Monitoring Coastal Erosion and SST Trends along the Coast of Mandvi–Mundra, Kachchh, Gujarat

(1994–2024)

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With deep gratitude,

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PREFACE

The present project report, titled " **Monitoring Coastal Erosion and SST Trends along the Coast of Mandvi–Mundra, Kachchh, Gujarat (1994–2024)**", has been undertaken as a part of my academic journey to understand the dynamic nature of coastal erosion and the climatic factors influencing them. Coastal areas which are among the most productive and sensitive ecosystems on Earth have been increasingly subjected to various forms of environmental stress. The rising sea surface temperatures, the effects of global climate change and growing human interventions have all been recognized as critical challenges for the sustainability of coastal regions. Due to these concerns, the topic of this project was selected to explore the complex processes that drive shoreline changes and coastal vulnerability.

During the course of this project, valuable techniques were used to acquire new knowledge and apply geospatial techniques, including remote sensing and GIS, to study coastal erosion over time. The processes involved in extracting shoreline positions, analysing satellite imagery and interpreting climatic datasets have contributed to the enhancement of technical skills and analytical abilities. Additionally, a deeper understanding has been gained regarding how natural forces such as tides and climatic variations play crucial role to reshape coastal landscapes.

Through this study, important insights have been developed about the long-term patterns of coastal erosion, the role of changing sea surface temperature and the potential influence of broader climatic factors such as atmospheric carbon dioxide concentrations and solar activity. The experience of working on this project has not only strengthened academic knowledge but has also helped to build a proper understanding to analyse the complexity and vulnerability of coastal systems.

It is sincerely hoped that this modest effort will contribute to a better understanding of coastal erosion processes and their climatic drivers and in this way, it will encourage future studies aimed at promoting the sustainable management of fragile coastal environments.

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CHAPTER 1: INTRODUCTION

1.1 Background of the Study

Coastal environments have always been regarded as some of the most dynamic and fragile systems on Earth. These landscapes are constantly shaped by the interaction of atmospheric, oceanic and terrestrial forces (Prasetya, 2008). However, in recent decades coastal regions across the world have been facing unique pressures due to a combination of natural processes and human-induced activities. The impacts of global climate change, particularly rising sea levels and sea surface temperatures (SST), have intensified the vulnerability of coastal areas to erosion, flooding and habitat loss (Mahapatra et al., 2015).

Sea-level rise is considered as one of the most significant consequences of climate change (Patel et al., 2022). Low-lying coastal regions and small islands have been increasingly threatened by inundation and shoreline retreat. It has been observed that oceans have absorbed a majority of the excess heat resulting from greenhouse gas emissions which leads to a rise in SST (Prasetya, 2008). In turn the rising SST has contributed to thermal expansion of ocean water and intensified coastal erosion in vulnerable areas (Mahapatra et al., 2015; Patel et al., 2022).

The state of Gujarat, located along the Arabian Sea, possesses one of the longest coastlines in India, extending over 1600 km. Due to its geographical significance, studies focusing on the relationships among SST rise, sea-level changes and coastal erosion have done before (Patel et al., 2022). But this type of study, especially for localized regions such as the coastal stretch in Mandvi–Mundra taluka in the Kachchh district have not done yet. While earlier studies have documented shoreline changes in Gujarat using remote sensing techniques (Patel & Bhandari, 2018; Majethiya et al., 2016), a systematic analysis connecting these changes with climatic drivers like SST, solar activity and CO_2 emissions has not been extensively done at taluka level.

The Mandvi–Mundra coast is characterized by a unique combination of sandy beaches, tidal mudflats, dune systems and mangrove ecosystems (ICMAM-PD, 2001; Majethiya et al., 2016). This area has been increasingly affected by natural processes such as tides, waves and longshore currents, as well as by human interventions including port development, salt pan expansion and large-scale industrialization (Gupta et al., 2001; Patel & Bhandari, 2018). Accelerated shoreline retreat in recent years has raised concerns about long-term coastal stability in this region.

In addition to direct anthropogenic impacts, long-term climatic variations influenced by solar phenomena such as sunspot cycles and rising atmospheric CO_2 levels are believed to play a crucial role in modifying SST patterns and sea-level trends (Prasetya, 2008). Although the exact relationships between solar activity, greenhouse gas concentrations and coastal changes remain complex and subject to scientific debate. It is generally recognized that multi-decadal climate variability can influence shoreline behaviour over time.

In this context, it becomes necessary to carry out a comprehensive spatio-temporal analysis of coastal erosion combined with an examination of climatic influences to support sustainable coastal management. Modern tools such as multi-temporal remote sensing data, Geographic Information Systems (GIS) and climate datasets provide an effective framework for monitoring and understanding these changes (Mahapatra et al., 2015).

The towns of Mandvi and Mundra are growing rapidly along the coastline which is driven by port development, industrialization, tourism and urban expansion. Mundra has emerged as one of India's largest private port hubs while Mandvi has seen significant growth in coastal tourism and related economic activities. The expansion of urban infrastructure close to the shoreline has increased the exposure of human settlements to coastal hazards such as coastal erosion, storm surges and sea-level rise.

The present study has been undertaken to analyse the shoreline changes along the Mandvi–Mundra coastal stretch from 1994 to 2024 and to examine the possible influences of sea surface temperature rise, sea-level variation, sunspot activity and atmospheric CO_2 emissions on coastal erosion dynamics. Through this integrated approach the study aims to provide valuable insights into the processes which drives coastal change and to contribute toward the broader understanding of coastal vulnerability in Gujarat at taluka levels.

In this context, the monitoring and analysis of coastal erosion along with an evaluation of SST trends and related climatic factors have become crucial for coastal management and resilience planning. Remote sensing techniques offer reliable tools for multi-temporal shoreline change detection, while climate datasets provide critical insights into driving factors.

The present study aims to analyse the spatio-temporal changes in the shoreline of the Mandvi–Mundra coastal stretch over the period 1994–2024. In addition, the study aims to examine the role of rising SST and sea-level trends in influencing coastal erosion. Further, an attempt is made to understand the relationships between SST variation, sunspot activity and atmospheric CO_2 emissions. Through this integrated approach, the research offers a scientific basis for understanding coastal erosion in the Mandvi and Mundra taluka and for recommending sustainable management practices.

1.2 Literature Review

Understanding coastal erosion along the Mandvi–Mundra coast requires insights into both regional studies and broader coastal processes. Several scientific studies have explored similar coastal environments in Gujarat and across India. The key findings from these studies have been reviewed below to support the present research.

1) A long-term erosion assessment was conducted by Patel et al. (2022) for the entire Gujarat coast, where shoreline changes were mapped from 1978 to 2020 using Landsat satellite data. High Tide Line (HTL) indicators were used to analyse erosion and accretion patterns. It was found that Kachchh coast experienced the highest erosion with SST (Sea Surface Temperature) rise and CO_2 emissions identified as contributing factors (Patel et al., 2022).

2) Shoreline change dynamics and land use were studied by Misra and Balaji (2015) along the South Gujarat coast. Using DSAS (Digital Shoreline Analysis System), the End Point Rate (EPR) was calculated to understand erosion patterns. The study also involved a land-use classification using satellite imagery which helped in identifying vulnerable ecological zones.

3) Mahapatra, Ramakrishnan and Rajawat (2015) used a GIS-based Coastal Vulnerability Index (CVI) method to assess physical risks from sea level rise. Param like geomorphology, slope, tidal range and wave height were considered. Their study categorized the Mandvi–Mundra area under "high to very high vulnerability," due to its flat topography, tidal energy and exposed mudflats.

4) A more localized assessment was done by Patel and Bhandari (2018), who focused on Mandvi–Mundra itself. Using Landsat imagery from 1990 to 2014 and DSAS analysis, it was found that Mandvi showed stable to accreting behaviour, while Mundra experienced strong erosion. The results suggested that industrial development and port activities in the region had influenced sediment dynamics.

5) A geomorphological study by Majethiya et al. (2016) explored landforms between Mandvi and Mundra. Features such as beaches, spits, tidal flats and dunes were mapped. It was noted that the area was undergoing tectonic uplift and is influenced by both marine and aeolian processes. The presence of raised beaches and ancient dune ridges indicated long-term coastal evolution.

6) The "Geomorphological Field Guidebook of Kachchh" (Thakkar, 2017) provided detailed insights into the geological and structural controls in the Mandvi–Mundra region. The coast was divided into segments such as cuspate beaches and mudflat plains. The guidebook explained how faults like the Katrol Hill Fault influence regional uplift, which in turn affects sedimentation and shoreline behaviour.

7) Ecological concerns were highlighted in a biodiversity assessment by ICMAM-PD (2001). It was shown that mangroves, corals and intertidal species along the Mandvi–Mundra coast were under pressure due to salt pan development, oil spills and infrastructure expansion. It was suggested that mangrove degradation has weakened natural coastal protection, making erosion more likely.

8) The protective role of coastal forests and trees was explained by Prasetya (2008), who emphasized the importance of mangroves, salt marshes and dune vegetation. It was shown that dense mangroves can reduce wave energy by up to 95%. The report recommended hybrid approaches such as green belts combined with breakwaters for long-term coastal protection.

9) A comparative study by Nath et al. (2024) on the Digha coast applied image-based shoreline change analysis using DSAS. Errors due to tides, image resolution and digitization were accounted for using weighted models. This detailed method of standardizing HTL extraction and mapping erosion/accretion rates can be effectively adapted for Mandvi–Mundra.

10) Lastly, a case study on Digha by Bandyopadhyay et al. (2009) examined how hard engineering structures like sea walls and dykes affected coastal dynamics. Although short-term protection was achieved, long-term beach lowering and reflection of wave energy were observed. This study highlighted the limitations of engineering-only approaches and said for integrating soft options like dune migration and controlled retreat.

