Check for updates

Assessment of mangrove cover dynamics and its health status in the Gulf of Khambhat, Western India, using high-resolution multi-temporal satellite data and Google Earth Engine

Jigarkumar B. Solanki · Nikhil Lele ·
Anup Kumar Das · Parul Maurya ·
Rina Kumari

Abstract Anthropogenic activity is a major driving factor of greenhouse gas emission, leading to climate change worldwide. So, the best natural approach to lowering the carbon from the atmosphere is mangroves which have more potential to sequestrate carbon. But mangroves are under threat due to land use land cover change. This research has been carried out on the mangroves of Gulf of Khambhat, Gujarat, India, where anthropic activity is affecting the mangrove forest cover with spatiotemporal heterogeneity. In the present study, multi-temporal high-resolution satellite data AVNIR-2 (Advanced Visible and Near Infrared Radiometer type-2) and LISS-4 (Linear Imaging Self-Scanning Sensors-4) were used for the demarcation of various land use/land cover class (LULC), and change analysis and assessment of mangroves health for the years 2009, 2014, and 2019. The impact of saltpan/aquaculture on mangroves growth and its health status has been calculated by various MODIS (Moderate Resolution Imaging Spectroradiometer) satellite data products such as gross primary productivity (GPP), enhanced vegetation index (EVI), and leaf area index (LAI) in Google Earth Engine (GEE), and field-based method was also considered.

This study suggests that there is a marginal increase (17.11 km^2) in mangrove cover during the assessment period 2009–2019; on other side, 65.42 km^2 was degraded also. However, increase in saltpan/aquaculture is imposing an adverse effect on mangroves' basal area, plant density, and productivity. Change analysis also suggests a reduction in healthy mangrove area (from 25.20 to 2.84 km^2), which will have an impact on ecosystem services.

Keywords Land use land cover dynamics · Multi-temporal satellite data · Vegetation indices · MODIS

J. B. Solanki · P. Maurya · R. Kumari (✉)
School of Environment and Sustainable Development,
Central University of Gujarat, Gandhinagar, Gujarat, India
e-mail: rina.sesd@cug.ac.in

N. Lele · A. K. Das
Space Applications Centre, Ahmedabad, Gujarat, India

Introduction

Worldwide economic and population growth were the major drivers of CO_2 emission from fossil fuel burning and from various other anthropic activity (IPCC, 2014). In 2010, the burning of fossil fuels and industrial emissions emitted more than 30 GtCO^2-eq/year (gigatonnes of CO^2–equivalent per year), accounting for 65% of total greenhouse gas emissions (IPCC, 2014). Forests sequester and store more carbon compared to any other terrestrial ecosystem, so there is one effective way to reduce the CO_2 from the atmosphere by plants or autotrophs (Gibbs et al., 2007).

Mangroves cover only 0.7% area of the total tropical forest region, yet they have the potential to sequestrate carbon four times more per unit area than other terrestrial forests of tropics (Donato et al.,

2011; Giri et al., 2011; Murray et al., 2011). Every year, mangroves are sequestrating 22.8 million metric tons of carbon (11% of the total terrestrial carbon) (Giri et al., 2011). In the Indo-Pacific region, mangroves were found, as a more carbon-rich (on average, 1023 tC ha^{-1}) ecosystem than the boreal, temperate, and tropical upland forest ecosystems (Donato et al., 2011). Globally, the spatial coverage of mangroves is limited by climatic variables such as change in temperature variation, precipitation, tides, waves, and freshwater input which affects the distribution and biomass of mangroves at the regional scale (Alongi, 2012). Mangroves are found in 118 nations around the world, covering 137,760 km^2 as of 2000, and they are disseminated between latitude 30°N and 30°S (Giri et al., 2011). Globally, 54 true mangroves species were recorded (Kuenzer et al., 2011). Mangroves of South and Southeast Asia form the world's most extensive and diverse mangrove systems comprising 40% of global mangroves (FSI, 2019). Indian mangrove accounts for 3% of global cover and 8% of the South Asian mangrove cover, respectively (FAO, 2007), which are distributed along all the maritime states, covering an area of about 4975 km^2 along the Indian coastline (FSI, 2019). In India, West Bengal has the largest cover of mangrove (2,112 km^2) followed by Gujarat, encompassing the second largest mangrove cover (1,177 km^2), whereas Puducherry has the lowest mangrove cover (2 km^2) (FSI, 2019).

This vital ecosystem provides numerous important ecosystem services such as (1) it acts as bio-shield from the storms, erosion, tsunami, etc., and thus, it provides shoreline stabilization; (2) acts as a shelter for many organisms; (3) provides food; (4) medicines; (5) fuel; (6) construction material for local people; (7) it also traps and recycles nutrients; (8) acts as screening of the UV-B radiation; (9) controlling the flood; and (10) it provides a valuable site for developing a tourist place (Bal et al., 2018; Kathiresan, 2012). Various studies have been focused on to evaluate the economic values of mangrove (Bann, 1997; Costanza et al., 1997; Gunawardena & Rowan, 2005; Hoang Tri et al., 1998; Ruitenbeek, 1992; Sathirathai, 1998) but in general, the value is ranging from USD 2000 to USD 9000 per hectare per year (Spalding et al., 2010). Despite their significance, mangroves are globally regressing at a rate of 1–2% each year (Spalding et al., 2010), and since 1980, the loss rate was between 20 and 35% (FAO, 2007; Polidoro

et al., 2010). The worldwide ever-increasing population growth has been observed in coastal areas due to industrialization and other land use practices such as aquaculture production, particularly in Asia as it provides 90% of the world's aquaculture production (FAO, 2002; FSI, 2019), a loss in mangroves cover were reported. In Thailand, from 1979 to 1987, 25% of the nation's mangroves were lost while in India, the mangrove cover has decreased 50% from 1963 to 1977 (World Resources Institute, 1996). Duke et al. (2007) predicted that if current rate of mangrove loss continues, then after 100 years, there is no single mangrove present on the Earth. Therefore, continuous monitoring of mangroves cover is required both spatially and temporally.

In this context, remote sensing data, due to its continuous, synoptic, and multispectral nature, is a worthy source to monitor the mangrove ecosystems. Many studies have been published related to detecting the change in the spatial extent of mangrove using different datasets with different classification methods (Chen et al., 2017; Giri et al., 2007, 2011, 2015; Held et al., 2003; Jia et al., 2015; Kamal & Phinn, 2011; Long & Giri, 2011; Pasha et al., 2016).

Remote sensnig data provides the spectral reflectance of the canopy, so by utilizing this reflactrance, scientists have prepared various vegetation indices to monitor, the vegetation cover, quantitatively and qualitatively (Chellamani et al., 2014). Authors have also used MODIS (Moderate Resolution Imaging Spectroradiometer) products (GPP [gross primary productivity], LAI [leaf area index], EVI [enhanced vegetation index]) to assess the health of the mangrove ecosystem along with other satellite data (Ishtiaque et al., 2016; A. Kumar et al., 2017; Shrestha et al., 2019). Google Earth Engine (GEE) cloud computing platform facilitates the processing of the enormous MODIS data in very short time. Many studies were done on the spatial extent and change in mangrove cover (Chen et al., 2017; Giri et al., 2015; Jia et al., 2015) but there are very few authors who studied the biophysical parameters of mangrove (Cougo et al., 2015; Kovacs et al., 2013; Kumar et al., 2017) using remote sensing.

According to Nayak and Bahuguna (2001), in India, the mangrove cover has degraded due to various land use practices, although detailed studies have been done on few mangrove forest (Awty-Carroll et al., 2019; Bhavsar et al., 2014; Giri et al., 2007; Kripa et al.,

2019; Maurya & Kumari, 2021b; Nakhawa et al., 2012; Pasha et al., 2016; Prerna et al., 2015; Shimu et al., 2019; Vijay et al., 2005). The present study has been done on Gulf of Khambhat mangrove, Gujarat, West Coast of India. Gujarat is the fastest growing industrial state with 1600 km longest coastline and the mangrove cover has reduced in many parts of the state (Maurya & Kumari, 2021; Nayak & Bahuguna, 2001; Pasha et al., 2016). So present study aims to (1) quantify the spatial and temporal changes in mangrove cover, (2) estimate the health status of mangroves, and (3) assess the effect of saltpan/aquaculture on mangrove growth and its health.

Material and method

Study area

Present study area, the Gulf of Khambhat, also known as the Gulf of Cambay, located between the land masses of Saurashtra and South Gujarat in India extends between the latitudes of 20°35′–22°20′ N and longitudes of 72°05′–72°55′ E, is a large macro-tidal embayment that opens to the south into the Arabian Sea (Misra & Balaji, 2015). The trumpet-shaped gulf has length of about 200 km and width varying from 70 km at the southern end towards the sea to about 20 km at its northern end (Fig. 1). The average depth of the gulf is around 30 m. The gulf experiences semi-diurnal tidal current with the maximum tidal amplitude reaching up to 11 m, which is primarily responsible for erosion and deposition along the coasts (Kumar & Kumar, 2010; Kumar & Balaji, 2015; Misra & Balaji, 2015; Saha et al., 2018). The region receives average annual precipitation between 600 and 800 mm, mostly from the southwest monsoon (VishnuRadhan et al., 2018). The summer and winter temperatures of the region vary from 37 to 43 °C and 10 to 18 °C, respectively (Upadhyaya et al., 2014).

The gulf receives freshwater from Kalubhar, Bhadar, Bhogava, and Shetrunji rivers in the west, and from Sabarmati, Mahi, Dhadhar, Narmada, and Tapti rivers in the north and east (Saha et al., 2018). The Gulf of Khambhat also encompasses rich landform features comprising of estuaries, mangroves, creeks, and mudflats, with rich biodiversity (VishnuRadhan et al., 2018). Previous study found 15 different mangrove species in the area (Pandey & Pandey, 2013), but their abundance and distribution are not uniform.

During fieldwork, several anthropogenic pressures were observed on the mangroves as the local population depends on their livelihood such as fuel, fodder (for camels and buffalos), and construction materials from the mangrove's vegetation. It was also observed that in many places, the mangroves are cleared for construction or expansion of jetties, salt-pan, and aquaculture. Significant amount of industrial wastes (such as effluents from the chemicals, fertilizers, pharmaceuticals, dye, and petrochemical industries) and domestic wastes are reported to be dumped or drained into the gulf from the neighboring areas (VishnuRadhan et al., 2018). Most importantly, Asia's largest ship breaking yard is also located at the bank of the Gulf of Khambhat, which also releases enormous pollutants such as asbestos, heavy metals, oil, paints, plastic, glass, and ceramics, which is significantly affecting its ecosystem (Shah et al., 2010).

Field survey

Ground surveys were conducted from east (Surat) to west (Gopnath Temple in Alang) during December 2018 to March 2019. A total of 91 locations were visited along the shore of the gulf to record the types and extents of mangroves and other land use/land cover (LULC) features using a handheld Garmin GPS. These locations, also called the ground-truth points, were used for assessment of classification accuracy of the satellite images. High-resolution Google Earth images were also used during the accuracy assessment.

