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Study of decadal variations in width and mangrove cover of the Thane Creek, Maharashtra, India, using remote sensing

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The present study depicts decadal variations in the area, width and mangrove cover of Thane Creek, Maharashtra, India, using the remote sensing technique. The study is significant because the Creek has lush-green mangrove cover on its vast intertidal region and considerable urban developmental activities are occurring around it. Landsat datasets were used for different years from 1972 to 2014 and Sentinal 2A satellite data were used for the year 2020. To understand the variations in width from mouth to upstream, the Creek was divided into three zones, viz. mouth, middle and upstream. For mangrove cover estimation, supervized classification analysis was used for images from 2005 to 2014, while object-based image classification analysis with multi-spectral resolution was used for images from 2020. From the results, it can be confirmed that there is an overall increase in the spatial extent of mangroves and a reduction in the width of Thane Creek. The study also shows that creek width had decreased by 1.15 km at the mouth and 0.08 km at the upstream end from 1972 to 2020, while mangrove cover had increased by 14.1 km^2 from 2005 to 2020 (15 years). The overall reduction in the area between the west and east banks of the Creek was around 15.3 km^2 from 1972 to 2020. This study shows that Thane Creek is rapidly narrowing at its northern end.

Keywords: Creek, decadal variations, mangrove cover, mudflats, remote sensing.

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CREEKS and estuaries are important coastal features as they play a crucial role in materials transport, groundwater recharge, nutrient cycling, controlling floods and sediment filtration, thus helping balance the ecological processes[1]. The intertidal regions of the creeks generally have a rich growth of mangroves along with mudflats that play a significant role in the nutrient enrichment of the creeks. The presence of mangroves in the creeks is important in the transport of organic matter and nutrients, thus providing breeding grounds for various marine organisms, including fishes.

Mumbai is one of the most populous metropolitan cities in Maharashtra, India. It is also called the financial capital of India and is one of the densest industrial hubs. Three creeks, viz. Thane, Gorai and Malad are found in the Mumbai coastal region. Among these three major creeks, Thane Creek has numerous drainage streams coming from Mumbai sub-urban areas. This Creek has a vast intertidal extent on both sides. It has been subjected to changes over a period of time due to anthropogenic activities on both the east and west banks. A study of the variations of mangrove cover is essential for planners. Remote sensing and GIS are the most suitable techniques to study and monitor coastal features.

Remote-sensing data give information on various components of the coastal environment, viz. mangrove density mapping, shoreline changes, tidal boundaries, brackish-water areas, suspended sediment dynamics, coastal currents, pollution, zonation of mangrove communities, etc. Only a few studies have been carried out to explain the variation in mangrove cover on the west coast of India. Mangrove cover in Thane Creek has been studied by several researchers using the remote sensing technique[2–6]. Ritesh *et al.*[7], using satellite data, estimated the mangrove cover of three creeks, viz. Malad, Manori and Thane. They found that mangroves around the Thane and Manori creeks have increased from 50.7 to 57.6 km^2 and 8.4 to 25.2 km^2 respectively. However, there was a decrease in mangrove cover around Malad Creek from 13.3 to 9.7 km^2 from 1972 to 2016.

Using IRS P6 dataset, Abhyankar *et al.*[8] found that mangrove cover in the Mumbai region had decreased marginally from 50.5 km^2 in 2004 to 48.7 km^2 in 2013. Their study was confined to the area between the west and east coasts of Mumbai. The east coast of Thane Creek was not considered in the study. On the contrary, Abdul Azeez *et al.*[9], who studied the multi-decadal changes in a mangrove forest of Mumbai using satellite data from 1990 to 2017, found that the mangrove cover had increased from 79 to 155 km^2 in 27 years. Their area of interest was much larger than that considered by Abhyankar *et al*.[8]. The study domain of Abdul Azeez *et al*.[9] covered the west coast of Mumbai, the east and west coasts of Thane Creek and the northern part of Amba Estuary.

Prerna *et al.*[10] studied the decadal variations of mangrove cover and coral cover of the southern Gulf of Kachchh using satellite data. Their study showed that the mangrove cover in the southern Gulf of Kachchh had increased while coral reef cover had decreased from 1999 to 2010.

Here, we study the decadal variations in area, width and mangrove cover of Thane Creek using satellite data.

The objectives of this study are to estimate the following:

- Changes in the area between the western and eastern banks of Thane Creek from 1972 to 2020.
- Mangrove cover around Thane Creek from 2005 to 2020.
- Changes in the width of Thane Creek from mouth to upstream from 1972 to 2020.