The above studies collectively provide a strong foundation for understanding coastal erosion patterns, the influence of climatic factors and the importance of adopting coastal zone management strategies. They offer crucial insights that helped in the present study on the Mandvi–Mundra coastal region.

1.3 Research Gap

Although many studies have been carried out on shoreline changes and coastal vulnerability along the Gujarat coast but important gaps still remain to understand the detailed behaviour of coastal erosion at the local level like, coastal erosion in Mandvi and Mundra taluka. While previous research has focused on regional shoreline mapping, coastal landforms and vulnerability assessment, very few studies have tried to link shoreline changes directly with climatic factors such as sea surface temperature (SST) rise, sunspot activities and atmospheric CO_2 levels.

The Mandvi–Mundra coastal stretch holds particular importance because of its unique geomorphological features, including extensive mudflats, sandy beaches, tidal creeks and fragile dune systems. This region has witnessed rapid industrialization, large-scale port activities, salt pan expansion and mangrove degradation over the past few decades. Such environmental and anthropogenic pressures have made it one of the most sensitive coastal areas in Gujarat. However, detailed micro-level studies connecting these changes with climatic drivers like SST rise, sunspot variability and atmospheric CO_2 levels have not yet been carried out.

Most earlier studies have been focused on broader patterns of erosion and accretion. However, the deeper climatic reasons behind these changes have not been properly studied, especially for smaller areas like the Mandvi–Mundra coastal stretch. Even though concerns about sea-level rise and ocean warming have increased but the influence of solar activity and greenhouse gas emissions on SST trends and coastal erosion has not been systematically examined for this particular region.

Another important gap is the lack of multi-temporal analysis using high-quality satellite data that is specific to Mandvi–Mundra over the last three decades (from 1994 to 2024). The combined effects of natural forces and human activities have been mentioned in some works, but their relationship with climatic changes has not been clearly measured.

Because of these missing areas, the present study has been planned to carry out a detailed spatio-temporal analysis of shoreline changes along the Mandvi–Mundra coast from 1994 to 2024. It will also explore how SST rise, sunspot activities and CO_2 emissions may have influenced coastal erosion patterns. By filling these gaps, it is hoped that this research will help to build a better understanding of coastal risks for the region.

1.4 Research Objectives

The present study has been done with the following objectives:

1) To analyse the spatio-temporal changes in the shoreline in Mandvi and Mundra talukas from 1994 to 2024 using multi-temporal remote sensing data.
2) To investigate the influence of climatic factors such as sea surface temperature (SST) rise and sea-level changes on coastal erosion patterns in the study area.
3) To examine the possible relationships between solar activity (sunspot numbers), atmospheric CO_2 and changes in sea surface temperature over the study period and their impact on coastal erosion in Mandvi and Mundra taluka.

CHAPTER 2: METHODOLOGY

2.1 Methodology for Collecting Information of the Study Area

To provide a detailed understanding of the physical and human environment of the study area, various secondary data sources were collected and analyzed. These data were used to describe the geomorphological setting, land use patterns, tidal influences, demographic characteristics and administrative boundaries of Mandvi and Mundra talukas.

Table 2.1: Topic of study with data sources and tools.

Sl. No.	Theme/Topic	Purpose	Data source	Software/Tool used
1.	Location map	To understand location and administrative boundary	Survey of India	QGIS
2.	Geomorphology	To classify coastal landforms and terrain features	Bhuvan portal, GSI, secondary maps	QGIS, Excel
3.	Geology	To understand rock types and structural features	USGS portal	QGIS, Excel
4.	Soil	To examine soil types and their distribution	FAO-DSMW	QGIS, Excel
5.	Elevation	To analyse coastal relief and elevation patterns	NASA Earth Data (SRTM - 30m)	QGIS (Raster DEM tools)
6.	Drainage	To map rivers and coastal streams	HydroSHEDS	QGIS, Excel
7.	Climate	To describe climatic characteristics of the region	NASA POWER (DAV), Climate-data	Excel
8.	Tidal Data	To align image timing with tidal stages	WXtide32 Software	WXtide32, Excel
9.	Biotic elements	To identify biodiversity, especially coastal ecosystems	Forest Department reports, published research papers	PDF references
10.	Demographic profile	To understand population distribution and density	District Census Handbook Kachchh 2011 PART-XII-A	Excel
11.	Economic profile	To describe occupational patterns and income sources	District Census Handbook Kachchh 2011 PART-XII-A	Excel
12.	Transportation	To study regional connectivity and coastal access routes	Open Street Map dataset	QGIS
13.	Land Use-Land Cover	To observe land use change, urbanization, vegetation cover	Esri Land Cover - ArcGIS Living Atlas (2024), Sentinel-2 satellite imagery	QGIS, Excel

2.2 Shoreline Change Analysis

The analysis phase of this study involved the extraction of shorelines, computation of shoreline changes rates, spatial classification of erosion–accretion zones and the correlation of coastal changes with climatic variables. A step-by-step approach was followed as described below.

2.2.1 Satellite imagery details

For shoreline extraction, Landsat satellite images were selected for the years 1994, 2004, 2014 and 2024. These images were obtained from the USGS Earth Explorer portal. Only cloud-free images acquired near high tide conditions were used to maintain consistency.

Table 2.2.1: Details of satellite images for Mandvi and Mundra talukas.

Scene ID	Covering area	Satellite	Acquired date	Acquired time (IST)	Spatial resolution (m)
Path-151, Row- 044	Mandvi	Landsat 5	22-12-1994	10:34 AM	30
		Landsat 7	25-12-2004	11:10 AM	30
		Landsat 8	27-11-2014	11:21 AM	30
		Landsat 8	08-12-2024	11:21 AM	30
Path-150, Row- 044	Mundra	Landsat 5	15-12-1994	10:28 AM	30
		Landsat 7	18-12-2004	11:10 AM	30
		Landsat 8	20-11-2014	11:04 AM	30
		Landsat 8	17-12-2024	11:15 AM	30

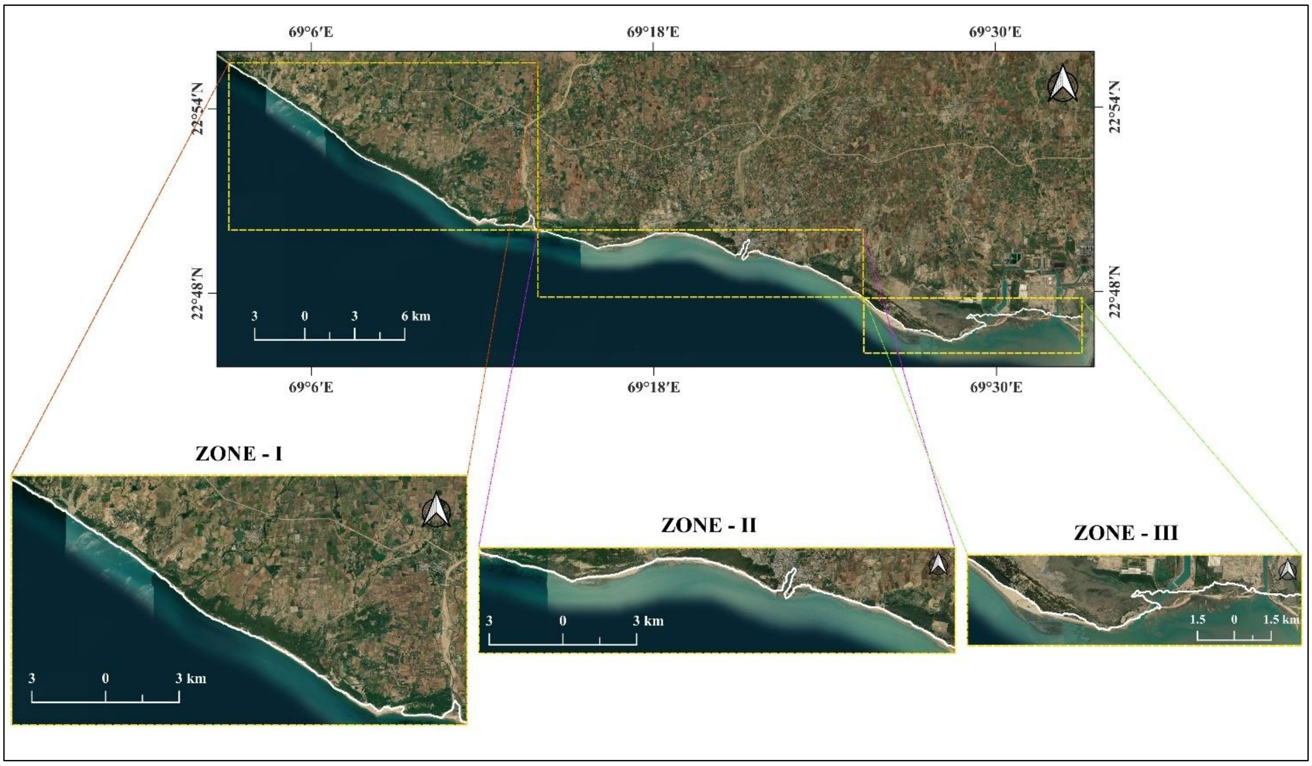
(*Source: Landsat imagery, metadata- Base data; Table prepared by author*)