During field survey, ground-truthing was done at 91 locations which include both mangroves and non-mangroves area. Out of these, 48 ground-truthing points were used for mangrove vegetation inventory collection, assigned as sampling plots. Quadrate method was used for sampling and sizes of each plot were 10 m × 10 m. Within these quadrates, detailed inventory of mangroves vegetation which included measurement of plant height (tree, shrub, and herb) and stem diameter of each mangroves tree (more than 1.3 m height) within a plot, recording of mangroves species composition and plant density, were carried out. From the inventory data, various parameters such as plant density, frequency, abundance, relative

Fig. 1 Study area showing sampling plots and ground-truth points with district boundaries
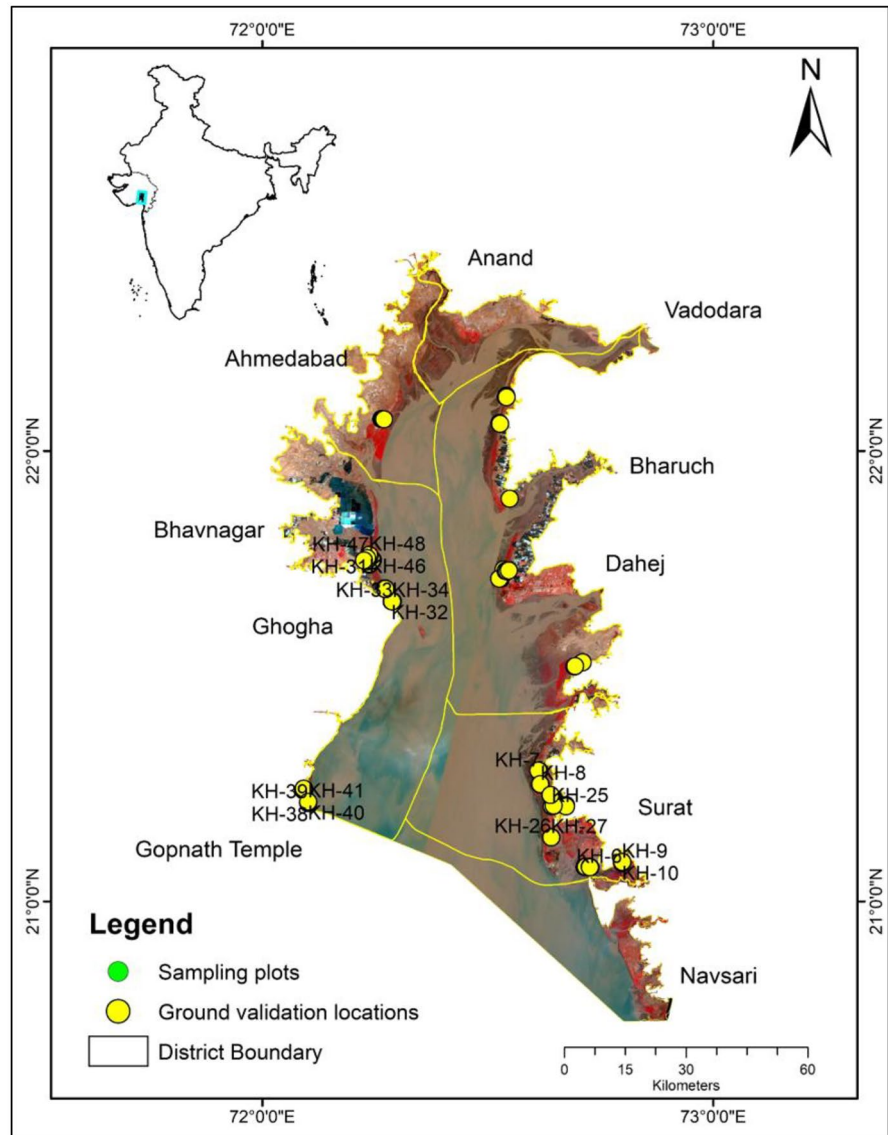
density, relative frequency, relative dominance, and abundance to frequency ratio (Devi & Pathak, 2016; Nautiyal et al., 2015; Whitford, 1949) were computed. Also, species diversity was calculated by Shannon index (H) and Simpson's index of diversity (1-D) (Shannon & Weaver, 1963; Simpson, 1949).

Satellite data

In this study, high-resolution multispectral satellite data of Advanced Visible and Near Infrared Radiometer type-2 (AVNIR-2) sensor of Japanese ALOS-1 (Advanced Land Observation Satellite) and Linear Imaging Self Scanning Sensor-4 (LISS-4) of Indian ResourceSat-2 & 2A were used to monitor changes in the mangrove land cover and vegetation dynamics of the Gulf of Khambhat. Cloud-free AVNIR-2 images were used for the year 2009 from Japan Aerospace Exploration Agency (JAXA) and LISS-4 images were procured for the years 2014 and 2019 from National Data Centre (NDC, NRSC), Hyderabad. Terra MODIS, 8-day composite products, GPP, and LAI, as well as aqua MODIS, 16-day composite product, EVI, were used for the years 2009, 2014, and 2019. This MODIS product was

accessed and processed in the GEE. Table 1 shows details of satellite data used in this study.

Data processing and analysis

Data processing and analysis were done in two parallel stages. In first, land cover classification and change analysis were done. The second includes the mangroves health analysis.

Land cover classification and change analysis

For the preparation of the LULC map, satellite images were pre-processed such as image stacking, mosaicking, and subset of the study area were carried out for the years 2009, 2014, and 2019. Spectral reflectance characteristics were used to discriminate the mangroves from other features. Various key visual interpretation parameters such as color, texture, pattern, and tone were also considered for this discrimination. Based on these characteristics, first, distinction was performed between mangrove and non-mangrove area. Further, the non-mangrove areas were classified into various LULC classes such as built-up, mudflat, saltpan/aquaculture, saline soil, water, and other (agriculture land, wasteland, and non-mangrove vegetation). Exactly same number of classes was mapped

for 2009, 2014, and 2019 data. The accuracy assessment of the classifications was carried out based on ground-truth data, and accordingly, the user's, producer's, and overall accuracy figures were calculated for each class.

Further, the quantification of spatiotemporal changes and change for each class were calculated using union tool to create a confusion matrix between 2009–2014 and 2014–2019. The annual rate of change (in km^2/ year) of mangrove cover was calculated using the following formula:

$$\text{Annual change rate} = \frac{(T_{2019} - T_{2009})}{n}$$

where T_{2019} and T_{2009} represent in km^2 the area of the mangrove cover in 2019 and 2009, respectively, and "n" is the number of years during the period.

Mangroves health analysis

The Normalized Difference Vegetation Index (NDVI) of the mangrove area were calculated from the AVNIR-2 and LISS-4 data for the years 2009, 2014, and 2019 and were categorized into 4 classes, i.e., 0 to 0.2 (very poor vegetation), 0.21 to 0.3 (poor vegetation), 0.31 to 0.4 (moderate vegetation), and more than 0.4 (healthy vegetation)

Table 1 Details of optical multispectral data and MODIS product used in the present study

Study parameter	Satellite/senor	Spectral bands	Spatial resolution	Periods of acquisition
Land use land cover (LULC)	ALOS-1/AVNIR-2	Band 1: 0.42–0.50 μm (blue); Band 2: 0.52–0.60 μm (green); Band 3: 0.61–0.69 μm (red); Band 4: 0.76–0.89 μm (NIR)	10 m	2009
LULC	ResourceSat-2/LISS-4	Band 2: 0.52–0.59 μm (green); Band 3: 0.62–0.68 μm (red); Band 4: 0.77–0.86 μm (NIR)	5.8 m	2014
LULC	ResourceSat-2 & 2A/LISS-4	Band 2: 0.52–0.59 μm (green); Band 3: 0.62–0.68 μm (red); Band 4: 0.77–0.86 μm (NIR)	5.8 m	2019
Gross primary productivity (GPP)	MODIS-Terra (MOD17A2H)	Band 1: GPP	500 m	2009, 2014, and 2019
Leaf area index (LAI)	MODIS-Terra (MOD15A2H)	Band 2: LAI	500 m	2009, 2014, and 2019
Enhanced vegetation index (EVI)	MODIS-Aqua (MYD13Q1)	Band 2: EVI	250 m	2009, 2014, and 2019

(Chellamani et al., 2014). The mangroves cover under each of these categories was determined. NDVI values over these mangrove classes were analyzed for understanding the change in health of the vegetation.

In addition, two approaches were used to assess the impact of saltpan/aquaculture on mangroves health. The first approach was field based, in which mangroves health in terms of the plant density (no. of plants/ha) and plant basal area (m^2/ha) were studied over 20 quadrates selected (out of 48) near and away from the saltpans/aquaculture, avoiding locations with nearby settlement and freshwater bodies. The second approach was based on satellite data, in which time series analyses of the different MODIS products (GPP, LAI, and EVI) were done in the GEE, for the years 2009, 2014, and 2019. The NDVI images from AVNIR-2 and LISS-4 data were also used. This time series analysis was carried out over a few areas of mangrove to assess the health of the mangrove, before and after construction of saltpan/aquaculture. The GPP data is represented in gm C per m^2. The EVI value ranges from 0 (no vegetation) to 1 (healthy vegetation).

The keywords for all the land cover classes used in the whole manuscript are as follows: built-up — BU, mangrove — MG, mudflat — MF, other — OT, saline soil — SS, saltpan/aquaculture — S/A, and water — WR.

The complete methodology of the work is given in the form of flow chart in Fig. 2.

Results and discussion

Land use land cover

This study quantifies the changes in various LULC classes of Gulf of Khambhat for the years 2009, 2014, and 2019. One of the primary objectives of the study was to understand spatiotemporal changes in the mangrove vegetation over a decade. On the basis of spectral characteristics and visual interpretation keys, high-resolution LISS-4 data and AVNIR-2 data were classified for 7 LULC classes, viz. built-up, mangrove, mudflat, other (non-mangrove vegetation, agriculture land, and wasteland), saline soil, saltpan/ aquaculture, and water in the study area. Figure 3 presents the LULC maps of the study area for the years 2009, 2014, and 2019. The classification accuracies were tested over randomly collected ground validation points. The overall classification accuracy of 88.57% (kappa 0.87) was achieved for the year 2009. Similarly, for years 2014 and 2019, overall accuracies of 97.75% (kappa 0.96) and 97.75% (kappa 0.96) were obtained, respectively. The area under each LULC class corresponding to the years is presented in Table 2.

The study revealed that during 2009–2019, there is an increase in mangrove cover by 17 km^2 in the study area that corresponds to a 9.7% rise in the decade, and overall increment of mangrove from 2009 to 2019 is 1.71 km^2/year. Though it showed that the rise during 2009 to 2014 was marginally lower as compared to