Thane Creek, which is surrounded by the cities of Mumbai, Thane and Navi Mumbai, is one of the largest creeks in Asia. It is situated between long. 72.55° and 73.00°E and lat. 19.00° to 19.15°N (Figure 1). Mumbai Harbour is located in the southern end while it extends northwards connecting to River Ulhas by a minor channel near Thane city at Kasheli. It is narrower and shallower at the northern end and broader and deeper towards the sea; both its banks consist of mangroves. Thane Creek is dominated by tidal action and fringed with mangroves and mudflats along both banks, with larger areas on its eastern side. The Creek receives a heavy load of domestic and industrial effluents[11]. Two major ports, Mumbai Port Trust (MbPT) and Jawaharlal Nehru Port Trust (JNPT), are situated at the mouth of the Creek. Dredging is carried out periodically at the mouth to maintain the navigational channel to the ports. Two islands, namely, Elephanta and Butcher, are situated in the southern part of the Creek. The maximum water depth (12 m) below the chart datum occurs at the mouth of the Creek and decreases upstream[12]. The region experiences semi-diurnal tides with appreciable diurnal inequality. The tidal range is more or less unchanged south of Pir Pau and increases rapidly towards the north due to a funnelling effect. There is a small connection between Thane Creek and Ulhas Estuary, which is situated at Kasheli. Thus, tidal water enters the channel first through the Ulhas Estuary rather than Thane Creek during floods[13]. Two tidal inlets, viz. Nhava–Sheva and Panvel are the major tributaries to the Creek. Water entering from the eastern side of the mouth tends to move towards the Panvel Creek, whereas water mass passing through the western side is directed towards the main channel of the Thane Creek depending on the tidal excursion[12]. Eddies and high residual current values showed intense mixing capacity in the southern region of the Creek. A high rate of sedimentation was found in the central and northern parts of the Creek. Jubin *et al.*[14] reported that the Creek is well-mixed vertically and the flushing time is more (3.68 days) compared to the Ulhas Estuary, which has 1.5–2.57 days of flushing time[7]. The present study shows that the horizontal gradient of salinity from mouth to upstream in the Creek is smaller during summer compared to monsoon season.

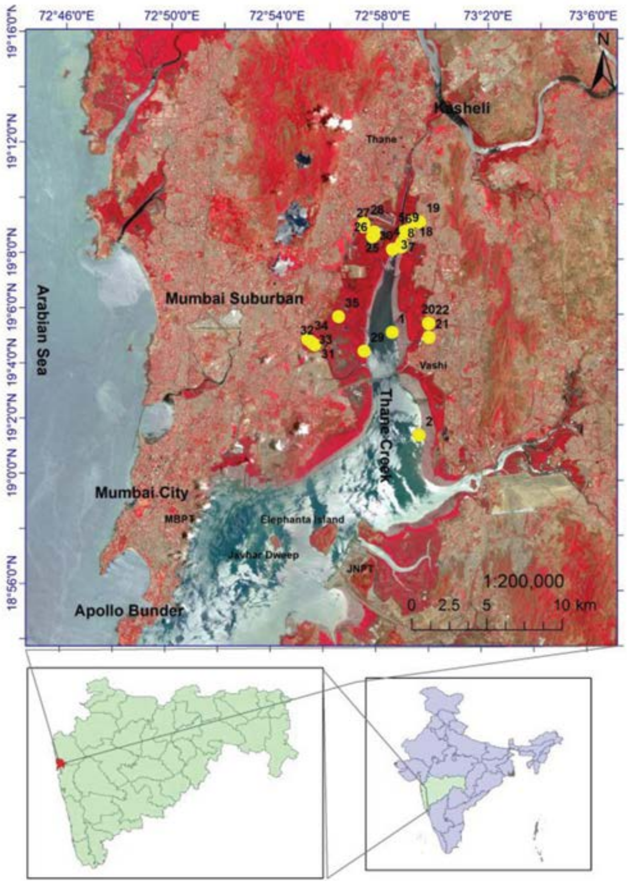

Figure 1. Location map of the Thane Creek, Maharashtra, India (yellow dots are observational locations).