2.2.2 Coastal zonation of Mandvi and Mundra talukas

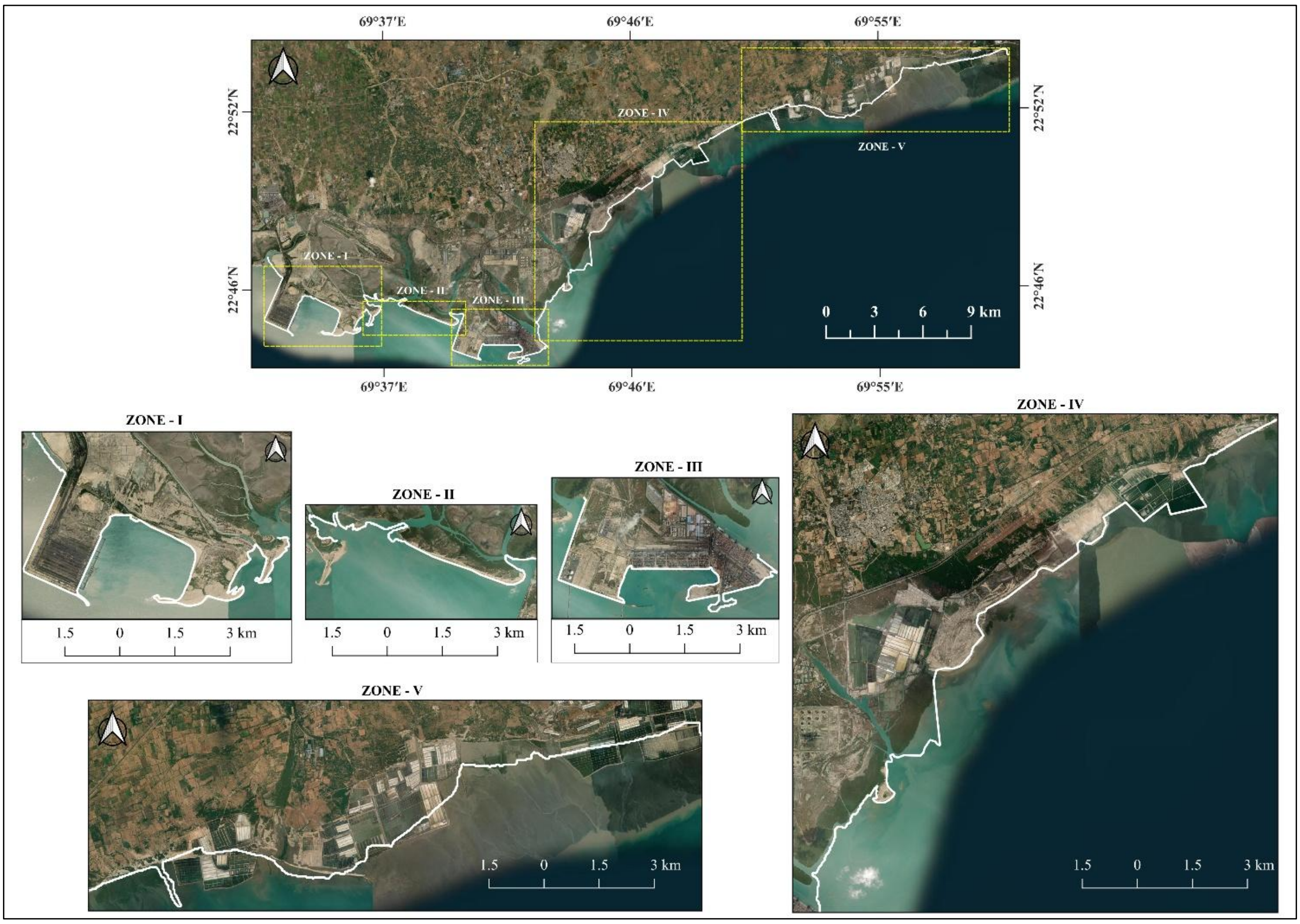
To analyse shoreline dynamics in a structured manner, the coastal stretch was divided into zones. This zonation was done separately for Mandvi and Mundra, based on spatial extent in Mandvi and functional land use in Mundra. The purpose of this approach was to enable zone-specific analysis of shoreline change, erosion–accretion trends and associated human or environmental influences.

The Mandvi coast was divided into three zones (Zone I, II, III), each covering approximately 32 km in length. The division was made using distance-based segmentation, to maintain equal coastal coverage and allow uniform spatial comparison. Although the land use and morphology vary slightly within zones, the equal-length zonation helped to assess whether erosion or accretion is concentrated in any particular coastal segment regardless of development intensity.

In Mundra, zoning was done based on dominant coastal activities and land use functions observed from satellite imagery and secondary data. Like, Zone I and III for industrial port area with dredging, reclamation and shipping activities, Zone II with relatively mixed characteristics and Zone IV and V with intensive aquaculture, salt pans and creek-lined landscapes.



Map 2.2.2.1: Zonation map of Mandvi taluka. (*Source: ESRI imagery- Base data; Map prepared by author*)



Map 2.2.2.2: Zonation map of Mundra taluka. (*Source: ESRI imagery- Base data; Map prepared by author*)

This coastal zonation approach made it possible to differentiate between naturally eroding zones and anthropogenically influenced ones and to interpret results in a more meaningful spatial context.

2.2.3 Coastal zonation of Mandvi and Mundra talukas

Shoreline extraction was a critical part of the analysis, as accurate shoreline positions were needed to measure long-term coastal changes. In this study, the High Tide Line (HTL) was used as the shoreline proxy and the Modified Normalized Difference Water Index (MNDWI) was applied to enhance the land–water boundary in all Landsat images.

Landsat images for the years 1994, 2004, 2014 and 2024 were downloaded from the USGS Earth Explorer platform. All images were chosen based on cloud-free conditions, seasonal similarity (all are in winter season) and similar tidal conditions which was verified through WXtide32. Images were already radiometrically and geometrically corrected by USGS.

The Modified Normalized Difference Water Index (MNDWI) was applied to enhance water features and reduce noise from built-up or vegetated surfaces near the coastal areas. The MNDWI was calculated using the following formula, MNDWI= ((Green – SWIR 1)/(Green + SWRI 1)).For Landsat 5 and 7(Green = Band 2, SWIR1 = Band 5); Landsat 8 and 9 (Green = Band 3, SWIR1 = Band 6)

This index allowed a clearer identification of water boundaries, making it easier to trace the High Tide Line (HTL) with precision. The MNDWI-enhanced raster output was visually interpreted in QGIS. The HTL was digitized manually by tracing the sharpest boundary between water and land along the coastline. Digitization was performed at a uniform scale of 1:10,000 and shorelines were saved as vector polyline shapefiles for each year for Mandvi and Mundra talukas separately.

2.2.4 Uncertainty calculation for shoreline data

In any remote sensing-based shoreline study, some amount of positional uncertainty is always associated with the digitized shoreline data. There are two types of uncertainty according to Fletcher et al,(2012). these are, positional which means to seasonal and tidal fluctuations and measurement that indicate the digitizing, pixel and rectification error. To ensure the reliability of shoreline change results, the total uncertainty (U_t) was calculated using a Root Mean Square Error (RMSE) approach, combining multiple error components.

The formula to calculate the uncertainty is

$$U_t = \pm\sqrt{\left(E_t^2 + E_s^2 + E_d^2 + E_r^2 + E_p^2\right)}$$

where,

E_s = Seasonal error, E_t = Tidal fluctuation, E_r = Rectification error, E_d = Digitizing error and E_p = Pixel error.

Table 2.2.4.1: Uncertainty calculation for shorelines of Mandvi taluka.

Positional Error (m)	Year								Remarks
	1994		2004		2014		2024		
	Error (m)	Error^2 (m^2)	Error (m)	Error^2 (m^2)	Error (m)	Error^2 (m^2)	Error (m)	Error^2 (m^2)	
Seasonal error (Es)	0	0	0	0	0	0	0	0	All datasets acquired in same season
Tidal fluctuation (Et)	1.63	2.66	4.00	16.00	1.67	2.80	2.85	8.14	As per Tidal Data
Rectification error (Er)	4.78	22.85	4.55	20.70	5.79	33.52	7.19	51.70	As per the Geometric RMSE model
Digitizing error (Ed)	15	225	15	225	15	225	15	225	As per spatial Resolution
Pixel Error (Ep)	0	0	0	0	0	0	0	0	All datasets have uniform spatial resolution
Summation of Error^2	250.51		261.70		261.32		284.84		
Shoreline position error (Esp) (m)	15.83		16.18		16.17		16.88		

(*Source: Landsat imagery, metadata, : WXtide32 Software - Base data; Table prepared by author*)

Table 2.2.4.2: Uncertainty calculation for shorelines of Mundra taluka.

Positional Error (m)	Year								Remarks
	1994		2004		2014		2024		
	Error (m)	Error^2 (m^2)	Error (m)	Error^2 (m^2)	Error (m)	Error^2 (m^2)	Error (m)	Error^2 (m^2)	
Seasonal error (Es)	0	0	0	0	0	0	0	0	All datasets acquired in same season
Tidal fluctuation (Et)	4.18	17.48	4.00	2.72	4.75	22.52	2.90	8.39	As per Tidal Data
Rectification error (Er)	4.78	22.85	4.8	23.04	6.7	44.89	8.2	67.24	As per the Geometric RMSE model
Digitizing error (Ed)	15	225	15	225	15	225	15	225	As per spatial Resolution
Pixel Error (Ep)	0	0	0	0	0	0	0	0	All datasets have uniform spatial resolution
Summation of Error	265.33		250.76		292.41		300.63		
Shoreline position error (Esp) (m)	16.29		15.84		17.10		17.34		

(*Source: Landsat imagery, metadata, : WXtide32 Software - Base data; Table prepared by author*)

By estimating and incorporating this uncertainty, a more realistic and cautious interpretation of shoreline movement was ensured throughout the study.

The tidal data which is used to get tidal fluctuation (Et) is,

Table 2.2.4.3: Tidal data of Mandvi and Mundra taluka as per Landsat images.