Fig. 2 Flow chart of the methodology
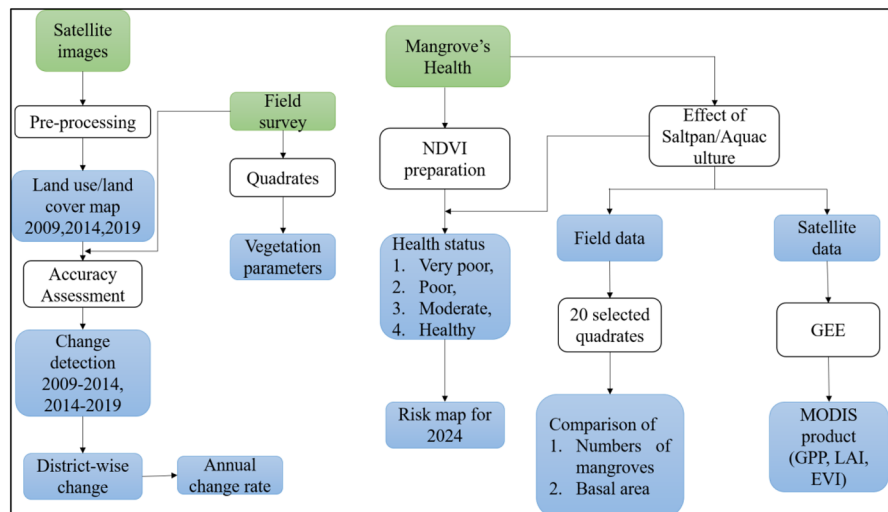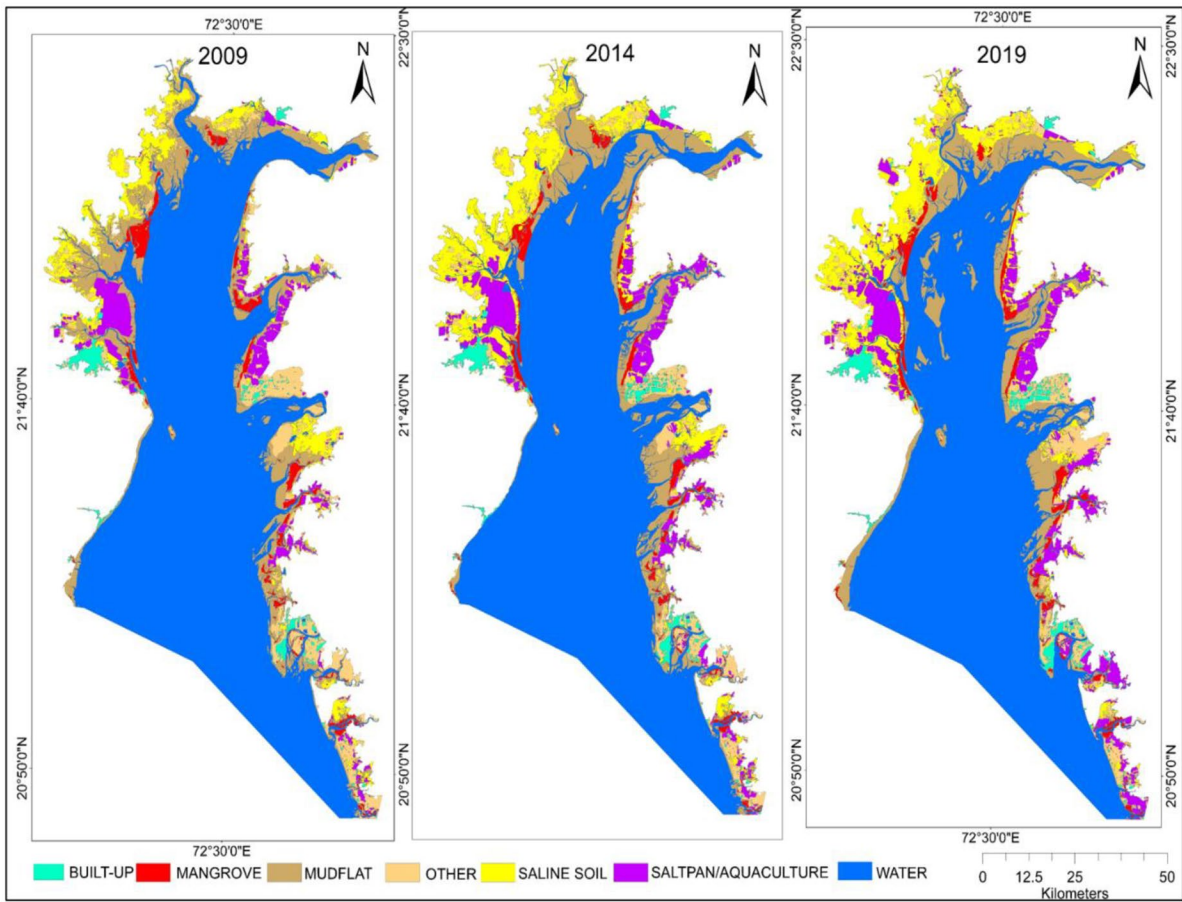
Fig. 3 Land use/land cover map of the Gulf of Khambhat

that in the later period, the study also revealed substantial change in saltpan/aquaculture in the region, which showed an increase in area by 248 km^2 during 2009–2019 that corresponds to 74% increase in these activities, clearly indicating economic boom
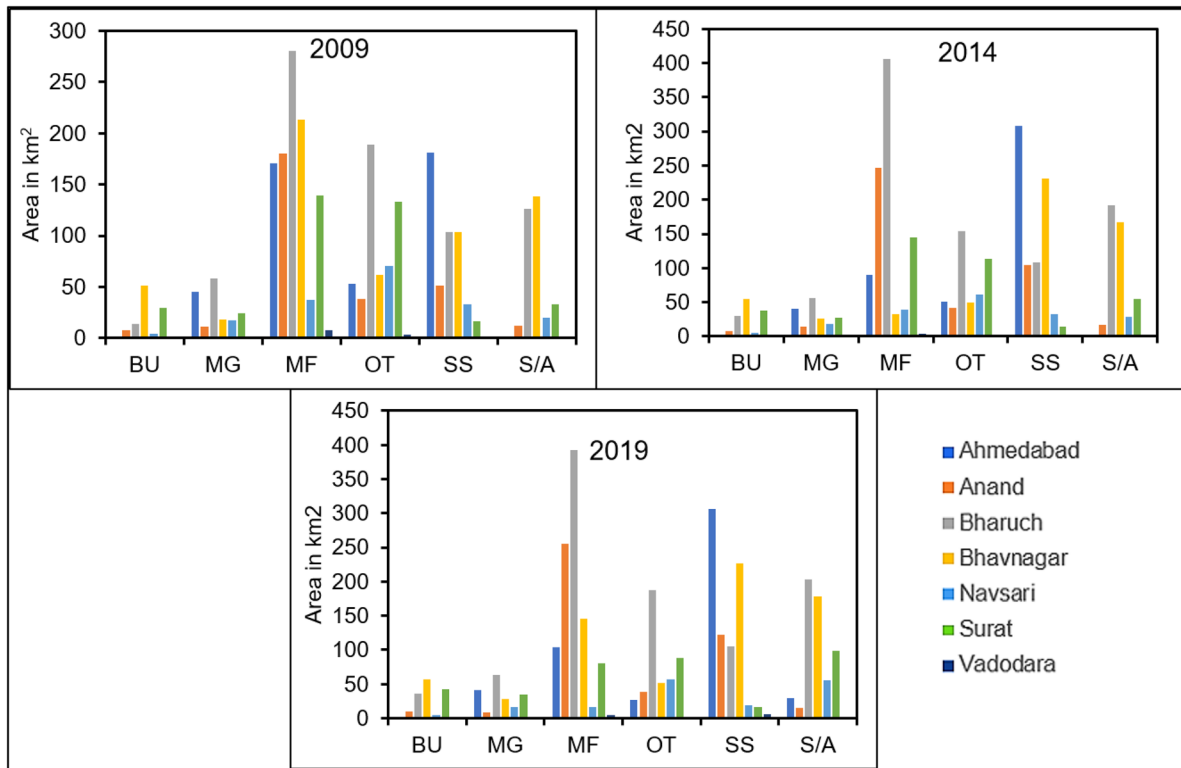
in the region. Built-up area has shown rapid increase during 2009–2014 but indicated a slowdown during 2014–2019. During 2009–2019, built-up area, mangrove, saline soil, and saltpan/aquaculture land have increased by 44.74 km^2, 17.11 km^2, 313.01 km^2, and 248.26 km^2, respectively.

District-wise land use land cover

The study area encompasses approximately 8014.9 km^2, spanning over the districts of Ahmedabad, Anand, Bharuch, Bhavnagar, Navsari, Surat, and Vadodara (Fig. 4). Among the districts, Bharuch accounts for the largest area (2257.90 km^2) of the Gulf of Khambhat followed by Bhavnagar (2117.81 km^2), Surat (1364.89 km^2), Navsari (891.38 km^2), Ahmedabad (747.73 km^2), Anand (620.55 km^2), and Vadodara (14.65 km^2).

Table 2 Area statistics of LULC (area in sq. km)

Class	2009	2014	2019
Built-up	107.86	135.86	152.6
Mangrove	175.1	182.05	192.21
Mudflat	1028.7	963.65	996.94
Other	547.92	470.22	452.56
Saline soil	489.63	798.51	802.64
Saltpan/aquaculture	332.18	458.98	580.44
Water	5333.52	5005.66	4837.53
Total	**8014.91**	**8014.91**	**8014.91**

Fig. 4 District-wise LULC distribution (6 classes) in 2009, 2014, and 2019 (built-up — BU, mangrove — MG, mudflat — MF, other — OT, saline soil — SS, saltpan/aquaculture — S/A, and water — WR)

The district-wise distribution of each LULC class, excluding water for the years 2009, 2014, and 2019, is illustrated in Fig. 4. Bharuch district has the highest cover of mangroves, attributed to the natural regeneration capability of the mangroves and plantation activity conducted by the government and non-government agencies (Khare & Shah, 2019), followed by Ahmedabad, Surat, Bhavnagar, Navsari, and Anand districts. Locally, the coastal area on the Northern side or Anand side of the gulf is known as "Bhal" meaning "forehead" where nothing grows. The term is revealing the harsh environmental condition of the region, which is one of the causes of the lower mangrove extent (Patel et al., 2014). Bhavnagar district had the highest cover of built-up followed by Surat, Bharuch, Anand, Navsari, and Ahmedabad districts.

Land use land cover change analysis

Change detection analysis was performed for 2009–2014 and 2014–2019, to understand conversion of

one LULC class to the other. Class to class conversion matrix for respective time period essentially conveys natural/anthropogenic activities taking place in a region. Tables 3 and 4 show class-wise changes during 2009–2014 and 2014–2019, respectively.

Change analysis explains the loss and expansion of each class. During 2009–2014, the data showed reduction in mangrove cover and its conversion to other classes (Table 3). With considering 2009 as baseline, maximum conversion of mangrove area was observed in mudflats with net conversion of 6.8% (11.97 km^2), followed by conversion into saltpan/aquaculture 4.2% (7.39 km^2) and waterbody 4.9% (8.58 km^2). Mangrove class was converted into various classes such as built-up, mudflat, other, saline soil, saltpan/aquaculture, and water with an area of 0.01% (0.01 km^2), 6.83% (11.97 km^2), 0.38% (0.67 km^2), 2.35% (4.12 km^2), 4.22% (7.39 km^2), and 4.90% (8.58 km^2), respectively. In other word, overall, 32.74 km^2 mangrove area was converted into different land use during 2009–2014, and in 2014–2019, the overall loss is 32.69 km^2.

Table 3 Change detection result of 2009–2014 (in percentage), where *BU*, built-up; *MG*, mangrove; *MF*, mudflat; *OT*, other; *SS*, saline soil; *S/A*, saltpan/aquaculture; *WR*, water

2014	2009						
	BU	**MG**	**MF**	**OT**	**SS**	**S/A**	**WR**
BU	100.00	0.01	0.29	4.26	0.25	0.00	0.00
MG	0.00	81.31	3.74	0.08	0.01	0.00	0.01
MF	0.00	6.83	45.64	1.73	2.06	0.15	8.66
OT	0.00	0.38	1.30	81.36	1.82	0.01	0.03
SS	0.00	2.35	30.86	5.24	88.45	0.08	0.27
S/A	0.00	4.22	5.37	6.32	6.14	99.71	0.00
WR	0.00	4.90	12.81	1.01	1.27	0.05	91.02
Total	100	100	100	100	100	100	100

The conversion of mangrove to built-up and saltpan/aquaculture is purely man-made, which leads to degradation of mangrove which is 4.23% (7.40 km^2) (2009–2014), and 1.82% (3.32 km^2) (2014–2019) indicates ongoing anthropogenic activity in the area. Mangrove to mudflat conversion may occur due to both natural and anthropogenic activities. Natural causes include storm surge, saltwater intrusion, wind, and extreme rainfall, erosion (Sippo et al., 2018; Thomas et al., 2017). Khare and Shah (2019) also have reported conversion of mangrove areas to mudflats during 2000 to 2012 in Jambusar Taluka and is likely due to accretional activities in the river. The data revealed that only 45% of the mudflats remained intact during this period, and 30.8% were converted to saline soils. Reduction of mudflats and its conversion to saline soils may suggest increasing sediment deposition in this time period.