Table 1. Datasets used in the study

Satellite	Sensor	Resolution (m)	Date of pass	Bands used
Landsat-1	MSS	60	11 November 1972	1,2,3,4
Landsat-1	MSS	60	21 November 1978	2,3,4,5
Landsat-5	TM	30	19 March 1988	4,3,2
Landsat-7	TM	30	25 February 2000	7,6,5,4,3
Landsat-7	TM	30	5 January 2010	7,6,5,4,3
Landsat-8	OLI/MSS	30	23 February 2014	5,4,3
Sentinel-2A	MSI	20	11 May 2020	8,4,5

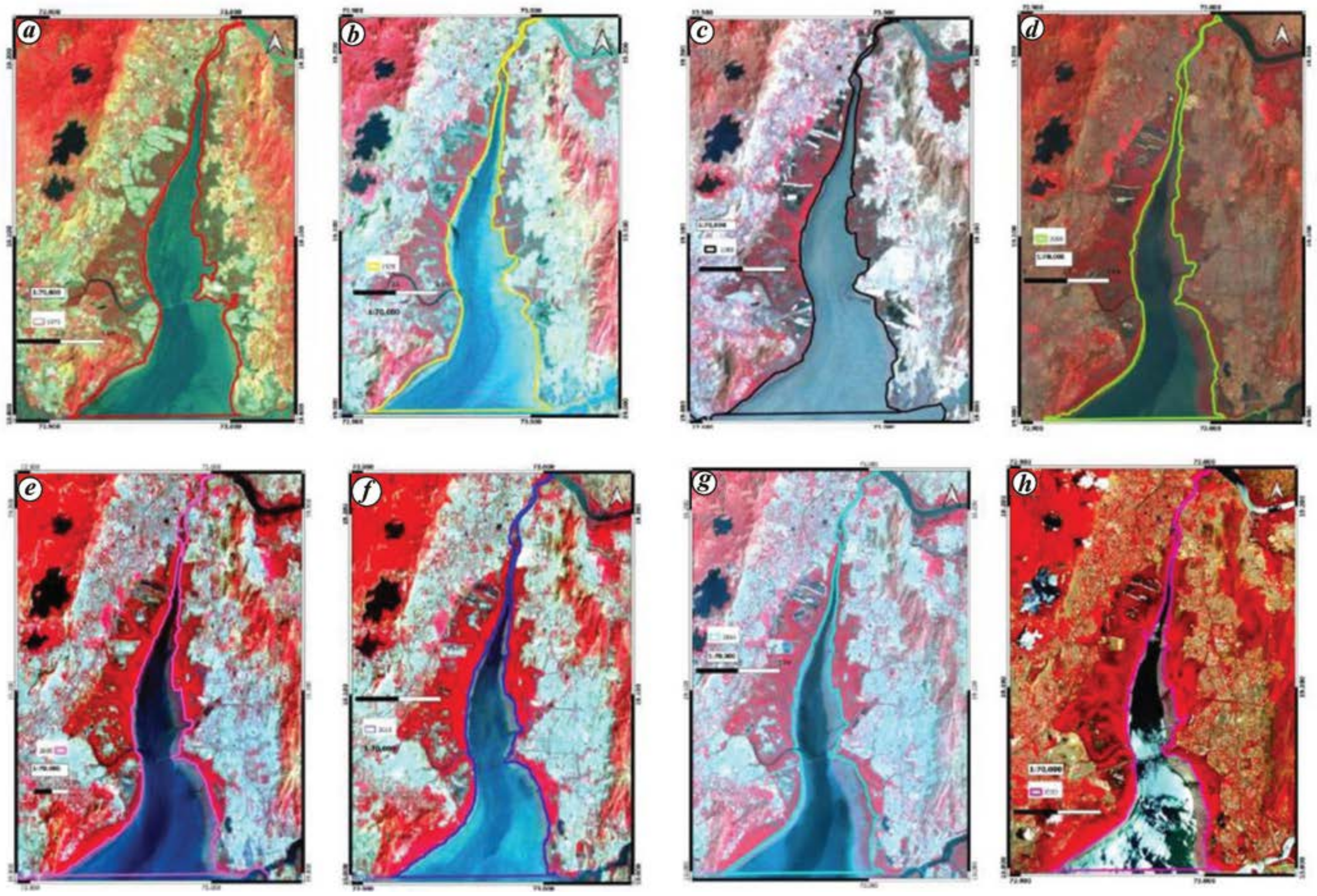

Figure 2. FCC images of the Thane Creek at low tide for the years: ***a***, 1972; ***b***, 1978; ***c***, 1988; ***d***, 2000; ***e***, 2005; ***f***, 2010; ***g***, 2014; ***h***, 2020.