Image taken time	1st tide time	1st tide height (m)	2nd tide time	2nd tide height (m)	3rd tide time	3rd tide height (m)	4th tide time	4th tide height (m)	Interpolated height (m)	Tidal Status
10:34 AM	4:13 AM	High - 5.9	10:31 AM	Low - 1.6	4:10 PM	High - 5.0	10:08 PM	Low - 1.1	1.63	Slack
10:28 AM	12:29 AM	High - 5.3	6:34 AM	Low - 2.2	11:53 AM	High - 4.9	6:23 PM	Low - 1.0	4.18	Rising
11:10 AM	1:26 AM	High - 5.6	7:39 AM	Low - 2.1	12:50 PM	High - 4.9	7:15 PM	Low - 0.8	4.00	Rising
11:04 AM	6:15 AM	High - 5.4	1:05 PM	Low - 1.6	6:59 PM	High - 4.7	11:59 PM	Low - 2.0	2.72	Falling
11:15 AM	12:23 AM	High - 5.3	6:21 AM	Low - 1.9	12:02 PM	High - 5.2	6:27 PM	Low - 0.9	4.75	Rising
11:21 AM	4:51 AM	High - 6.0	11:14 AM	Low - 1.6	4:52 PM	High - 5.1	11:01 PM	Low - 1.0	1.67	Slack
11:21 AM	12:04 AM	Low - 1.4	6:32 AM	High - 5.5	1:27 PM	Low - 1.7	6:58 PM	High - 4.6	2.85	Falling
11:15 AM	3:06 AM	High - 6.2	9:26 AM	Low - 1.7	2:45 PM	High - 5.2	9:05 PM	Low - 0.5	2.90	Rising

(*Source: WXtide32 Software – Base Data; Table compiled by the Author*)

2.2.5 Shoreline change mapping

After shoreline digitization and uncertainty adjustment, shoreline change analysis was carried out using the Digital Shoreline Analysis System (DSAS) and QGIS. These tools enabled the calculation of spatial and statistical changes in shoreline position over the selected time intervals.

Baseline and transect generation:

A shore-parallel baseline was created approximately 200 m inland from the farthest shoreline using the buffer tool in QGIS. Transects were generated at a regular interval of 100 m, to the baseline. Each transect intersected all four shoreline layers (1994, 2004, 2014, 2024), enabling temporal comparison across all time periods. The baseline and transects were exported into the DSAS plugin environment for further processing.

Computation of shoreline change statistics:

Using DSAS, the following shoreline change parameters were calculated for each transect.

Net Shoreline Movement (NSM) to measure the total linear distance (in meters) between the oldest (1994) and most recent (2024) shoreline at each transect. End Point Rate (EPR) to calculate the average rate of shoreline change (in meters per year) between the first and last year. Weighted Linear Regression (WLR) to use all available shoreline positions and assigns weights to determine the statistically optimized rate of shoreline movement over time. The results were exported as attribute tables containing NSM, EPR, WLR and uncertainty-adjusted values for each transect.

Mapping of shoreline change:

The DSAS outputs were linked to the corresponding transects in QGIS to generate thematic maps showing shoreline change. The transects were color-coded based on NSM and EPR values, following a four-class scheme: high erosion (NSM < (–100) m), low erosion (NSM between (–100) m and 0 m), low accretion (NSM between 0 m and 100 m) and high accretion (NSM > 100 m).

The maps were generated separately for; each decadal period (1994–2004, 2004–2014, 2014–2024), overall change from 1994–2024 and each zone (Mandvi Zone I to Zone III, Mundra Zones I to Zone V). These maps provided a spatial understanding of erosion and accretion patterns, highlighting critical zones of shoreline retreat and growth.

Zonal summary:

Each transect was spatially assigned to a zone using spatial join in QGIS. Zonal averages for NSM and WLR were calculated using attribute statistics with help of Excel. Maps were also generated to show zone-wise comparison of erosion and accretion trends, to interpret natural versus anthropogenic coastal dynamics.

2.3 Sea Surface Temperature (SST) Analysis

The analysis of Sea Surface Temperature (SST) was conducted to understand the potential climatic influence on long-term shoreline changes in the Mandvi and Mundra coastal zones. SST is considered an important oceanographic variable that reflects the thermal condition of the sea surface and can influence coastal erosion, tidal patterns and sediment dynamics. In this study, SST data were collected, processed and analyzed over a 50-year period from 1974 to 2024.

Annual SST data for the period 1974 to 2024 were obtained from KNMI Climate Explorer website, which provide interpolated global SST records. The SST values used in the study represented regional averages for the northern Gulf of Kachchh, near the coastlines of Mandvi and Mundra. The data were cleaned and standardized in Excel. A time series plot was created to observe the temporal trend in SST values.

2.3.1 SST and Atmospheric CO_2 analysis

To explore the possible influence of climate change on coastal dynamics, a combined analysis of Sea Surface Temperature (SST) and Atmospheric CO_2 concentration was conducted. These two parameters are considered as key indicators of global warming and ocean–atmosphere interactions. Their long-term trends were studied over a 50-year period from 1974 to 2024 and compared with observed shoreline changes in the Mandvi–Mundra coastal region. The atmospheric CO_2 data was collected from World Meteorological Data.

To quantify the strength of the relationship between atmospheric CO_2 and SST, a Pearson correlation analysis was performed in Excel. And to confirm that the correlation was statistically significant p-value was also calculated in Excel. A scatter plot and regression line were created to visualize the relationship between CO_2 and sea surface temperature with the help of Excel.

2.3.2 SST and Annual mean sunspot number analysis

In addition to anthropogenic factors like CO_2, natural solar variability was also considered in this study to understand its possible influence on Sea Surface Temperature (SST) in the Mandvi–Mundra coastal region. Sunspot numbers are widely used as indicators of solar activity and changes in solar radiation output which are believed to have minor but detectable effects on Earth's climate system, including SST.

Annual mean sunspot numbers were collected from Solar Influences Data Analysis Centre and matched with SST values for each year from 1974 to 2024. A scatter plot and regression line were created to visualize the relationship between solar activity and sea surface temperature by Excel. To analyse the relation between SST and sunspot number a Pearson's correlation coefficient and p-value were calculated in same method like before by using Excel.

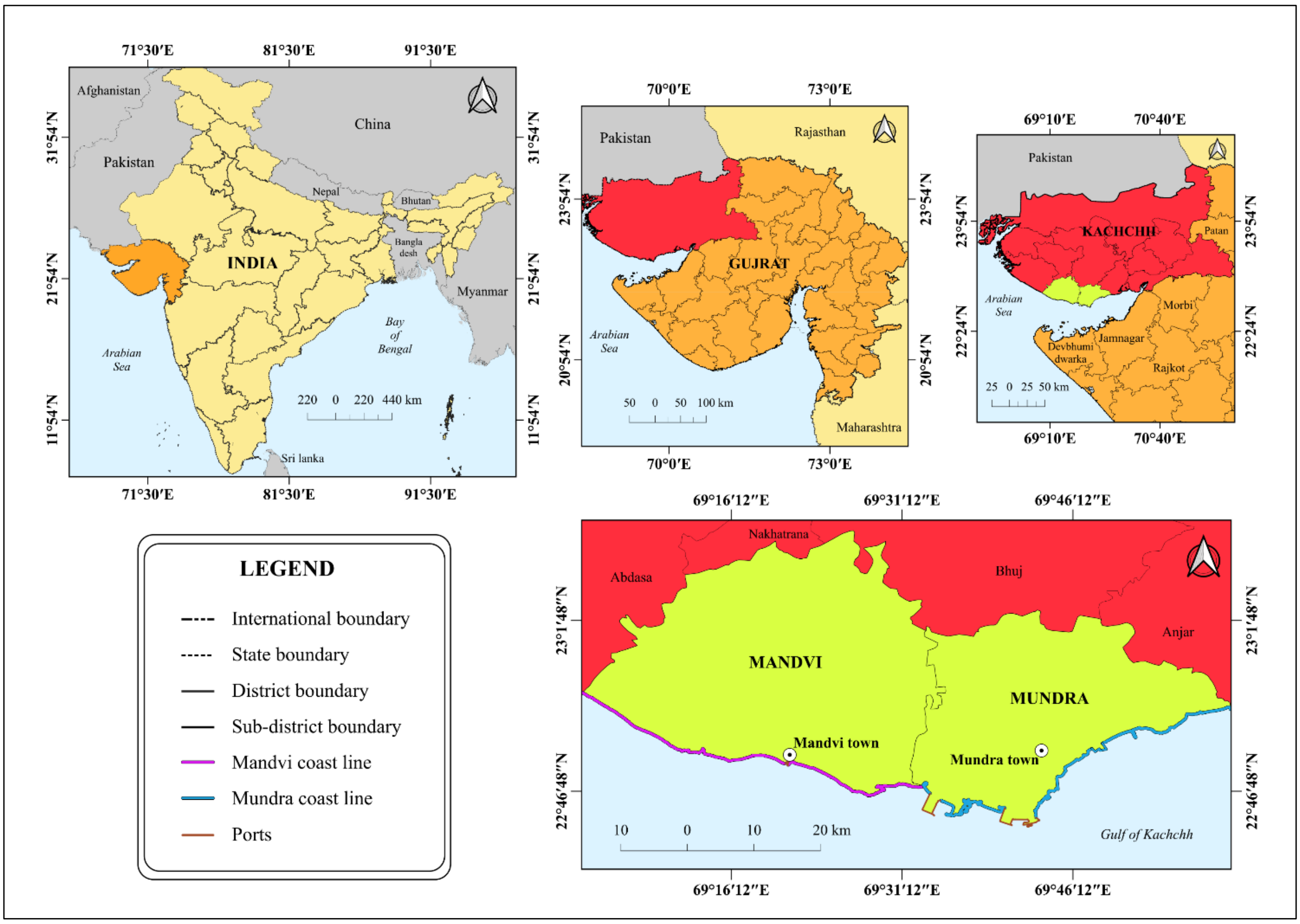
A comprehensive methodological framework was presented to assess shoreline changes along the Mandvi–Mundra coast and to evaluate the possible climatic influences on those changes. Multi-temporal Landsat satellite images were used to extract shoreline positions using the MNDWI technique and shoreline change rates were computed using the DSAS tool in QGIS. Zonal analysis was conducted to capture spatial variations in erosion and accretion patterns.