Major anthropogenic activities which lead to degradation and deforestation in the study area are dependency of local people on mangrove for their fuel requirement, people graze their animals in the mangrove field, and removal of mangrove cover to expand their saltpan/aquaculture activity, due to the land requirement as well as for port activity. Also, local peoples in the area are barricading the patch of mangrove from other mangrove areas, so that isolated mangrove patch will degrade due to scarcity of water and nutrients, and that area becomes barren and used for other activity.

During 2009–2014 and 2014–2019, approximately 4.9% (8.58 km^2) and 4.33% (7.89 km^2) of mangrove area were converted into water class. This could be occurred due to the high tidal activity observed in the region, and when there is a high tide then some part of mangrove becomes submerged into water, it is difficult to distinguish water and mangrove from the satellite images. In 2014, 3 tiles of LISS-4 were acquired during the high-tide condition, so for the demarcation of mangroves boundary, we have used ground-truthing points, a base map, and google earth imagery which corresponds with LISS-4 data, and it confirms that high tide does not play any role in this mangrove conversion. Another reason could be due to storm, heavy rain, or high tidal activity, which causes high coastal erosion or washout of the mudflat on which mangrove is present.

Table 4 Change detection result of 2014–2019 (in percentage)

2019	2014						
	BU	**MG**	**MD**	**OT**	**SS**	**S/A**	**WR**
BU	99.94	0.01	0.01	2.68	0.44	0.00	0.01
MG	0.00	82.04	4.03	0.28	0.19	0.00	0.02
MF	0.00	4.27	57.05	2.51	3.34	0.19	7.99
OT	0.06	0.06	1.70	65.89	14.09	1.92	0.10
SS	0.00	7.47	10.33	14.77	74.19	1.33	0.43
S/A	0.00	1.81	2.27	12.62	6.61	96.41	0.01
WR	0.00	4.33	24.62	1.24	1.15	0.16	91.43
Total	100	100	100	100	100	100	100

The change detection analysis result indicates that some classes such as mudflat, other, saline soil, and water were also converted to mangrove from 2009 to 2019, accounting as an area of 77.27 km^2, 1.8 km^2, 1.51 km^2, and 1.9 km^2, respectively. This conversion has occurred due to both natural expansion and by man-made plantation. In some places of the gulf, the mangrove plantation has been carried out by the forest department. Water was converted to mangrove by intermediate process such as construction of mudflats and conversion of these mudflats into mangrove.

District-wise change

The district-wise change in built-up, mangroves, and saltpan/aquaculture classes is given in Table 5. Built-up class in each district has increased continuously during 2009–2019 period, from 107.86 km^2 in 2009 to 152.60 km^2 in 2019. The net growth of built-up was 44.74 km^2 and its annual change rate is 4.47 km^2 during 2009–2019. The highest area of built-up class was observed in the Bhavnagar district, but the highest increase was observed in Bharuch (13.66 to 36.67), followed by Surat (29.83 to 42.47), Bhavnagar (51.22 to 57), Anand (7.65 to 9.35), Ahmedabad (1.23 to 2.25), and Navsari (4.26 to 4.86). Bharuch district had a higher annual change rate (built-up class) of 2.3 km^2/year during 2009–2019. Bharuch and Surat were the highest gainers in built-up area because of development activities near Dahej and Hazira port. Mangroves forest cover has increased from 2009 to 2019, from 175.10 km^2 to 192.21 km^2. Increases in the mangroves cover were observed in

the Bharuch (57.99 to 63.08 km^2), Bhavnagar (18.21 to 28 km^2), and Surat (24.63 to 34.60 km^2) districts, whereas the cover was declined in Ahmedabad (45.41 to 41.87 km^2), Anand (11.50 to 8.04 km^2), and Navsari (17.36 to 16.61 km^2) districts. However, in a particular period of 2009–2014, mangrove depletion was observed in Bharuch district (57.99 to 55.51 km^2) (Table 5 and Fig. 4). Surat and Bhavnagar districts had a higher annual change rate (mangroves class) of 0.9 km^2/year during 2009–2019. During field visit mangroves, plantation was observed in the Bhavnagar and Bharuch districts done by the forest department (Fig. 5e).

Saltpan/aquaculture class in each district has increased continuously during the 2009–2019 period, from 332.18 km^2 in 2009 to 580.8 km^2 in 2019. The net growth of saltpan/aquaculture was 284.26 km^2 and its annual change rate is 24.82 km^2 during 2009–2019. The highest gain was observed in Bharuch (77.23 to 203.22 km^2), followed by Surat (33.34 to 98.74 km^2), Bhavnagar (138.50 to 178.30 km^2), Navsari (20.41 to 55.44 km^2), Ahmedabad (1.50 to 29.47 km^2), Anand (12.42 to 15.43 km^2), and Vadodara (0 to 0.19 km^2) (Table 5 and Fig. 4). Bharuch district had a higher annual change rate (saltpan/aquaculture class) of 7.7 km^2/year during 2009–2019. The annual change rate (ACR) (km^2/year) of built-up, mangroves, and saltpan/aquaculture in each district during 2009–2014 and 2014–2019 is shown in Fig. 6a.

The percentages of mangroves class converted into the various land cover class in each district of the Gulf of Khambhat are shown in Fig. 6b and 6c. Among 7 districts, the highest degradation of

Table 5 District-wise area of built-up, mangroves, and saltpan/aquaculture in 2009, 2014, and 2019 in sq. km

| Class	Ahmedabad	Anand	Bharuch	Bhavnagar	Navsari	Surat	Vadodara	Total (km^2)
BU_09	1.23	7.65	13.66	51.22	4.26	29.83	0.00	107.86
BU_14	1.32	7.81	29.76	54.46	4.51	38.00	0.00	135.86
BU_19	2.25	9.35	36.67	57.00	4.86	42.47	0.00	152.60
MG_09	45.41	11.50	57.99	18.21	17.36	24.63	0.00	175.10
MG_14	40.72	14.43	55.51	26.25	17.61	27.53	0.00	182.05
MG_19	41.87	8.04	63.08	28.00	16.61	34.60	0.00	192.21
S/A_09	1.50	12.42	125.99	138.50	20.41	33.34	0.00	332.18
S/A_14	2.17	16.25	191.28	166.51	28.65	54.12	0.00	458.98
S/A_19	29.47	15.43	203.22	178.30	55.44	98.74	0.19	580.80
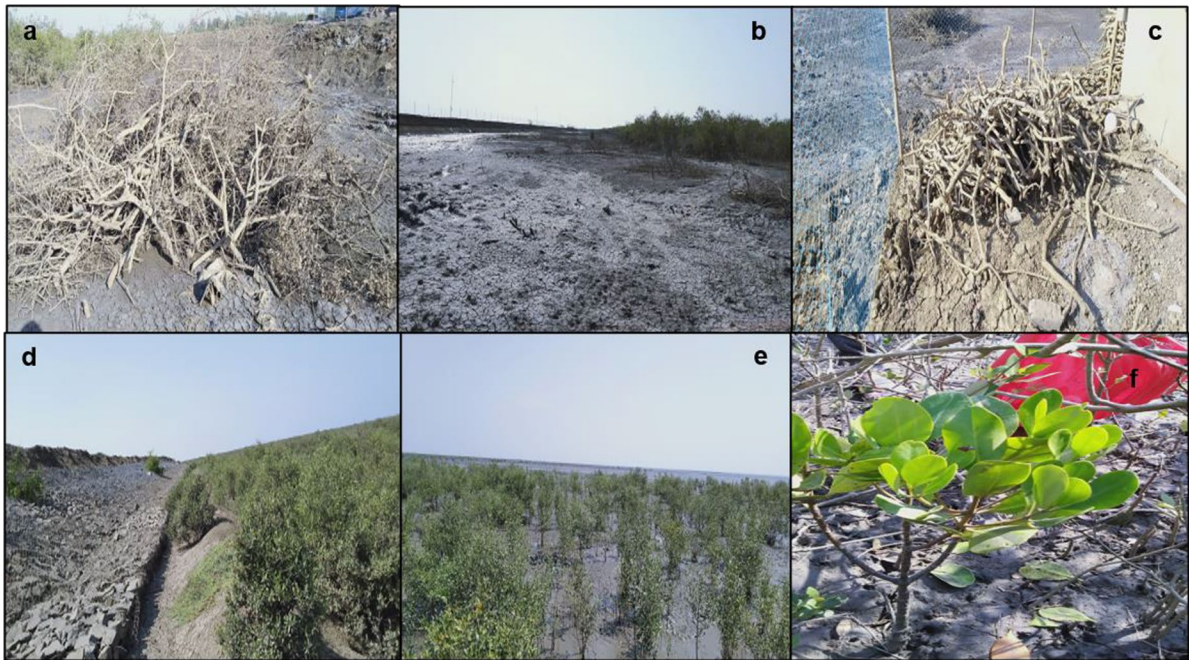
Fig. 5 Destruction of mangrove near Surat area (**a**; **b**; **c**), saltpan prevent the landward growth of mangrove (**d**), plantation of mangrove near Gopnath temple (**e**), *Ceriops tagalc* near Dahej area with 1 foot height (**f**)

mangroves was observed in Bharuch (12.85 km^2) and in Ahmedabad (11.96 km^2) during 2009–2014 and 2014–2019, respectively. During 2009–2014, after excluding water conversion, in Ahmedabad (22%) and Anand (61%), and during 2014–2019, in Ahmedabad (40%), Anand (69.2%), Bharuch (37.41%), and Bhavnagar (43.13%), salinity was the major cause of mangrove degradation. A notable amount of mangroves were transformed into saltpan/aquaculture in Bharuch (40.46%), Navsari (29.61%), and Surat (51.58%) during 2009–2014, and in Bharuch (5.51%), Navsari (66.86%), and Surat (49.85%) during 2014–2019. In each district, conversion of mangroves into mudflats was observed, predominantly in Bharuch and Surat. Change detection results reveal that a total of 65.43 km^2 areas of mangroves were degraded or converted into another land use class from 2009 to 2019, while Malik et al. (2015) estimated the value of ecological services of mangrove forests in terms of carbon sequestration which is 550–1100 USD/ha/year. So, the cost of this degradation is 3,598,100–7,196,200 USD in terms of carbon sequestration.

Plant status

Six mangroves' species were found around during observation period in the Gulf of Khambhat, with *Avicennia marina* being the most abundant species. The rare distributions of *Rhizophora mucronata* and *Ceriops tagalc* species were also reported near the Dahej area with the plant heights barely exceeding 1 foot (Fig. 5e). Similarly, a very scanty population of *Acanthus ilicifolius* species was also found near Dumas and Khajod in the Surat area with the plant heights ranging around 2 to 3 feet. The list of occurrences of mangroves species in the study area is given in Table 6. Likewise, other mangrove forest comprise a diverse range of mangroves are Pichavaram (35 species), Godavari and Krishna estuary (36 species), and Mumbai mangrove (29 species) (Mandal & Naskar, 2008).