Thane Creek also comprises a Protected Area, viz. Thane Creek Flamingo Sanctuary (TCFS), situated on its north-western bank. The total area of TCFS is around 48 km^2. Water quality of Thane Creek is affected as huge amounts of wastewater are discharged from the industries located on both its banks. In addition, a large amount of domestic sewage also enters the Creek, mostly from the western shore. It is estimated that 3.5×10^8 and 1.8×10^8 l are discharged daily into the Creek as domestic and industrial wastewater respectively[15]. In addition, a huge quantity of sediments, usually fine-grained, enters the Creek through various inlets and from nearby mudflats. A report by the Central Water and Power Research Station, Pune, showed that a yearly load of 0.84×10^6 m^3 reaches the central parts of the Creek due to prevailing tidal currents[16]. Also, the sediment is fairly spread over the 250 km^2 area with a sedimentation rate of 4 mm/y (ref. 17).

In the present work, Landsat and Sentinel images were collected from the United States Geological Survey (USGS-Earth Explorer) as they have already been ortho-rectified, geo-coded and terrain-corrected. The spectral bands used for image analysis were green, red, near-infrared (NIR) and mid-infrared (MIR). Table 1 provides the details of the satellite images used in the study, along with band combinations.

For high-resolution mapping of mangroves in Maharashtra in 2005, the Mangrove Cell commissioned a project to the Maharashtra State Remote Sensing Centre. Very high-resolution Quickbird satellite datasets were used for 2005 and 2006 in the said project. Later, the Indian Institute of Space Sciences and Technology (IIST), Thiruvananthapuram, conducted a study sponsored by the Mangrove Foundation, Mumbai on mangrove cover in Maharashtra for the period 2018–20. For this, very high-resolution satellite data (World-view) of 2.5 m resolution were used. IIST also mapped the mangrove cover in Maharashtra for 2014 using open-source Landsat-8 data. All the above-mentioned datasets were used to estimate mangrove cover changes for 2005, 2014 and 2020 in the present study.

False colour composite (FCC) images are useful for analysing the finer NIR reflectance variations related to photosynthesizing vegetation[18–20]. In this study, two different satellite images were used (Landsat images for 1972, 1978, 1988, 2000, 2005, 2010, 2014 and Sentinel 2A image for 2020) to carry out the analysis (Figure 2 *a–h*). All the images were collected for low-tide conditions. The image analysis software ArcGIS 10.8 was used for band composition as a pre-processing tool.

To understand the variations of width from mouth to upstream, the Thane Creek was divided basically into three

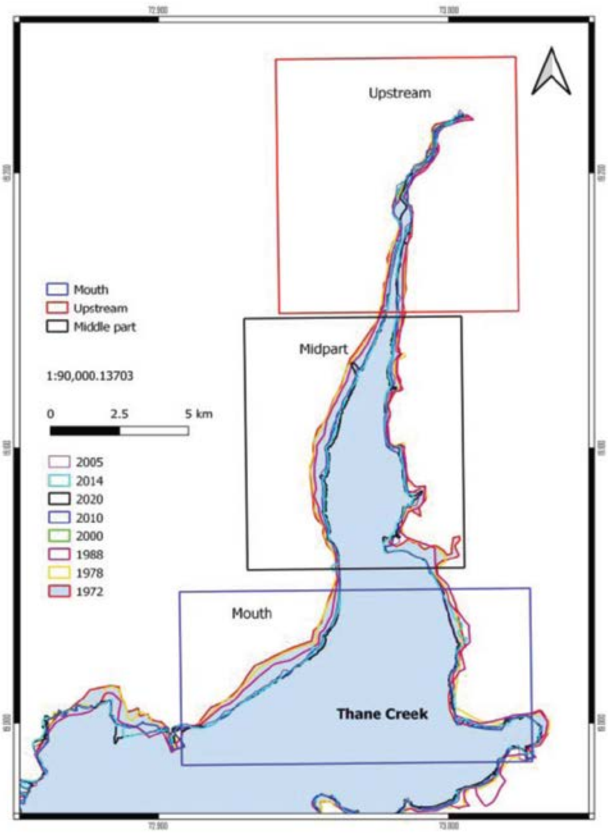

Figure 3. Mouth, middle and upstream zones of the Thane Creek.