Uncertainty in shoreline extraction was estimated using a standard error propagation formula to ensure the reliability of the outputs. Additionally, long-term sea surface temperature (SST) trends were analyzed in conjunction with atmospheric CO_2 levels and sunspot activity to explore potential climatic drivers of coastal change. Statistical correlations were performed to support these interpretations. The adopted methodology ensured that both spatial and climatic aspects of coastal transformation were addressed in a structured and scientifically valid manner.

CHAPTER 3: STUDY AREA

3.1 Location of the Study Area

The study area is located along the southern coastal belt of the Kachchh district in the western Indian state of Gujarat. It specifically covers two important coastal talukas which are Mandvi and Mundra. These coastal talukas lie along the northern margins of the Gulf of Kachchh, opening into the Arabian Sea. Geographically, the region extends approximately between 22°44′N to 23°09′N latitude and 69°03′E to 70°00′E longitude. The Mandvi taluka forms the western part of the study area, while Mundra taluka occupies the eastern portion. At the north western direction of Mandvi taluka, Abdasa and Nakhatrana talukas are situated. The Anjar taluka is situated at the north eastern direction of Mundra taluka. The Bhuj taluka is sharing its southern border with both Mandvi and Mundra talukas.



Map 3.1: Study area map of Mandvi and Mundra talukas. (*Survey of India – Base data*; *Source: Prepared by author*)

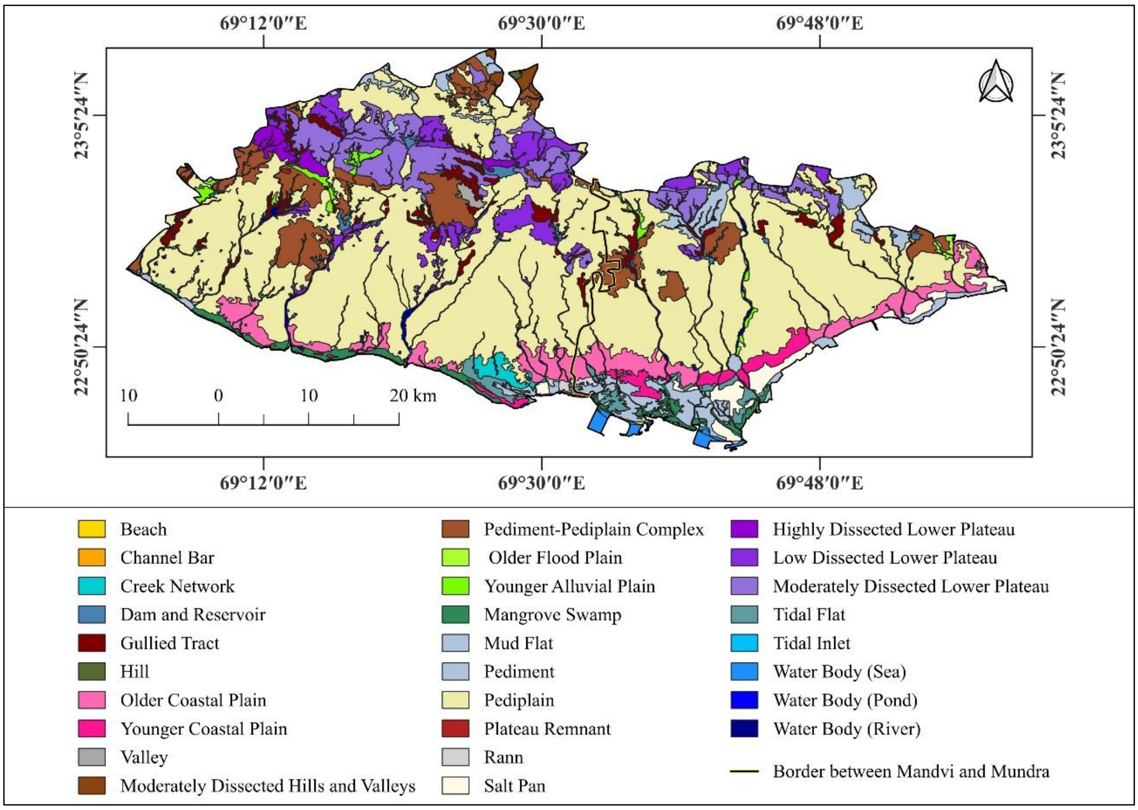
The towns of Mandvi and Mundra, both situated near the coastline but the Mandvi town is closer to coastline than Mundra town. These two towns have witnessed considerable urban and economic growth over recent decades. Mandvi is known for its historical importance as a port city and its expanding tourism sector, while Mundra has become one of India's major industrial hubs due to the establishment of the Mundra Port and related industrial activities. This stretch of coast holds strategic importance not only for its ecological and geomorphological diversity, but also for its economic activities which includes port operations in both taluka, fisheries and tourism.

The location map provided above helps to understand the spatial extent of the study area which highlights the administrative boundaries of Mandvi and Mundra talukas, major towns and the adjoining Gulf of Kachchh shoreline.

3.2 Physical Environment

The physical environment of the study region needs to be explored for better understanding of the process of coastal erosion and its management. The physical setting of the area, including its geomorphology, geology, climate, soil characteristics, elevation, drainage patterns, tidal influence and biotic communities plays a crucial role in determining the vulnerability and dynamics of the coastline.

3.2.1 Geomorphology of Mandvi and Mundra talukas



Map 3.2.1: Geomorphological map of Mandvi and Mundra talukas. (*Source: Bhukosh portal (Geological Survey of India) – Base Data; Map Prepared by the Author*)

The geomorphology of the Mandvi–Mundra region has been analyzed for the entire administrative extent of both talukas which covers both coastal and inland landscapes as shown in the map provided above.

Based on the geomorphological data obtained from the Bhukosh portal (Geological Survey of India), the area has been classified into six major geomorphological classes. These classes are denudational landforms, structural landforms, coastal landforms, fluvial landforms, salt/arid landforms and wetland/swamp features.

Table 3.2.1: Geomorphological classification and area distribution of Mandvi–Mundra talukas.

Major Geomorphological Classes	Minor Geomorphological Classes	Minor area in km^2	Major area in km^2	Percentage (%)
Coastal landforms	Older coastal plain	118.776	263.196	11.21
	Mud flat	62.955		
	Younger coastal plain	33.602		
	Tidal flat	25.056		
	Creek network	18.032		
	Beach	4.363		
	Channel bar	0.24		
	Tidal inlet	0.172		
Denudational landforms	Pediplain	1304.01	1529.516	65.13
	Pediment-pediplain complex	161.529		
	Pediment	55.599		
	Moderately dissected hills and valleys	7.453		
	Hill	0.925		
Fluvial landforms	Gullied tract	57.467	84.249	3.59
	Younger Alluvial plain	19.783		
	Valley	4.154		
	Older flood plain	2.845		
Salt/arid landforms	Salt pan	37.689	41.899	1.78
	Rann	4.21		
Structural landforms	Moderately dissected lower plateau	167.25	289.036	12.31
	Low dissected lower plateau	99.964		
	Highly dissected lower plateau	21.072		
	Plateau remnant	0.751		
Water bodies	River	75.495	107.291	4.57
	Dam and reservoir	26.382		
	Pond	2.763		
	Others	2.651		
Wetland/swamp features	Mangrove swamp	33.063	33.063	1.41
Total area including Mandvi and Mundra talukas		2348.251	2348.251	100

(*Source: Bhukosh portal (Geological Survey of India) – Base Data; Table compiled by the Author*)

Denudational landforms dominate the landscape by covering approximately 65.13% of the total area. These include extensive pediplains, pediment–pediplain complexes and moderately dissected hills and valleys which represent ancient erosional surfaces across the inland parts of both talukas. Structural landforms covering about 12.31% of total area are characterized by moderately to highly dissected lower plateaus and plateau remnants. This shows the tectonic history of the Kachchh region. Fluvial landforms (3.59%) such as gullied tracts, floodplains and valleys are present primarily along river courses and low-lying depressions. Salt/arid landforms (1.78%) including salt pans and small rann patches are mainly concentrated in the eastern part of Mundra taluka. Water bodies (4.57%) and wetland/swamp features (1.41%), including mangrove swamps enhance the region's geomorphological diversity. The mangrove swamps are highly concentrated along the shoreline of Mandvi taluka.

Though coastal landforms occupying a smaller share of 11.21%. These are geographically important as they include sensitive features such as tidal flats, mudflats, older and younger coastal plains, beaches and creek networks. These features are concentrated along the Gulf of Kachchh shoreline, particularly near the towns of Mandvi and Mundra.