During field survey, plant heights and stem diameters measurement was done for 2521 mangrove plants. The mangroves were predominantly represented by 3 species as shown in Table 7. *Avicennia marina* was found to be the predominant species
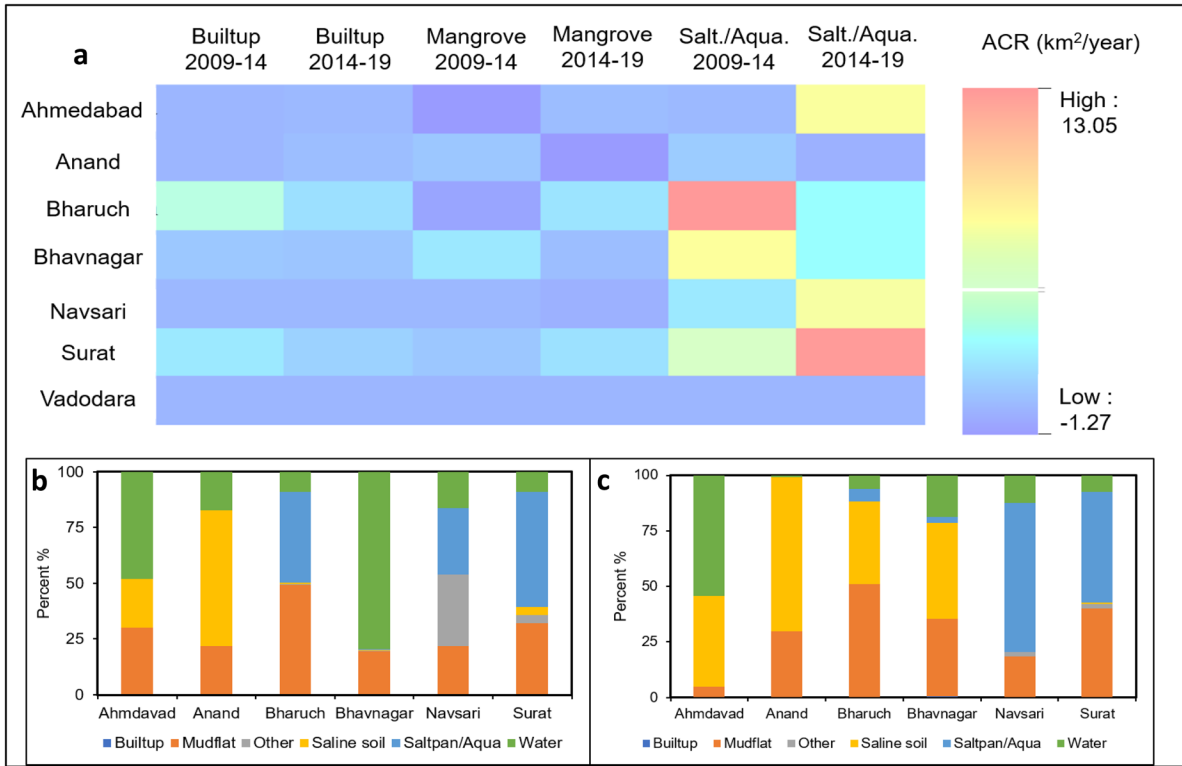
Fig. 6 ACR of built-up, mangroves, and saltpan/aquaculture class in each district during the two periods (**a**), percentage of mangroves class converted into other land cover classes in each district of Gulf of Khambhat during 2009–2014 (**b**) and 2014–2019 (**c**)

comprising 88.46% (present in 46 plots) of the total plants inventoried. Following that, *Sonneratia apetala* (present in 4 plots) and *Avicennia alba* (present in 2 plots) showed relative frequency of 7.69% and 3.85%, respectively. Table 7 presents the population parameters of the three major mangroves species found in the Gulf of Khambhat. The diversity, distribution, dominance, and productivity of mangroves species are dependent on the ability of species to tolerate salinity, surrounding environmental salinity, soil nutrient status, suitable hydrology, and topography (Duke et al., 1998).

Table 6 Mangroves diversity at different sites. Note: +, shows occurrence; - shows nonexistence

Species name	Vernacular name	Family	Status at different sites					
			Near Dahej	Near Bharuch	Near Surat	Near Bhavnagar	Near Ghogha	Near Gopnath
Avicennia marina	Tavar	Avicenniaceae	+	+	+	+	+	+
Avicennia alba	Tavar or Tivar	Avicenniaceae	+	+	-	+	-	+
Rhizophora mucronata	Kandel or Karod	Rhizophoraceae	+	-	-	-	-	-
Ceriops tagalc	Kanari	Rhizophoraceae	+	-	-	-	-	-
Sonneratia apetala	Motitavar	Lythraceae	-	-	+	-	-	-
Acanthus ilicifolius	Kantaliyo	Acanthaceae	-	-	+	-	-	-

Table 7 Vegetation characteristics of Gulf of Khambhat

Name of species	Density (N ha^{-1})	Abundance	% Frequency	Total basal area (m^2/ha)	A/F ratio	IVI
Avicennia marina	107.33	53.76	95.83	1.9	0.56	251.69
Avicennia alba	1.08	12.50	4.17	0.002	3.00	4.93
Sonneratia apetala	0.99	5.75	8.33	1.01	0.69	43.38

Diversity index

The abundance to frequency ratio is helpful to understand the distribution pattern of species. If the ratio is lower than 0.025, then it shows the regular distribution, if it lies between 0.025 and 0.050, then it suggests the random distribution, and if the ratio is more than 0.050, then it shows contagious distribution (Whitford, 1949). The calculated ratio suggests the distribution pattern of the above three species is contagious.

The Simpson index of dominance and the Shannon-Weaver diversity index were used (Shannon & Weaver, 1963; Simpson, 1949) and were calculated to analyze the supremacy and diversity of species. The value of the Simpson index of diversity (1-D) ranges from 0 to 1, 1 represents higher plant diversity. Here, the value is 0.04, which indicates that in the Gulf of Khambhat, mangrove diversity is low (dominated by one species). The value of the Shannon-Weaver index (H) is 0.11 for the study area. In comparison to other species, *A. marina*'s dominance can be linked to its ability to regenerate and adapt to varying surrounding conditions, particularly in terms of salinity (Beentje & Bandeira, 2007; Macamo et al., 2015). Pandey and Pandey (2013) reported 15 species of mangrove in Gulf of Khambhat, while our study reported relatively less (6 species), which indicates the abundance of species may decrease or be vanished from this region. The similar result is observed by Devi and Pathak (2016) and Singh (2020). The functioning of ecosystem can be governed by the biodiversity (Loreau, 2010). In most of the marine ecosystems, the relationship found positive between the biodiversity and functioning of ecosystem (Cardinale et al., 2006). As a result, the loss of biodiversity reduces the ecosystem's ability to provide services (Cardinale et al., 2012; Worm et al., 2006), as well as coastal population will have disastrous economic and environmental effect (Polidoro et al., 2010).

Mangrove's health analysis

The health of the mangrove is affected by both natural (the climatic factor, less freshwater input-riverine or precipitation, incline coastline) and by anthropogenic pressure such as industrial and municipal discharge, population growth, and saltpan/aquaculture growth (Chellamani et al., 2014; Rudianto et al., 2020). The NDVI is a commonly used index for studying the plant health, biophysical parameters, and phenology (Kripa et al., 2019). The time series analysis of NDVI is useful to measure the recent change in an ecosystem (Kripa et al., 2019). NDVI was calculated to categorize the mangrove into different health classes (Fig. 7) and to find out the relation of degradation of mangrove and health class.

Mangrove cover in 2009, 2014, and 2019 in the study were 175.1 km^2, 182.05 km^2, and 192.21 km^2, respectively. In 2009, 2014, and 2019, approximately 66.53% (116.5 km^2), 76.74% (139.69 km^2), and 81.58% (156.79 km^2) of mangrove area come under the category of very poor and poor health (Table 8), and the area of these categorized mangroves has increased from 2009 to 2019, thus the health status of mangrove is deteriorating. Change detection analysis indicates that from 2009 to 2014, around 32.73 km^2 of mangrove area has degraded, in which 80.60% (~ 26.21 km^2) degradation has occurred in the very poor and poor health category and during 2014 to 2019, ~ 32.69 km^2 area has been found as mangrove degraded area, in which 81.2% (~ 26.54 km^2) degradation took place in the very poor and poor health category. So, NDVI analysis is useful to find out the degradation trend, and if this trend will continue in the future, then ~ 32 km^2 (or ~ 25.6 km^2 from very poor and poor health category) mangrove area will be under the threat of degradation in the next 5 years (Fig. 8). Mostly, very poor and poor type of mangrove was present nearby the landward or saltpan or saline soil area. The area of healthy mangroves was decreased
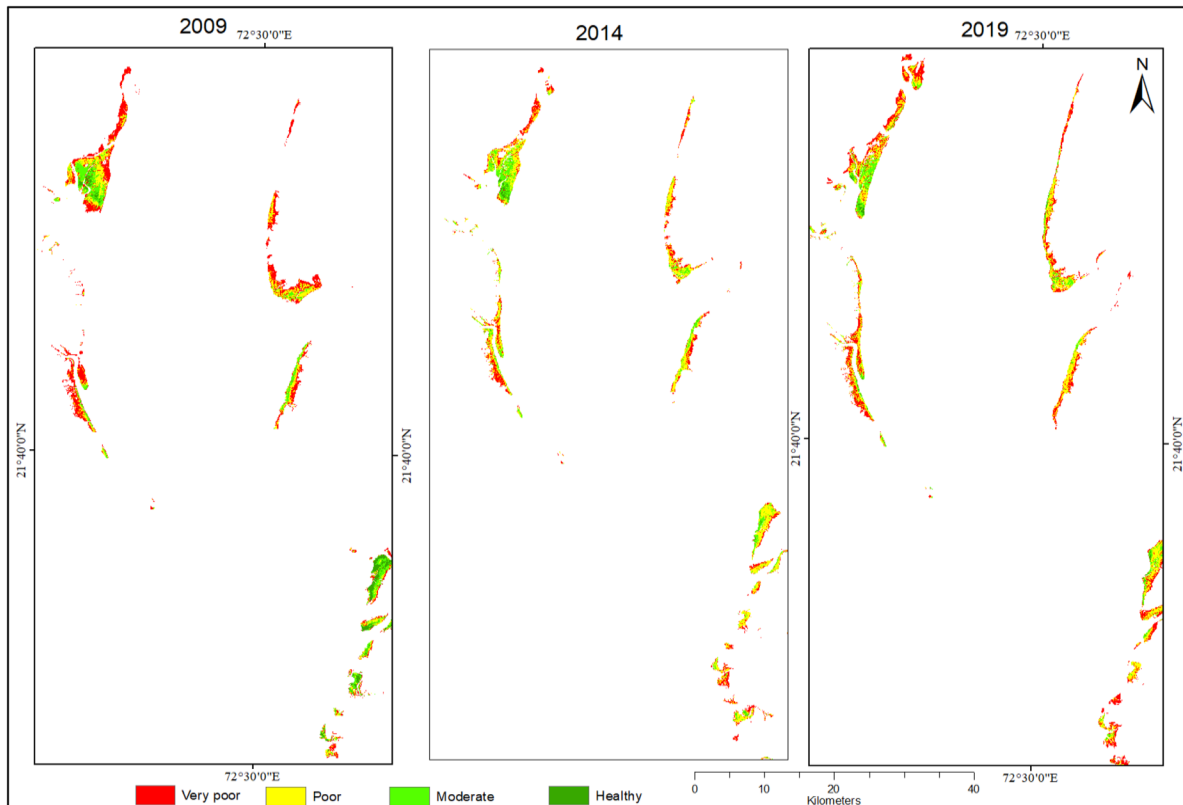
Fig. 7 Mangrove health index map of the study area for the years 2009, 2014, and 2019

during 2009–2019 from 25.20 to 2.84 km^2 (Table 8). In addition, the deterioration in health also affects the carbon sequestration potential of the ecosystem (Alongi, 2012; Elwin et al., 2019; Pande, 2005).

