satellite data of 1989–1991 and 2004–2006 time frames. Curr Sci 109(2):347–353

Rao BRM, Venkataratnam L (1991) Monitoring of salt affected soils—a case study using aerial photographs, salyut-7 space photographs, and Landsat TM data. Geocarto Int 6(1):5–11

Rogan J, Chen D (2004) Remote sensing technology for mapping and monitoring land-cover and land-use change. Prog Plan 61(4):301–325

Rundquist BC, Harrington JA Jr, Goodin DG (2000) Mesoscale satellite bioclimatology. Prof Geogr 52(2):331–344

Sasamal SK, Rao KH, Suryavansi UM (2007) Sewage and industrial pollution in and around Thane Creek, Mumbai using high resolution IRS data. Int J Remote Sens 28(19):4391–4395

Sreekala SP, Baba M, Muralikrishna M (1998) Shoreline changes of Kerala coast using IRS data and aerial photographs. Indian J Mar Sci 27(1):144–148

Sujatha G, Dwivedi RS, Sreenivas K, Venkataratnam L (2000) Mapping and monitoring of degraded lands in part of Jaunpur district of Uttar Pradesh using temporal spaceborne multispectral data. Int J Remote Sens 21(3):519–531

Tirkey N, Biradar RS, Pikle M, Charatkar S (2005) A study on shoreline changes of Mumbai coast using remote sensing and GIS. J Indian Soc Remote Sens 33(1):85–91

Verma KS, Saxena RK, Barthwal AK, Deshmukh SN (1994) Remote sensing technique for mapping salt affected soils. Int J Remote Sens 15(9):1901–1914

Vijay R, Khobragade PJ, Sohony RA, Kumar R, Wate SR (2014) Hydrodynamic and water quality simulation of Thane creek, Mumbai: an impact of sewage discharges. Indian J Geo-Mar Sci 43(10):1891–1898

Vyas L, Vyas S (2007) Simulation models for the dispersion of sewage outfalls along the west coast of Mumbai, India. In: Proceedings of the 7th WSEAS international conference on Simulation, Modeling and Optimization, Beijing, China, pp 503–508

Zha Y, Gao J, Ni S (2003) Use of normalized difference built-up index in automatically mapping urban areas from TM imagery. Int J Remote Sens 24(3):583–594