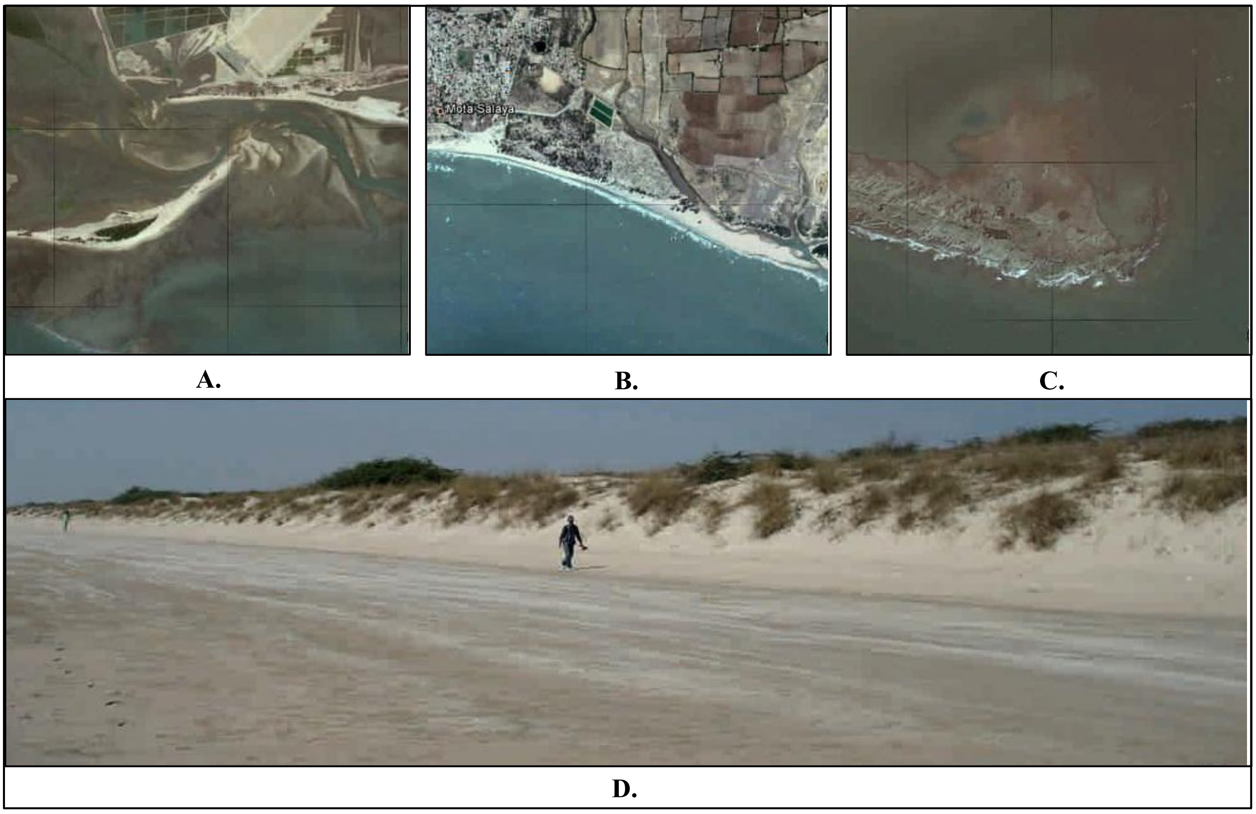
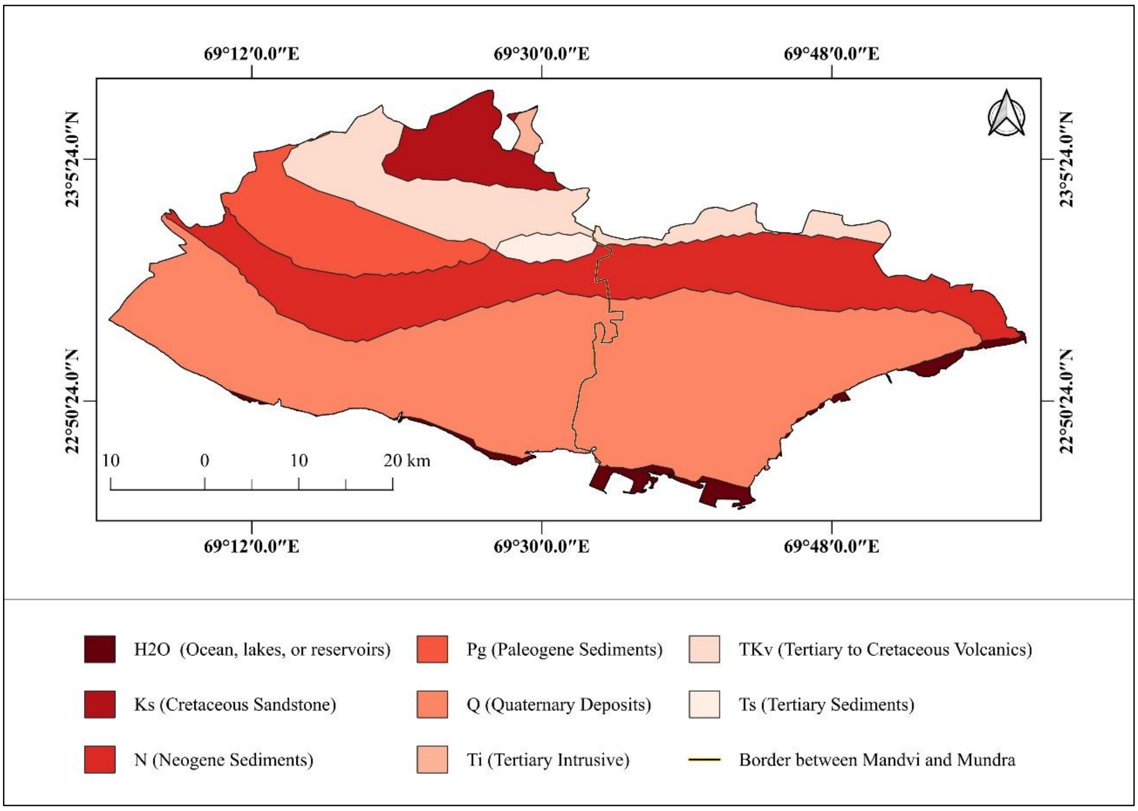


Figure 3.2.1: Coastal geomorphology in Mandvi to Mundra segment: **A.** Barrier islands and saltpan, **B.** Beach, dune, creek and tidal flat, **C.** Rocky exposure and origin of spit-bar-barrier, **D.** Coastal dunes and tidal flat. (*Source: Majethiya et al. 2016*).

In this way the geomorphological analysis highlights the spatial complexity and variation across the full stretch of Mandvi and Mundra talukas.

3.2.2 Geology of Mandvi and Mundra talukas

The geology of the Mandvi–Mundra region is a part of the larger geological framework of the Kachchh district, which represents one of the most tectonically active and structurally complex regions of western India. The geological formations in the study area are mainly composed of sedimentary rocks that were deposited during the Mesozoic and Cenozoic eras. The following map provides better insights about the geology of the entire administrative extent of both talukas.



Map 3.2.2: Geological map of Mandvi and Mundra talukas. (*Source: USGS portal – Base Data; Map Prepared by the Author*)

The dominant geological unit observed in the region is the Quaternary Deposits, covering approximately 51.79% of the total area. These deposits mainly consist of recent alluvium, coastal sands, mudflat sediments and other unstratified materials. Such sediments are prominently distributed along the coastal margins and low-lying inland plains. It makes these zones highly sensitive to coastal processes like erosion and sedimentation. The inland areas are predominantly occupied by Neogene Sediments (21.79%) and Paleogene Sediments (8.08%). These formations typically include silts, clays, sandstones and fluvio-marine deposits that were laid down during the Tertiary period.

Significant igneous activity can also be seen within the talukas, represented by Tertiary Intrusive rocks (11.49%) and Tertiary to Cretaceous Volcanic rocks (0.43%) related to volcanic flows and deccan traps.

These features show the tectonic and magmatic events that have shaped the subsurface geology of the Kachchh region.

Cretaceous Sandstone formations (4.78%) are also present in northern inland parts which represents ancient sedimentary environments. Minor occurrences of Tertiary Sediments (1.21%) including limestone, marl and shale, are also noted.