Effect of saltpan/aquaculture on mangroves

In the present study, the impact of saltpan/aquaculture on mangrove growth and health status were analyzed.

Table 8 Area statistics of NDVI (area in sq. km)

Class name	NDVI value	Area 2009	Area 2014	Area 2019
Very poor	0–0.2	72.89	53.7	75.49
Poor	0.21–0.3	43.61	85.99	81.3
Moderate	0.31–0.4	33.4	38.71	32.58
Healthy	> 0.4	25.2	3.65	2.84
Total (km^2)		175.1	182.05	192.21

Both field-based and satellite data-based approaches were used to assess the impact of saltpan/aquaculture on mangroves health.

Field-based approach

To assesses the impact of the saltpan, a total of 20 quadrates of mangroves were selected (out of 48 quadrates), in which 10 were located near saltpan/aquaculture area and another 10 were located far from the saltpan/aquaculture area, then two parameters of mangroves (such as number of mangroves plant and basal area) were compared at both sites (Fig. 9a and b).

The results indicate that there was a significant difference between the number of plants and basal area. In near saltpan/aquaculture areas, less number of plants (367 plats/ha) were reported with respect to (980 plants/ha) far from saltpan/aquaculture area. Similarly, at near saltpan/aquaculture area, the basal
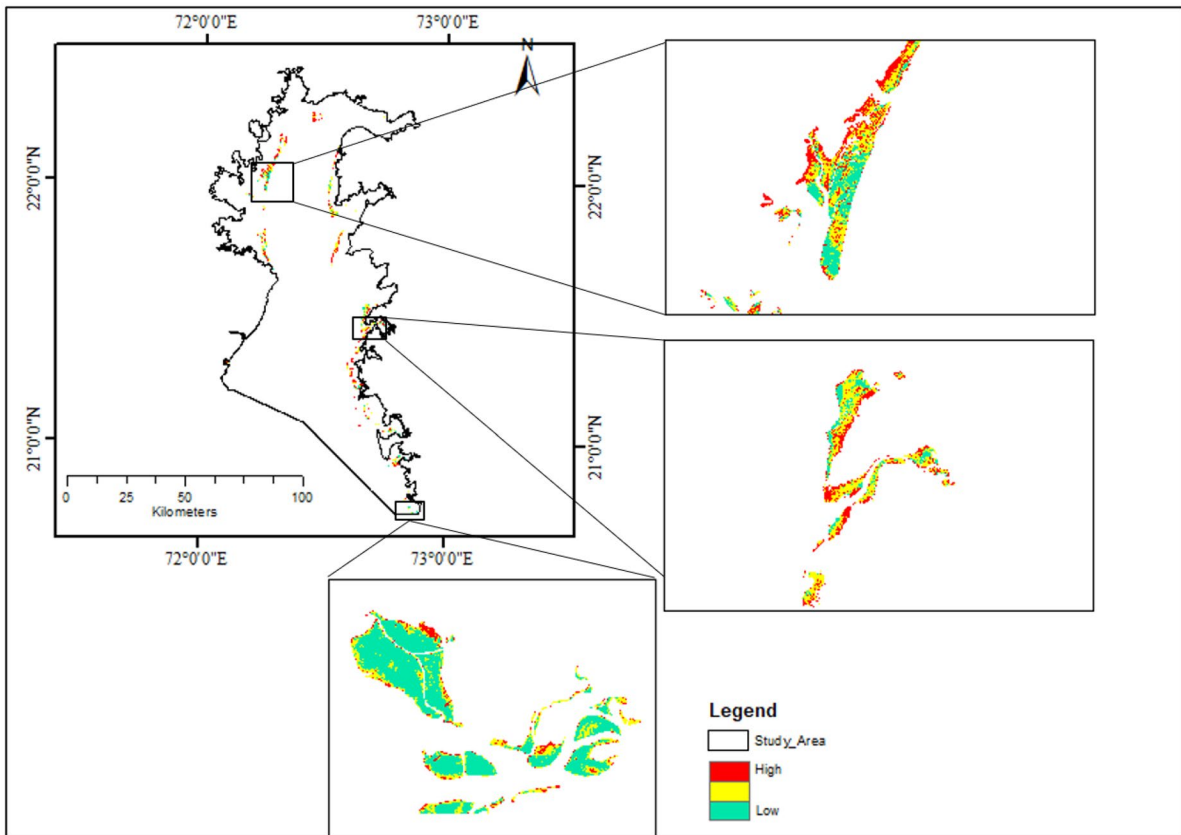
Fig. 8 Risk map of mangrove extent for 2024. Red and blue colors indicate high and low mangrove risk

area of the mangroves was lower (~ 0.045 m²/ha) than the mangroves situated far from saltpan/aquaculture (~ 0.072 m²/ha). In addition, mangroves forest which was far from saltpan/aquaculture had good basal area distribution than the mangroves near saltpan/aquaculture area, excluding mangrove plants with DBH between 5 and 10 cm which were approximately same in both sites. Mostly stunted growth in mangrove plants were observed near saltpan/aquaculture areas.

Satellite data based

The effects of the saltpan/aquaculture on mangroves were assessed using various satellite image-based products such as NDVI, EVI, GPP, and LAI. The NDVI was calculated from AVNIR-2 and LISS-4 data. The NDVI image is showing (Fig. 10-a1, a2, a3, b1, b2, and b3) the health status of mangrove before and after the construction of the saltpan/aquaculture,

Fig. 9 Basal area (m²/ha) at near and far from saltpan/aquaculture **a**, number of plants/ha at near and far from saltpan/aquaculture **b**
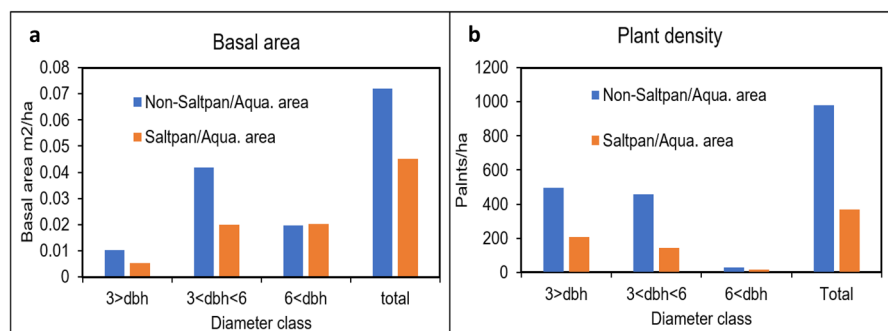
which clearly indicates that the healthy mangrove of 2009 was converted into the poor and very poor category (in 2014 and 2019) after construction of saltpan/aquaculture. This result was supported by the time series data of EVI, GPP, and LAI, which was generated in GEE. The average value of EVI, GPP, and LAI in 2009 (during the absence of saltpan/aquaculture), 2014, and 2019 (during presence of saltpan/aquaculture) is shown in Fig. 10c. The downfall of EVI, GPP, and LAI in 2019, as compare to 2009 (Fig. 10d, e, and f), is showing the deterioration of mangroves health due to saltpan/aquaculture construction. The LAI is directly proportional gross photosynthesis, evapotranspiration, and canopy interception (Fang & Liang, 2014). The downfall in GPP and LAI confirms the reduction of photosynthetic

capability of mangrove, which means lower carbon sequestration (Shrestha et al., 2019). The saltpan may increase the salinity of the area, so higher salinity level reduces the light use efficiency, which will affect the photosynthesis activity of leaves (Parida et al., 2002) and productivity. The selected two sites (Fig. 10a and b) is situated below the Narmada estuary and industrial area of Dahej city. So, along the bank of Narmada River and in the Dahej city, various industries like power station, petroleum industries, fertilizer industry, sewage discharge, chemical industries, manufacturing activity, and cement industries are present, which may also harm the mangrove ecosystem. So, to get wider picture of mangrove health deterioration, the water hydrochemistry and the sediment analysis should be done.

c	Product	2009_A1	2014_A2	2019_A3	2009_B1	2014_B2	2019_B3
	EVI	0.28	0.25	0.17	0.22	0.2	0.16
	GPP	12.23	9.99	7.12	12.69	10.2	8.19
	LAI	0.39	0.26	0.19	0.44	0.31	0.24
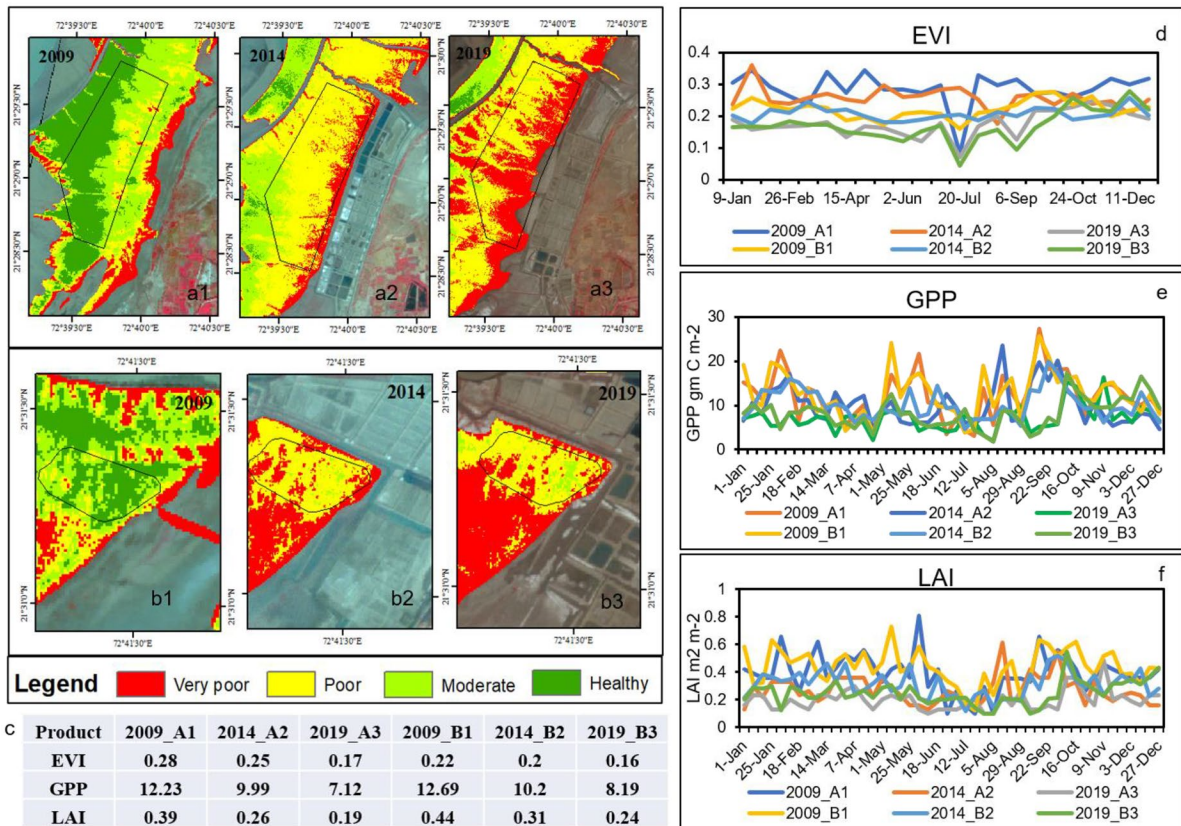
Fig. 10 Showing the health status of mangrove at two different sites, before and after construction of saltpan/aquaculture, during 2009, 2014, and 2019 (**a1**, **a2**, **a3**, **b1**, **b2**, and **b3**), average value of EVI, GPP, and LAI for the respective year at both sites (**c**), time series analysis of the EVI, GPP, and LAI for the respective year at both sites (**d**, **e**, **f**)