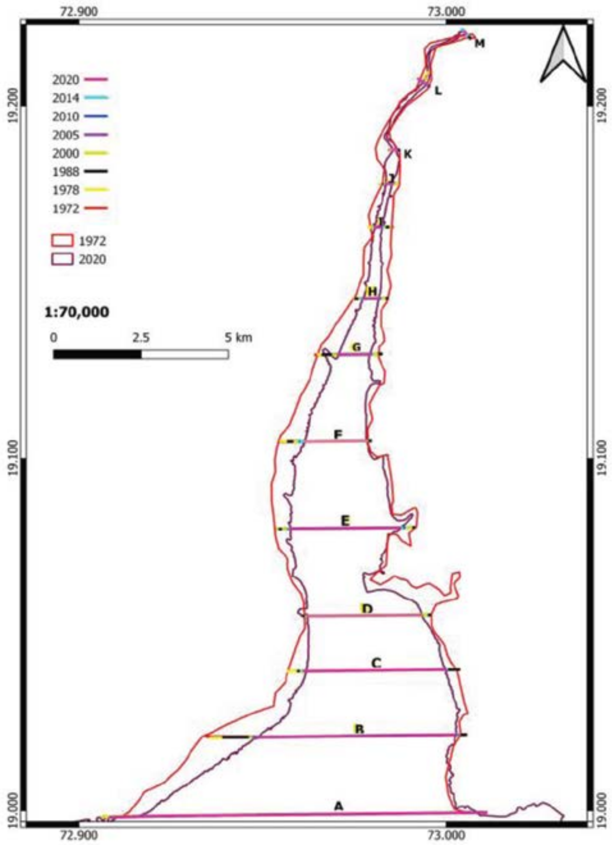

Figure 4. Map showing width variations of transects *A–M*.

Table 2. Variations in the width of the Thane Creek at several locations from 1972 to 2020

Profile	Width (km)								Change in width from 1972 to 2020	Percentage decrease
	1972	1978	1988	2000	2005	2010	2014	2020		
A	10.77	10.73	10.5	10.74	10.43	9.72	9.71	9.67	1.10	14
B	7.42	7.15	6.91	5.98	5.80	5.77	5.71	5.77	1.65	22
C	4.61	4.88	4.6	4.16	4.12	4.02	4.05	4.19	0.42	9
D	3.56	3.58	3.62	3.33	3.35	3.27	3.27	3.27	0.29	8
E	3.98	3.91	3.83	3.66	3.46	3.34	3.21	3.12	0.86	21.6
F	2.52	2.47	2.33	2.06	1.98	1.86	1.87	1.76	0.76	30.3
G	1.82	1.70	1.67	1.23	1.42	0.93	0.9	0.911	0.91	50
H	0.95	0.83	0.90	0.70	0.63	0.51	0.46	0.43	0.52	55
I	0.63	0.59	0.46	0.36	0.26	0.19	0.24	0.17	0.46	5.7
J	0.52	0.46	0.37	0.34	0.18	0.17	0.15	0.16	0.36	69
K	0.18	0.18	0.18	0.13	0.10	0.10	0.09	0.1	0.08	45
L	0.25	0.14	0.2	0.05	0.04	0.26	0.11	0.12	0.13	48.4
M	0.18	0.13	0.20	0.17	0.10	0.14	0.2	0.05	0.13	72.2

zones, viz. (a) mouth, (b) middle and (c) upstream (Figure 3) and is further into 13 single-line sections (*A–M*) to obtain a single value for carrying out the analysis (Figure 4). The width of these sections of the Creek was determined using ArcGIS 10.8 for 1972, 1978, 1988, 2000, 2005, 2010, 2014 and 2020 (Table 2). Digitization technique was used to estimate the area of the Creek and harbour separately.

Mangrove classification analysis is essential to understand the present status of mangroves. It serves as an important input for analysing the variations. Three datasets, viz. 2005, 2014 and 2020 were used to analyse these variations. The present study describes variations that occurred in the dense mangrove cover, sparse mangrove cover and mudflat during 2005, 2014 and 2020. A supervised classification technique