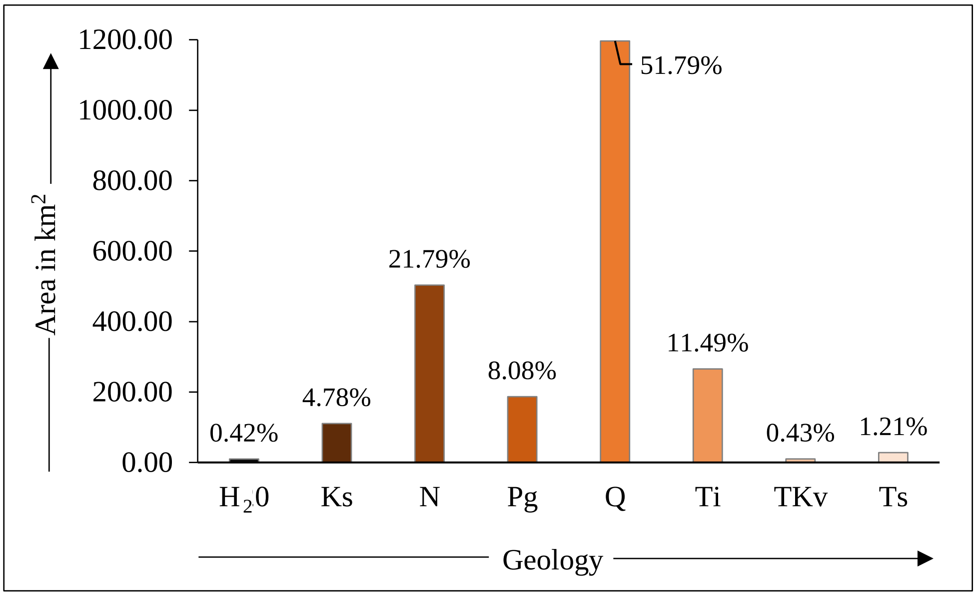
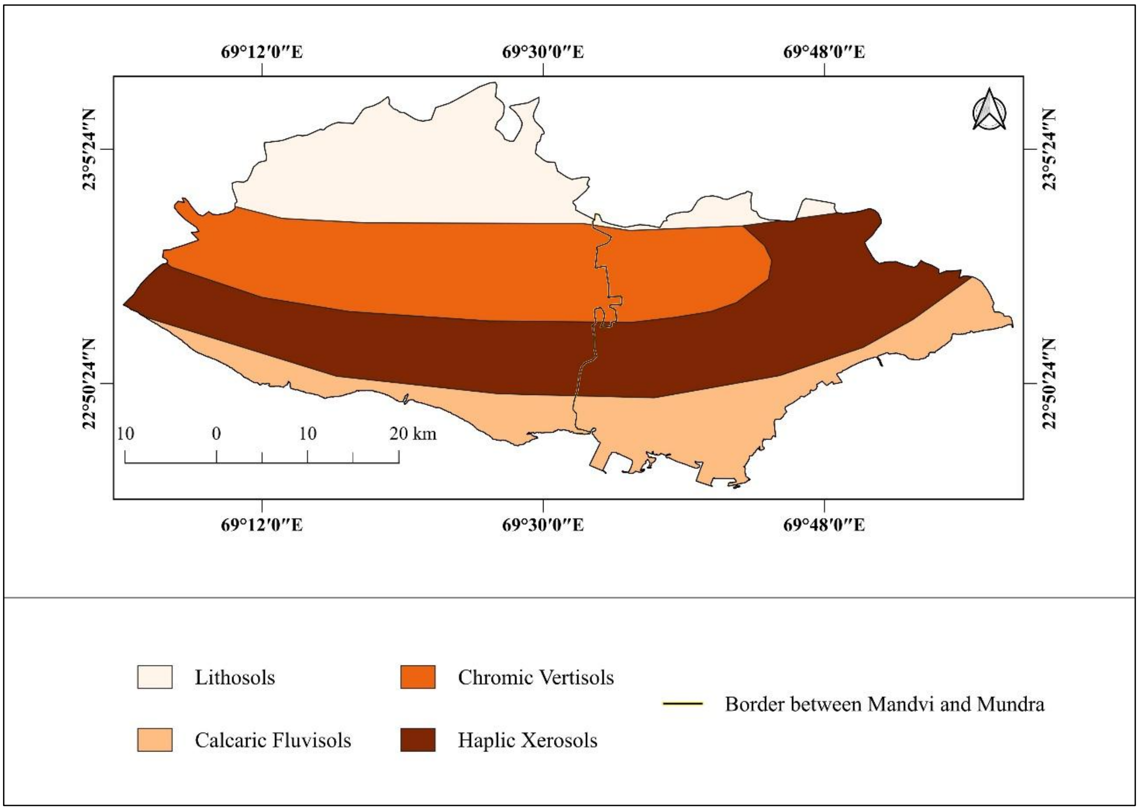


Figure 3.2.2: Geological classification and area distribution of Mandvi–Mundra talukas. (*Source: USGS portal – Base Data; Figure Prepared by the Author*)

The geology of the Mandvi–Mundra region is further influenced by major fault systems like the Katrol Hill Fault and associated minor fractures situated in the northern part of the talukas. The tectonic movements along these faults result into localized uplift, tilting and the formation of uplifted marine terraces and raised beaches along parts of the coastline in Mandvi-Mundra region.

3.2.3 Soil characteristics of Mandvi and Mundra talukas

The soil characteristics of the Mandvi–Mundra region are influenced by the geological formations, coastal processes and climatic conditions present in the Kachchh district. The entire administrative extent of Mandvi and Mundra talukas has a variety of soil types. Each associated with specific landforms and depositional environments. On the basis of the soil map, provided below there are four major soil types have been identified in the Mandvi-Mundra region. These are lithosols, chromic vertisols, haplic xerosols and calcaric fluvisols.



Map 3.2.3: Soil map of Mandvi and Mundra talukas. (*Source: FAO-DSMW – Base Data; Map Prepared by the Author*)

Lithosols cover the largest area in the region. It occupies 34.90% of the total inland area . These soils are very shallow, stony and poorly developed. They are mostly found in areas with rocky surfaces and uplands. Here in Mandvi-Mundra region the lithosols are highly concentrated in the northern part of both talukas. But Mandvi contains more lithosols in northern inland area than Mundra. This soil is not suitable for agriculture.

Chromic vertisols occupy approximately 28.18% of the study area. These are heavy clay soils that expand when they are wet and form deep cracks when they become dry. Vertisols are found mainly in low-lying inland areas. They are moderately fertile but require careful management for farming because of their swelling and shrinking nature. Again, Mandvi contains more vertisols in central inland area than Mundra. Haplic xerosols cover around 19.66% of the land. These soils are typically found in semi-arid regions. They have a sandy to loamy texture, low organic matter and often show high salinity or alkalinity. They are generally less fertile and support only sparse vegetation unless irrigation and soil treatments are applied.

Calcaric fluvisols cover around 17.26% of the area. These soils have developed along river valleys and coastal lowlands from younger alluvial deposits. They are rich in calcium carbonate and are comparatively more fertile. In both talukas this soil is concentrated in the southern part .

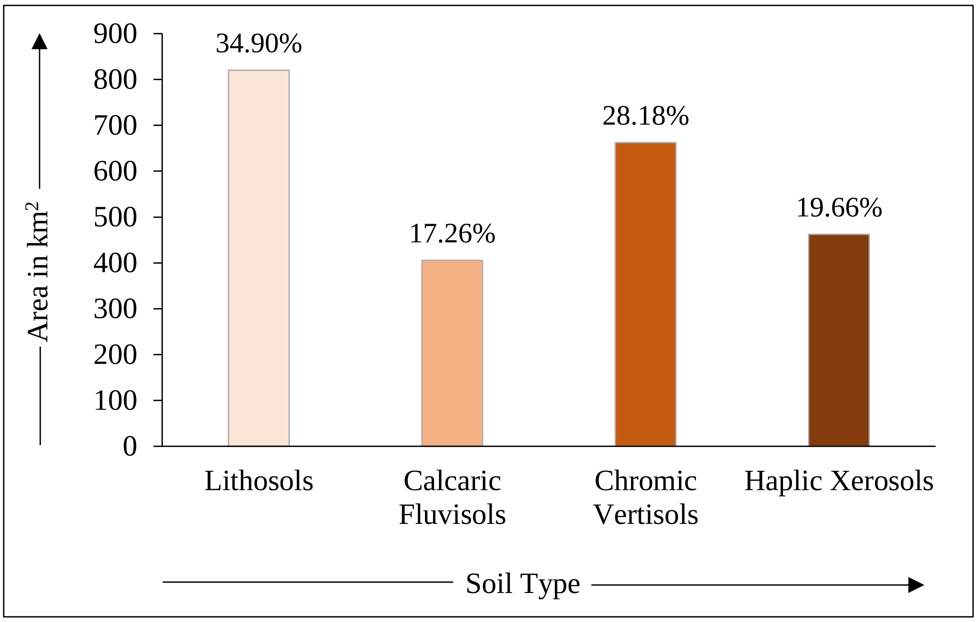
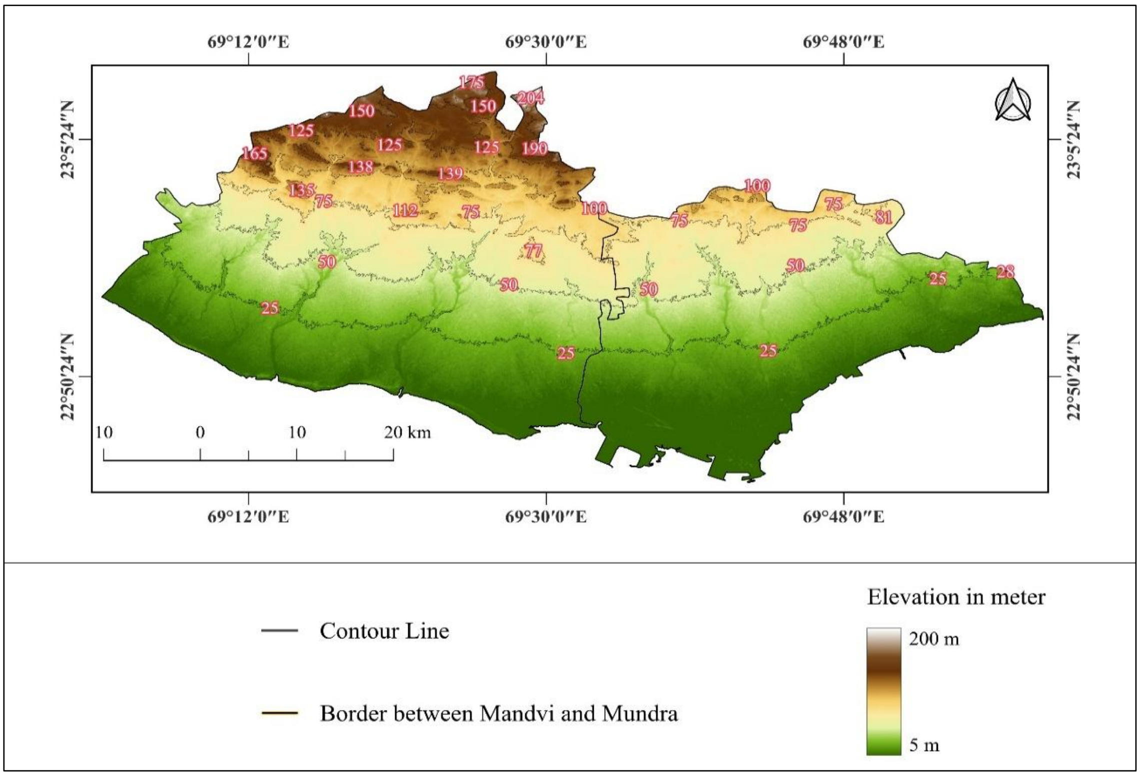


Figure 3.2.3: Soil classification and area distribution of Mandvi–Mundra talukas. (*Source: FAO-DSM)– Base Data; Figure Prepared by the Author*)

These soil characteristics strongly affect land use, vegetation patterns and the natural vulnerability to coastal and inland degradation in both talukas.