Conclusion

Land use/land cover change in the coastal region is an important concern worldwide, which is affecting the natural resources especially the mangroves, an important carbon sink to combat the climate change. Assessments of accurate LULC change are very important to identify the spatiotemporal changes, vulnerability assessment, and assess the loss to the ecosystem services. High-resolution earth observation satellite sensors provide very valuable data for mapping and monitoring LULC changes. In the present study, optical high-resolution data from Japanese ALOS-1 AVNIR-2 (2009) and Indian Resourcesat-2/2A LISS IV (2014 and 2019) were used for mapping LULC change in the Gulf of Khambhat region in Gujarat, India, over a decade. Visual interpretation methods were used to prepare the LULC map of the Gulf of Khambhat. From this study, a net increment in the mangrove area with 17.11 km^2 from 2009 to 2019 was observed. The study also revealed that a total of 65.43 km^2 area of mangroves vegetation were degraded in the area between 2009 and 2019 due to various anthropogenic activities primarily due to the expansion of saltpan/aquaculture and also due to an increase in the built-up area in the region. A total of 7.42 km^2 and 3.3 km^2 mangroves area were converted to saltpan/aquaculture during 2009–2014 and 2014–2019, respectively. The highest degradation of mangroves vegetation occurred in the Bharuch district (5.20 km^2) during 2009–2014 and in the Surat and Navsari districts (1.5 km^2 each) during 2014–2019. During a field visit to the Surat area, it was observed that even healthy mangrove patches were cleared and converted to saltpan/aquaculture. The present study revealed that from 2009 to 2019, mangroves area of 10.69 km^2 were converted into saltpan/aquaculture. The ecological services, for instance carbon sequestration, provided by mangroves will be affected by the degradation which trigger the climate change.

The values of the Simpson index of diversity (1-D) and Shannon-Weaver index (H) were observed as 0.04 and 0.11, respectively, which suggested that the diversity of the mangroves in the Gulf of Khambhat is very less (dominated by one species) and it is likely that only one mangroves species will remain in the region in the future, if the mangroves diversity is not protected.

NDVI-based analysis revealed that out of 32.73 km^2 of mangroves area that was degraded during 2009 and 2014, about 26.21 km^2 (~ 80.60%) of degradation occurred in the regions with very poor to poor health category of mangroves. Similarly, during 2014 to 2019, out of 32.69 km^2 mangroves area that was degraded, about 26.54 km^2 (~ 81.2%) degradation of mangroves took place in the very poor and poor health category. Risk maps were prepared from NDVI analysis, taking into consideration the current degradation rate indicated that if this trend continued at the present rate, in near future, approximately 32 km^2 of mangroves will be degraded of which approximately 25.6 km^2 degradation will result into poor to very poor health category of mangroves area.

Along with the NDVI, GPP, LAI, and EVI were used to assess the impact of saltpan/aquaculture on mangroves. It reveals that construction of saltpan/aquaculture is deteriorating the mangroves health, impairing productivity. The current research work would be helpful to conserve and manage the mangrove ecosystem of the Gulf of Khambhat. Moreover, the results of this study can help government and non-government organization to focus on the target areas where the mangroves are degraded or will be degrading in the future.

Declarations

References

Alongi, D. M. (2012). Carbon sequestration in mangrove forests. *Carbon Management, 3*(3), 313–322. https://doi.org/10.4155/cmt.12.20

Awty-Carroll, K., Bunting, P., Hardy, A., & Bell, G. (2019). Using continuous change detection and classification of landsat data to investigate long-term mangrove dynamics in the Sundarbans region. *Remote Sensing, 11*(23). https://doi.org/10.3390/rs11232833

Bal, G., Mallik, K., Sahu, S. S., & Banerjee, K. (2018). Study on above ground biomass and carbon of the selective mangrove species of Bhitarkanika wildlife sanctuary, Odisha. *National Conference on Waste to Energy, Carbon Capture and Storage*, 328–336.

Bann, C. (1997). *An economic analysis of alternative mangrove management strategies in Koh Kong Province, Cambodia.* https://iwlearn.net/files/pdfs/Bann%201997_Alternative%20mangrove%20management%20strategies%20in%20Cambodia.pdf

Beentje, H., & Bandeira, S. (2007). *Field guide to the mangrove trees of Africa and Madagascar.* Kew Publishing.

Bhavsar, D. O., Jasrai, Y. T., Pandya, H. A., Singh, V., Patel, A., & Kalubarme, M. H. (2014). Monitoring mangrove status using remote sensing and geo-informatics in Piram Island, Gulf of Khambhat, Gujarat State, India. *International Journal of Scientific & Engineering Research, 5*(6). https://www.ijser.org

Cardinale, B. J., Duffy, J. E., Gonzalez, A., Hooper, D. U., Perrings, C., Venail, P., Narwani, A., Mace, G. M., Tilman, D., Wardle, D. A., Kinzig, A. P., Daily, G. C., Loreau, M., Grace, J. B., Larigauderie, A., Srivastava, D. S., & Naeem, S. (2012). Biodiversity loss and its impact on humanity. *Nature, 486*(7401), 59–67. https://doi.org/10.1038/nature11148

Cardinale, B. J., Srivastava, D. S., Emmett Duffy, J., Wright, J. P., Downing, A. L., Sankaran, M., & Jouseau, C. (2006). Effects of biodiversity on the functioning of trophic groups and ecosystems. *Nature, 443*(7114), 989–992. https://doi.org/10.1038/nature05202

Chellamani, P., Prakash Singh, C., & Panigrahy, S. (2014). Assessment of the health status of Indian mangrove ecosystems using multi temporal remote sensing data. *Tropical Ecology*, *55*(2), 245–253. www.tropecol.com

Chen, P., Liew, S. C., & Kwoh, L. K. (2017, July). Mangrove mapping and change detection using satellite imagery. *2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS).* https://doi.org/10.1109/IGARSS.2017.8128306

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R. v., Paruelo, J., Raskin, R. G., Sutton, P., & van den Belt, M. (1997). The value of the world's ecosystem services and natural capital. *Nature*, *387*(6630). https://doi.org/10.1038/387253a0

Cougo, M., Souza-Filho, P., Silva, A., Fernandes, M., Santos, J., Abreu, M., Nascimento, W., & Simard, M. (2015). Radarsat-2 backscattering for the modeling of biophysical parameters of regenerating mangrove forests. *Remote Sensing*, *7*(12). https://doi.org/10.3390/rs71215873

Devi, V., & Pathak, B. (2016). Ecological studies of mangroves species in Gulf of Khambhat, Gujarat. *Tropical Plant Research*, *3*(3). https://doi.org/10.22271/tpr.2016.v3.i3.070

Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S., Stidham, M., & Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience, 4*(5), 293–297. https://doi.org/10.1038/ngeo1123

Duke, N., Ball, M., & Ellison, J. (1998). Factors influencing biodiversity and distributional gradients in mangroves. *Global Ecology and Biogeography Letters, 7*(1), 27–47.

Duke, N. C., Meynecke, J.-O., Dittmann, S., Ellison, A. M., Anger, K., Berger, U., Cannicci, S., Diele, K., Ewel, K. C., Field, C. D., Koedam, N., Lee, S. Y., Marchand, C., Nordhaus, I., & Dahdouh-Guebas, F. (2007). A world without mangroves? *Science*, *317*(5834). https://doi.org/10.1126/science.317.5834.41b

Elwin, A., Bukoski, J. J., Jintana, V., Robinson, E. J. Z., & Clark, J. M. (2019). Preservation and recovery of mangrove ecosystem carbon stocks in abandoned shrimp ponds. *Scientific Reports, 9*(1), 18275. https://doi.org/10.1038/s41598-019-54893-6

Fang, H., & Liang, S. (2014). Leaf area index models. In *Reference module in earth systems and environmental sciences*. Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.09076-X

FAO. (2002). *FAO yearbook. Fishery statistics: Commodities.*

FAO. (2007). *The world's mangroves 1980-2005.* Food and Agriculture Organization of the United Nations.

FSI. (2019). *India state of forest report 2019.*

Gibbs, H. K., Brown, S., Niles, J. O., & Foley, J. A. (2007). Monitoring and estimating tropical forest carbon stocks: Making REDD a reality. *Environmental Research Letters*, *2*(4). https://doi.org/10.1088/1748-9326/2/4/045023

Giri, C., Long, J., Abbas, S., Murali, R. M., Qamer, F. M., Pengra, B., & Thau, D. (2015). Distribution and dynamics of mangrove forests of South Asia. *Journal of Environmental Management*. https://doi.org/10.1016/j.jenvman.2014.01.020

Giri, C., Ochieng, E., Tieszen, L. L., Zhu, Z., Singh, A., Loveland, T., Masek, J., & Duke, N. (2011). Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography, 20*(1), 154–159. https://doi.org/10.1111/j.1466-8238.2010.00584.x

Giri, C., Pengra, B., Zhu, Z., Singh, A., & Tieszen, L. L. (2007). Monitoring mangrove forest dynamics of the Sundarbans in Bangladesh and India using multi-temporal satellite data from 1973 to 2000. *Estuarine, Coastal and Shelf Science*, *73*(1–2). https://doi.org/10.1016/j.ecss.2006.12.019

Gunawardena, M., & Rowan, J. S. (2005). Economic valuation of a mangrove ecosystem threatened by shrimp aquaculture in Sri Lanka. *Environmental Management*, *36*(4). https://doi.org/10.1007/s00267-003-0286-9

Held, A., Ticehurst, C., Lymburner, L., & Williams, N. (2003). High resolution mapping of tropical mangrove ecosystems using hyperspectral and radar remote sensing. *International Journal of Remote Sensing*, *24*(13). https://doi.org/10.1080/0143116031000066323

Hoang Tri, N., Adger, W., & Kelly, P. (1998). Natural resource management in mitigating climate impacts: The example of mangrove restoration in Vietnam. *Global Environmental Change*, *8*(1). https://doi.org/10.1016/S0959-3780(97)00023-X

IPCC. (2014). *Climate change 2014 synthesis report* (R. K. Pachauri & L. A. Meyer, Eds.; First). Intergovernmental Panel on Climate Change.