Table 3. Geographical coordinates of ground-truth observations

X	*Y*	Location	Latitude (°N)	Longitude (°E)	Description
72.97471	19.08751	L1	19.087509	72.974714	Creek
72.99262	19.02562	L2	19.025622	72.992623	Creek
72.98397	19.1485	L3	19.148499	72.983967	Mangroves
72.98342	19.14856	L4	19.148558	72.983422	Jetty (Airoli)
72.98237	19.14879	L5	19.148788	72.98237	Mangroves
72.98133	19.14796	L6	19.147958	72.981327	Creek
72.98031	19.14137	L7	19.141365	72.980312	Tidal flat
72.97995	19.13918	L8	19.139175	72.979945	Tidal flat
72.98258	19.14876	L9	19.148763	72.982582	Mangroves
72.98408	19.14849	L10	19.148491	72.984083	Mangroves
72.98434	19.14837	L11	19.148371	72.984336	Mangroves
72.00444	19.05194	L12	19.051944	73.004444	Associated mangroves
72.00528	19.0525	L13	19.0525	73.005278	Mangroves
72.02833	19.01194	L14	19.011944	73.028334	Associated mangroves
72.04611	19.01833	L15	19.018334	73.046111	Waterbody
72.0025	19.09167	L16	19.091667	73.0025	Terrestrial vegetation
72.00222	19.09306	L17	19.093056	73.002222	Terrestrial vegetation
72.98694	19.155	L18	19.155	73.986944	Waterbody
72.99139	19.15445	L19	19.154445	73.991389	Waterbody
72.99778	19.09333	L20	19.093333	73.997778	Mangroves
72.99806	19.08472	L21	19.084722	73.998056	Associated mangroves
72.99806	19.09306	L22	19.093055	73.998055	Mudflat
72.00194	19.09361	L23	19.093611	73.001944	Mudflat
72.9617	19.14528	L24	19.14528	72.961699	Terrestrial vegetation
72.96275	19.14635	L25	19.146352	72.962747	Land
72.96281	19.14807	L26	19.148073	72.962807	Mangroves
72.95602	19.15113	L27	19.151128	72.956019	Saltpan
72.9561	19.15308	L28	19.153079	72.956098	Saltpan
72.95719	19.07599	L29	19.075988	72.95719	Tidal flat
72.9743	19.13765	L30	19.137652	72.974297	Tidal flat
72.92595	19.07944	L31	19.079441	72.925951	Mangroves
72.92544	19.07982	L32	19.07982	72.925436	Creek
72.92426	19.08072	L33	19.080721	72.924258	Mangroves
72.92154	19.08275	L34	19.082749	72.921543	Mangroves
72.94087	19.09659	L35	19.096586	72.940866	Mangroves

was used to classify the mangroves and associated classes for 2005 and 2014. Similarly, the object-based image classification analysis (OBIA) technique was used for the image collected in 2020. Based on the above studies, six classes were identified, i.e. (i) dense mangroves, (ii) sparse mangroves, (iii) mudflat (open areas of silt within mangrove forests), (iv) tidal flat (open areas of silt between the mangroves and creek water channel – exposed during low tides), (v) saltpan and (vi) waterbody.

The mangrove cover map for 2020 was validated for classification accuracy with ground-truth data. Sufficient samples were collected from satellite data and the same were surveyed in January and October 2020. Ground-truth data were collected at 35 locations shown in Figure 1. Table 3 lists the geographical coordinates of these data. Overall accuracy and kappa coefficient were estimated to validate the mangrove density maps using Worldview satellite images. The accuracy of the classification was estimated as 86%. The classified map was further improved through contextual editing based on field knowledge and ground-truth information.

Figure 2 *a–h* shows FCC images for 1972, 1978, 1988, 2000, 2005, 2010, 2014 and 2020. These images reveal significant variations in the Thane Creek and mangrove cover over the years. The extent of waterbody has reduced in the Creek.

The width analysis was carried out by dividing Thane Creek into three parts: mouth, middle and upstream (Figure 3). Further, different profiles (*A–M*) were developed to analyse the width (Figure 4). Table 2 shows the results. The table indicates that maximum width found at the mouth and as it reaches northward, the width decreases during the study period. As shown in Table 2, the maximum width of 10.77 km and minimum width of 0.18 km were found at profiles *A* and *K/M* respectively, for 1972. For 2020, the maximum width (9.67 km) was found at profile *A* and the minimum width (0.05 km) at profile *M*. The highest reduction (1.15 km) of width occurred at profile *A* (mouth of the creek), whereas the minimum reduction was noticed at profile *K* (upstream) of the Creek (0.08 km) in 48 years. Figure 5 shows the change in width with respect to 1972 as the base year. However, considering width for the year 1972