Ishtiaque, A., Myint, S. W., & Wang, C. (2016). Examining the ecosystem health and sustainability of the world's largest mangrove forest using multi-temporal MODIS products. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2016.06.200

Jia, M., Wang, Z., Zhang, Y., Ren, C., & Song, K. (2015). Landsat-based estimation of mangrove forest loss and restoration in Guangxi Province, China, influenced by human and natural factors. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *8*(1). https://doi.org/10.1109/JSTARS.2014.2333527

Kamal, M., & Phinn, S. (2011). Hyperspectral data for mangrove species mapping: A comparison of pixel-based and object-based approach. *Remote Sensing*, *3*(10). https://doi.org/10.3390/rs3102222

Kathiresan, K. (2012). Importance of mangrove ecosystem. *International Journal of Marine Science*. https://doi.org/10.5376/ijms.2012.02.0010

Khare, S. S., & Shah, D. G. (2019). Structure and temporal changes in the mangrove vegetation of Jambusar Taluka of Gulf of Khambhat, India. *Tropical Ecology*, *60*(3). https://doi.org/10.1007/s42965-019-00043-y

Kovacs, J. M., Lu, X. X., Flores-Verdugo, F., Zhang, C., Flores de Santiago, F., & Jiao, X. (2013). Applications of ALOS PALSAR for monitoring biophysical parameters of a degraded black mangrove (Avicennia germinans) forest. *ISPRS Journal of Photogrammetry and Remote Sensing*. https://doi.org/10.1016/j.isprsjprs.2013.05.004

Kripa, M., Mudaliar, A., Lele, N., Mankad, A. U., & Murthy, T. V. R. (2019). Spatio-temporal variations in mangrove vegetation in conjunction with related environmental factors in Pichavaram (India) 1996-2016. *International Journal of Scientific Research in Biological Sciences*, *6*(2). https://doi.org/10.26438/ijsrbs/v6i2.1525

Kuenzer, C., Bluemel, A., Gebhardt, S., Quoc, T. V., & Dech, S. (2011). Remote sensing of mangrove ecosystems: A review. *Remote Sensing*, *3*(5). https://doi.org/10.3390/rs3050878

Kumar, A., Stupp, P., Dahal, S., Remillard, C., Bledsoe, R., Stone, A., Cameron, C., Rastogi, G., Samal, R., & Mishra, D. R. (2017). A multi-sensor approach for assessing mangrove biophysical characteristics in Coastal Odisha, India. *Proceedings of the National Academy of Sciences, India Section A: Physical Sciences*, *87*(4). https://doi.org/10.1007/s40010-017-0441-y

Kumar, S., & Kumar, A. (2010). Waves and currents in tide-dominated location off Dahej, Gulf of Khambhat, India. *Marine Geodesy*, *33*(2–3). https://doi.org/10.1080/01490419.2010.492299

Kumar, S. S., & Balaji, R. (2015). Tidal hydrodynamics along Gulf of Khambhat, West Coast of India. In G. S. Dwarakish (Ed.), *Aquatic Procedia* (Vol. 4). Elsevier. https://doi.org/10.1016/j.aqpro.2015.02.007

Long, J. B., & Giri, C. (2011). Mapping the Philippines' mangrove forests using Landsat imagery. *Sensors*, *11*(3). https://doi.org/10.3390/s110302972

Loreau, M. (2010). Linking biodiversity and ecosystems: Towards a unifying ecological theory. *Philosophical Transactions of the Royal Society B: Biological Sciences, 365*(1537), 49–60. https://doi.org/10.1098/rstb.2009.0155

Macamo, C. C. F., Balidy, H., Bandeira, S., & Kairo, J. (2015). Mangrove transformation in the Incomati Estuary, Maputo Bay, Mozambique. *Western Indian Ocean Journal of Marine Science*, *14*(1 & 2), 11–22.

Malik, A., Fensholt, R., & Mertz, O. (2015). Economic valuation of mangroves for comparison with commercial aquaculture in South Sulawesi, Indonesia. *Forests*, *6*(12). https://doi.org/10.3390/f6093028

Mandal, R. N., & Naskar, K. R. (2008). Diversity and classification of Indian mangroves: A review. *Tropical Ecology, 49*(2), 131–146.

Maurya, P., & Kumari, R. (2021). Spatiotemporal variation of the nutrients and heavy metals in mangroves using multivariate statistical analysis, Gulf of Kachchh (India). *Environmental Research*. https://doi.org/10.1016/j.envres.2021.110803

Misra, A., & Balaji, R. (2015). A study on the shoreline changes and land-use/land-cover along the South Gujarat Coastline. *Procedia Engineering*. https://doi.org/10.1016/j.proeng.2015.08.311

Murray, B., Pendleton, L., Jenkins, W., & Sifleet, S. (2011). *Green payments for blue carbon economic incentives for protecting threatened coastal habitats*.

Nakhawa, A., Markad, S., Vichare, P., & Shirdhankar, M. (2012). Mapping and change detection of mangrove forest in Sakhartar estuary of Ratnagiri district, Maharashtra. *International Multidisciplinary Research Journal, 2*(8), 04–08. https://irjs.info/

Nautiyal, S., Bhaskar, K., & Imran Khan, Y. D. (2015). *Methodology for biodiversity (flora and fauna) study*. Springer. https://doi.org/10.1007/978-3-319-15464-0_2

Nayak, S., & Bahuguna, A. (2001). Application of remote sensing data to monitor mangroves and other coastal vegetation of India. *Indian Journal of Marine Sciences, 30*(4), 195–213.

Pande, P. K. (2005). Biomass and productivity in some disturbed tropical dry deciduous teak forests of Satpura plateau Madhya Pradesh. *Tropical Ecology, 46*(2), 229–239.

Pandey, C. N., & Pandey, R. (2013). Carbon sequestration by mangroves of Gujarat India. *International Journal of Botany and Research*, *3*(2), 57–70. https://www.academia.edu/4525569/Carbon_Sequestration_by_mangroves_of_Gujarat_India

Parida, A., Das, A. B., & Das, P. (2002). NaCl stress causes changes in photosynthetic pigments, proteins, and other metabolic components in the leaves of a true mangrove, Bruguiera parviflora, in hydroponic cultures. *Journal of Plant Biology*, *45*(1). https://doi.org/10.1007/BF03030429

Pasha, S. V., Reddy, C. S., Jha, C. S., Rao, P. V. V. P., & Dadhwal, V. K. (2016). Assessment of land cover change hotspots in Gulf of Kachchh, India using multi-temporal remote sensing data and GIS. *Journal of the Indian Society of Remote Sensing, 44*(6), 905–913. https://doi.org/10.1007/s12524-016-0562-9

Patel, A., Singh, V., Mehmood, K., Kathota, J., Kalubarme, M. H., Pandya, C. H., Joshi, N., & Brahmabhatt Lomesh. (2014). Mapping and monitoring of mangroves in the coastal districts of Gujarat State using remote sensing and geo-informatics. *Asian Journal of Geoinformatics*, *14*(1).

Polidoro, B. A., Carpenter, K. E., Collins, L., Duke, N. C., Ellison, A. M., Ellison, J. C., Farnsworth, E. J., Fernando, E. S., Kathiresan, K., Koedam, N. E., Livingstone, S. R., Miyagi, T., Moore, G. E., Ngoc Nam, V., Ong, J. E., Primavera, J. H., Salmo, S. G., Sanciangco, J. C., Sukardjo, S., & Yong, J. W. H. (2010). The loss of species: Mangrove extinction risk and geographic areas of global concern. *PLoS ONE, 5*(4), e10095. https://doi.org/10.1371/journal.pone.0010095

Prerna, R., Naidu, V. S., Sukumaran, S., & Gajbhiye, S. N. (2015). Observed decadal changes in extent of mangroves and coral reefs in southern Gulf of Kachchh using principal component analysis and geo-spatial techniques: a case study. *Journal of Coastal Conservation, 19*(3). https://doi.org/10.1007/s11852-015-0385-9

Rudianto, R., Bengen, D. G., & Kurniawan, F. (2020). Causes and effects of mangrove ecosystem damage on carbon stocks and absorption in East Java, Indonesia. *Sustainability*, *12*(24). https://doi.org/10.3390/su122410319

Ruitenbeek, H. J. (1992). *EMDI environmental reports, 8 mangrove management: An economic analysis of management options with a focus on Bintuni Bay, Irian Jaya prepared by*. http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=48204680410D77158B8D4FB501D54256?doi=10.1.1.544.7409&rep=rep1&type=pdf

Saha, S., Burley, S. D., & Banerjee, S. (2018). Mixing processes in modern estuarine sediments from the Gulf of Khambhat, western India. *Marine and Petroleum Geology*. https://doi.org/10.1016/j.marpetgeo.2017.12.010

Sathirathai, S. (1998). *Economic valuation of mangroves and the roles of local communities in the conservation of natural resources*. https://idl-bnc-idrc.dspacedirect.org/bitstream/handle/10625/15261/108378.pdf?sequence=39&isAllowed=y

Shah, K., Mody, K., Keshri, J., & Jha, B. (2010). Purification and characterization of a solvent, detergent and oxidizing agent tolerant protease from Bacillus cereus isolated from the Gulf of Khambhat. *Journal of Molecular Catalysis B: Enzymatic*, *67*(1–2). https://doi.org/10.1016/j.molcatb.2010.07.010

Shannon, C. E., & Weaver, W. (1963). *The mathematical theory of communication*. University of Illinois press.

Shimu, S. A., Aktar, M., Afjal, M. I., Nitu, A. M., Uddin, Md. P., & al Mamun, Md. (2019). NDVI based change detection in Sundarban Mangrove Forest using remote sensing data. *2019 4th International Conference on Electrical Information and Communication Technology (EICT)*. https://doi.org/10.1109/EICT48899.2019.9068819

Shrestha, S., Miranda, I., Kumar, A., Pardo, M. L. E., Dahal, S., Rashid, T., Remillard, C., & Mishra, D. R. (2019). Identifying and forecasting potential biophysical risk areas within a tropical mangrove ecosystem using multi-sensor data. *International Journal of Applied Earth Observation and Geoinformation*. https://doi.org/10.1016/j.jag.2018.09.017

Simpson, E. H. (1949). Measurement of Diversity. *Nature, 163*(4148). https://doi.org/10.1038/163688a0

Singh, J. K. (2020). Structural characteristics of mangrove forest in different coastal habitats of Gulf of Khambhat arid region of Gujarat, west coast of India. *Heliyon, 6*(8), e04685. https://doi.org/10.1016/j.heliyon.2020.e04685

Sippo, J. Z., Lovelock, C. E., Santos, I. R., Sanders, C. J., & Maher, D. T. (2018). Mangrove mortality in a changing climate: An overview. *Estuarine, Coastal and Shelf Science, 215*, 241–249. https://doi.org/10.1016/j.ecss.2018.10.011

Spalding, M., Kainuma, M., & Collins, L. (2010). *Worlds atlas of mangroves*. Earthscan.

Thomas, N., Lucas, R., Bunting, P., Hardy, A., Rosenqvist, A., & Simard, M. (2017). Distribution and drivers of global mangrove forest change, 1996–2010. *PLOS ONE, 12*(6), e0179302. https://doi.org/10.1371/journal.pone.0179302

Upadhyaya, D., Survaiya, M. D., Basha, S., Mandal, S. K., Thorat, R. B., Haldar, S., Goel, S., Dave, H., Baxi, K., Trivedi, R. H., & Mody, K. H. (2014). Occurrence and distribution of selected heavy metals and boron in groundwater of the Gulf of Khambhat region, Gujarat, India. *Environmental Science and Pollution Research*, *21*(5). https://doi.org/10.1007/s11356-013-2376-4

Vijay, V., Biradar, R. S., Inamdar, A. B., Deshmukhe, G., Baji, S., & Pikle, M. (2005). Mangrove mapping and change detection around Mumbai (Bombay) using remotely sensed data. *Indian Journal of Marine Sciences, 34*(3), 310–315.

VishnuRadhan, R., Eldho, T. I., Vethamony, P., Saheed, P. P., & Shirodkar, P. V. (2018). Assessment of the environmental health of an ecologically sensitive, semi-enclosed, basin — A water quality modelling approach. *Marine*

Pollution Bulletin. https://doi.org/10.1016/j.marpolbul.2018.10.035

Whitford, P. B. (1949). Distribution of woodland plants in relation to succession and clonal growth. *Ecology*, *30*(2). https://doi.org/10.2307/1931186

World Resources Institute. (1996). *World resources 1996-97*. Oxford University Press.

Worm, B., Barbier, E. B., Beaumont, N., Duffy, J. E., Folke, C., Halpern, B. S., Jackson, J. B. C., Lotze, H. K., Micheli, F., Palumbi, S. R., Sala, E., Selkoe, K. A., Stachowicz, J. J., & Watson, R. (2006). Impacts of biodiversity loss on ocean ecosystem services. *Science, 314*(5800), 787–790. https://doi.org/10.1126/science.1132294