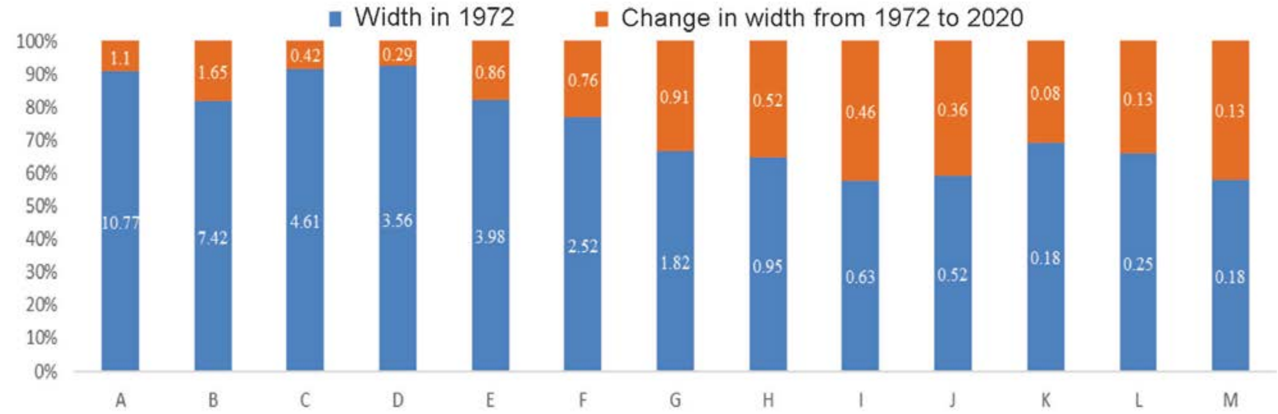

Figure 5. Change in width with respect to 1972 as the base year.

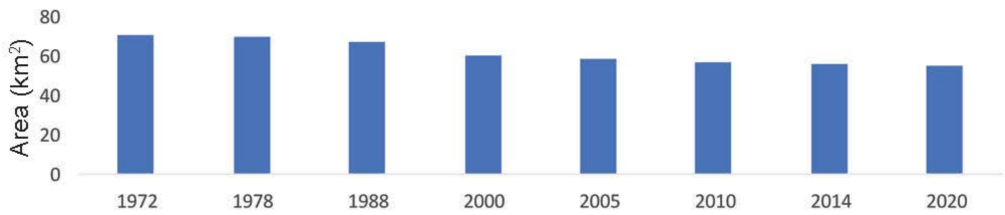

Figure 6. Variations in area of the Thane Creek from 1972 to 2020.

as the base value, it was observed that percentage-wise reduction was highest in profile *M* (76), i.e. at the upstream, whereas it was lowest at profile *A* (24), i.e. at the mouth of the Creek.

Figure 6 presents these changes in the Thane Creek area from 1972 to 2020. The results reveal that the area of the Creek from the mouth (profile *A*) to upstream (profile *M*) has reduced from 70.15 km^2 in 1972 to 54.87 km^2 in 2020, i.e. a decrease of 21.8% in area. Thus, the reduction in area of the Thane Creek is estimated at 15.28 km^2 between 1972 and 2020. The overall rate of decrease in the area has been 0.3 km^2/yr.

Land-use/land-cover maps for 2005, 2010 and 2020 were prepared to understand the variability of mangrove extent in the Thane Creek intertidal region. Totally six classes were considered (Figure 7 *a–c*). From the figure, it is evident that the mangrove cover had increased in 2020. To quantify the classes, a table was prepared (Table 4). From the table, it can be found that the total mangrove cover (dense + sparse) observed around the Thane Creek (from profiles *A* to *M*) was 42.7 km^2 in 2005 and 56.8 km^2 in 2020, showing an increase of about 14.1 km^2, while the mudflats had decreased almost by 1.2 km^2. The increase in mangrove cover (14.1 km^2) is less when compared to the results of Abdul Azeez *et al.*[9], who found an increase in the mangrove area of 75.4 km^2 in 27 years. The high value is attributed to the fact that they considered more areas (part of Amba Estuary and the western coast) for comparison. The tidal flat increased by 3.1 km^2 from 2005 to 2020, which was estimated using satellite images of the lowest low-tide conditions. From the results, it can be noticed that most of the sparse mangroves have been converted to dense mangroves and mudflats have also been occupied by mangroves in the intertidal region of Thane Creek. The mangroves have increased towards the creek-ward side from the western and eastern banks. The maximum increase in mangrove cover is found in the central zone of the Creek. The reason for the increase in intertidal extent in Thane Creek is sedimentation. The Creek has two major ports, viz. MbPT and JNPT at the mouth. To maintain navigational channels for the ports, dredging is carried out periodically. Generally, the sediments that reach the northern region of the Creek settle down at the intertidal region[16,17]. Mumbai and Navi Mumbai are situated along the Creek. Reclamation of land at the high tide line in the northern part of the Creek may have caused changes in the tidal circulation, which could result in changes in the extent of intertidal areas of the Creek.

The results of the present study show that the overall reduction in the Thane creek area has been 15.3 km^2 in 48 years (from 1972 to 2020). Maximum area reduction was found at the mid zone. The study also reveals an overall increase in the mangrove cover (14.1 km^2) in the intertidal regions of Thane Creek from 2005 to 2020. A significant increase in the area of mangrove cover was found in the mid-zone of the western bank. The increase in mudflats and tidal flats along the Creek could be the possible reason for the increase in mangrove cover. The width of Thane Creek was reduced by 1.18 km in the mouth region, while it had

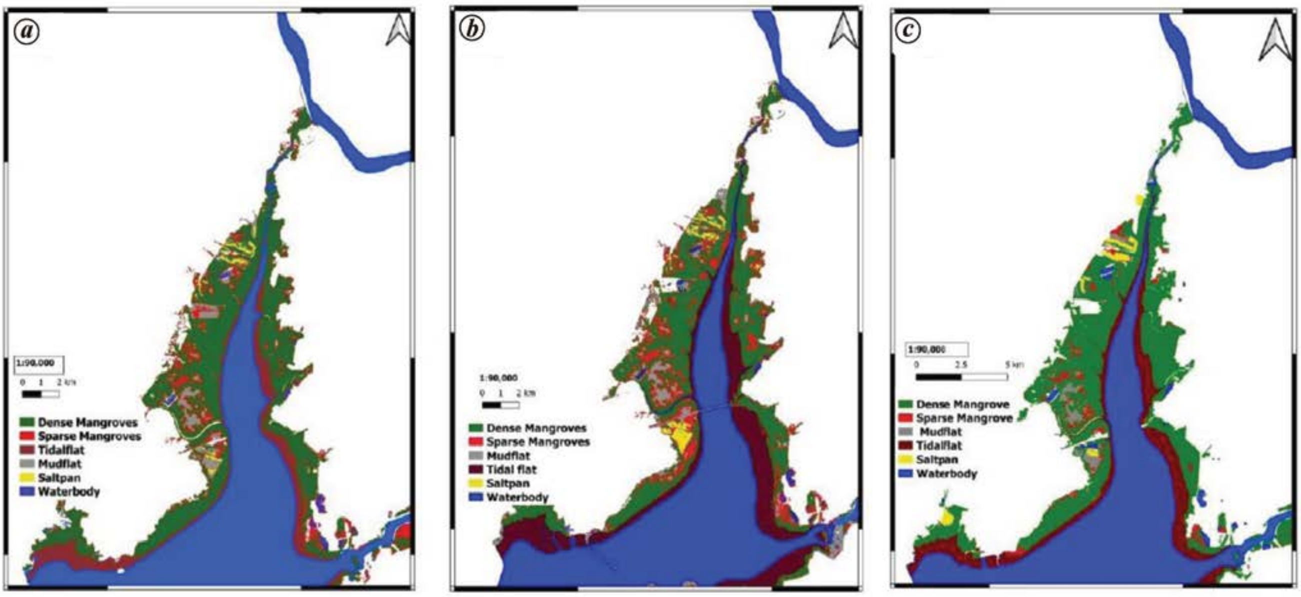

Figure 7. Land-use/land-cover maps for the year: ***a***, 2005; ***b***, 2014; ***c***, 2020.

Table 4. Change in mangrove cover from 2000 to 2020

	Area (km^2)		
Class	2005	2014	2020
Dense mangroves	37.9	33.06	51.5
Sparse mangroves	4.8	18.0	5.3
Mudflat	6.5	2.1	5.3
Saltpan	1.9	6.01	1.83
Tidal flat	18.2	20.4	21.3
Total mangrove cover	42.7	51.06	56.8

reduced by 0.08 km upstream. However, the rate of reduction in width was high in the upstream region. Reclamation along the banks and dredging near the mouth may alter the circulation pattern in Thane Creek. These might be the factors resulting in increased sedimentation rate in the Creek. The present study shows that the shrinkage of the Creek is higher towards the northern end. If no measures are undertaken to reduce the rate of sedimentation, it may result in permanent blocking of freshwater input from Ulhas River to the Thane Creek in a few decades.

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Addendum

Set cover model-based optimum location of electric vehicle charging stations

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On page 1450, col 2, under the section ‘Formulation of set cover problem’, read the first sentence as ‘The formulation of set cover problem is adapted from Vazifeh *et al.*[6].’

The correction has been made in the online version. – Editor