3.2.4 Elevation of Mandvi and Mundra talukas



Map 3.2.4: Elevation map of Mandvi and Mundra talukas. (*Source: NASA Earth Data (SRTM - 30m) – Base Data; Map Prepared by the Author*)

The Mandvi–Mundra region shows a wide range of elevations, as observed from the elevation and contour map provided above. The elevation across the study area varies between 5 m and approximately 200 m above mean sea level. There is total 7 contour lines with 25m interval which are 25 m, 50 m, 75 m, 100 m, 125 m, 150 m, 175 m. Based on this, the study area can be divided into several elevation zones.

The lowest elevation zone (below 5 to 25 m) is found along the immediate coastal margins. This zone includes tidal flats, beaches, mudflats and low-lying coastal plains. Areas near Mandvi and Mundra towns fall within this zone. The Mandvi town experiences an average elevation of 13 m above mean sea level where as town Mundra experiences an average elevation of 14 m. The next elevation zone (25 to 50 m) covers slightly elevated coastal plains and inland areas. This zone is characterized by gently sloping surfaces, supporting limited vegetation and salt-tolerant ecosystems.

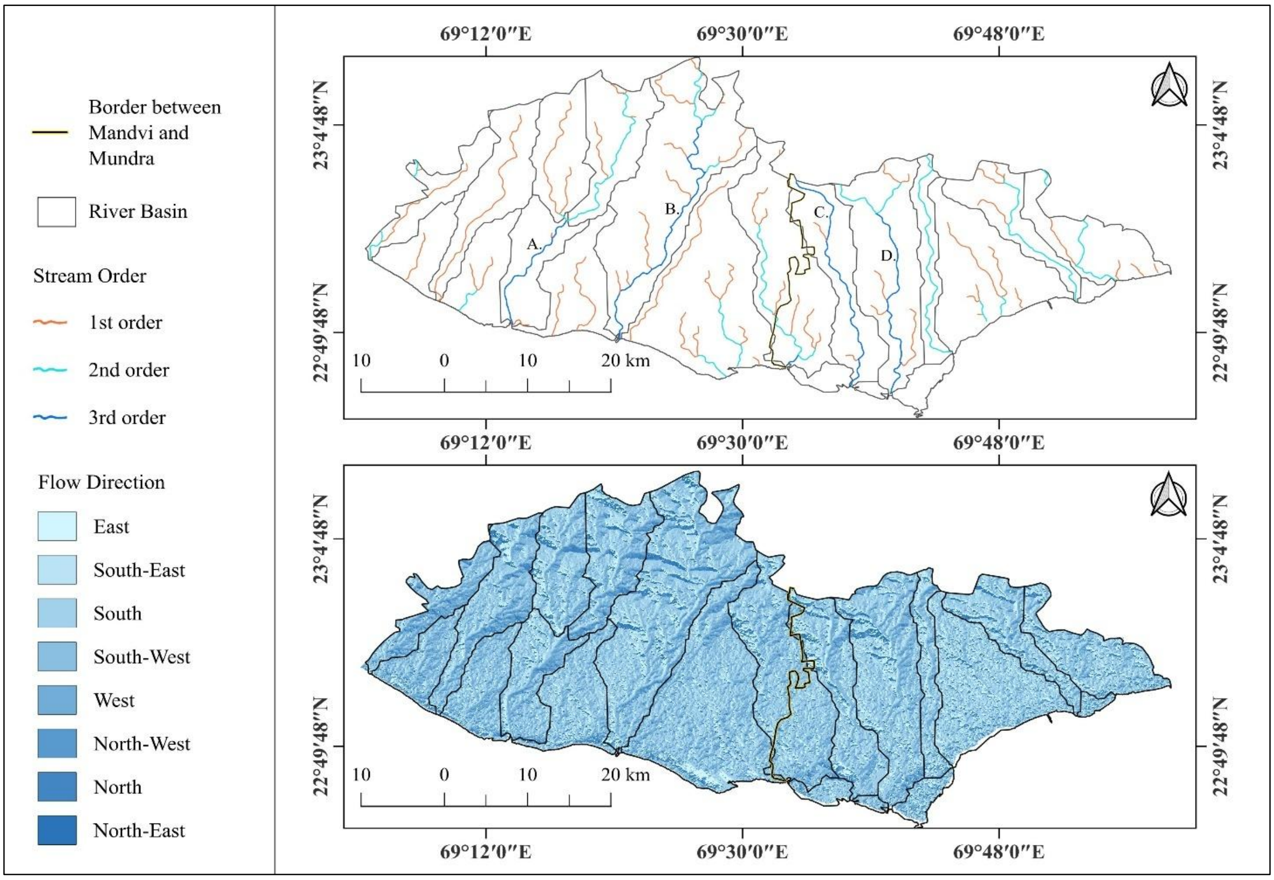
Between 50 to 100 m contours the third zone stands. The land surface gradually rises and forms undulating uplands. These areas are shaped by old pediplains, minor hillocks and weathered structural surfaces. Seasonal streams often dissect these uplands and creates shallow valleys and small gullies.

Fourth elevation zone between 100 and 150 m contours represent moderately high upland zones. These areas are associated with more resistant geological formations such as hard sandstones, older sedimentary rocks and plateaus. The highest elevations, reaching up to 175 to 200 m. This sixth elevation zone occurs in isolated spots across the interior of the study area. These areas include ancient structural remnants and dissected plateaus formed through long-term erosional processes.

If we notice both talukas side by side then we can understand, only Mandvi taluka experiences elevation above 100 m which goes up to more than 200 m in some areas in the northern part of the taluka. But in Mundra the highest contour is 100 m. There is no further elevation above 112 m in Mundra taluka. Lower elevation zones close to the coast are more prone to erosion and tidal hazards, while higher upland zones are relatively more stable.

3.2.5 Drainage characteristics of Mandvi and Mundra talukas

The drainage system of the Mandvi–Mundra region is influenced by the area's geomorphology, semi-arid climate and proximity to the Gulf of Kachchh. Based on drainage mapping and analysis, the study area displays a sparse and seasonal drainage network with a dendritic drainage pattern. The entire combined area of Mandvi and Mundra talukas has been treated as a single large river basin for the purpose of drainage analysis. The total area considered for the drainage density calculation is 2363.4 km² which covers the full extent of both talukas.



Map 3.2.5: Drainage and Flow direction map of Mandvi and Mundra talukas. (*Source: HydroSHEDS – Base Data; Map Prepared by the Author*)

The drainage pattern is predominantly dendritic in Mandvi-Mundra region which is especially visible in the upland zones. Stream ordering analysis shows that first-order streams are the most dominant one, comprising about 56.14% of the total number of streams. These first-order streams are small and seasonal in nature. They flow mainly during the monsoon season and remaining dry during the rest of the year. Second-order streams represent 28.95% and third-order streams represent 14.91% of the total stream segments.

Four major third-order rivers have been identified within the study area and have been labelled on the drainage map as, A = Kharod river, B = Rukmavati river, C = Nagmati river, D = Suraai river. The Kharod River and Rukmavati River are flowing in Mandvi taluka and the Nagmati River and Suraai River in Mundra taluka. These rivers act as the principal drainage lines by collecting flow from numerous first-order and second-order streams before ultimately discharging towards the Gulf of Kachchh.

The general flow direction of streams is from the elevated inland areas towards the Gulf of Kachchh. In the western part of the study area streams mostly flow westward and south-westward while in the eastern portion streams show a south-eastward flow towards the coastal zone.

Table 3.2.5: Drainage density of Mandvi–Mundra talukas.

Stream Order (*u*)	Number of Stream segment (N*u*)	Percentage Composition of Stream Order (%N*u*)	Length in km	Drainage Density (km/km^2) [Total length of all streams / Total area]
1st order	64	56.14	333.31	[630.24 / 2363.4] = 0.267
2nd order	33	28.95	177.66	
3rd order	17	14.91	119.27	
Total	114	100.00	630.24	

(*Source: HydroSHEDS – Base Data; Table compiled by the Author*)

The total length of all mapped streams is 630.24 km and the total area of both talukas is 2363.4 km² which covers the full extent of Mandvi-Mundra region. Based on this, the drainage density of the study area has been calculated as 0.267 km/km² which indicates a low drainage density. This low value reflects the region's semi-arid climate, limited surface runoff and the presence of resistant rocky and sedimentary surfaces.

In the coastal belt, the drainage network becomes poorly defined and fragmented due to the dominance of tidal flats, mudflats and saline marshes. Overall, the drainage system of Mandvi–Mundra is characterized by low drainage density, short seasonal flows and dendritic patterns in uplands. These features play a crucial role in affecting soil salinity, groundwater recharge and the vulnerability of coastal areas to flooding and erosion.

3.2.6 Climate of Mandvi and Mundra talukas

The climate of the Mandvi–Mundra region is characterized as hot semi-arid, which is a BSh climate classification under the Koppen–Geiger climate system (Peel et al., 2007). This classification is supported by the region's low annual precipitation, high temperatures and a distinct dry season lasting for most of the year. The study area's coastal location along the northern Gulf of Kachchh influences its climatic characteristics. Although continentality, low vegetation cover and monsoonal variability remain the primary controlling factors behind the climate.

The following climatic parameters for both Mandvi and Mundra talukas represent monthly averages which are calculated over a 30-year period from 1991 to 2021.

Temperature:

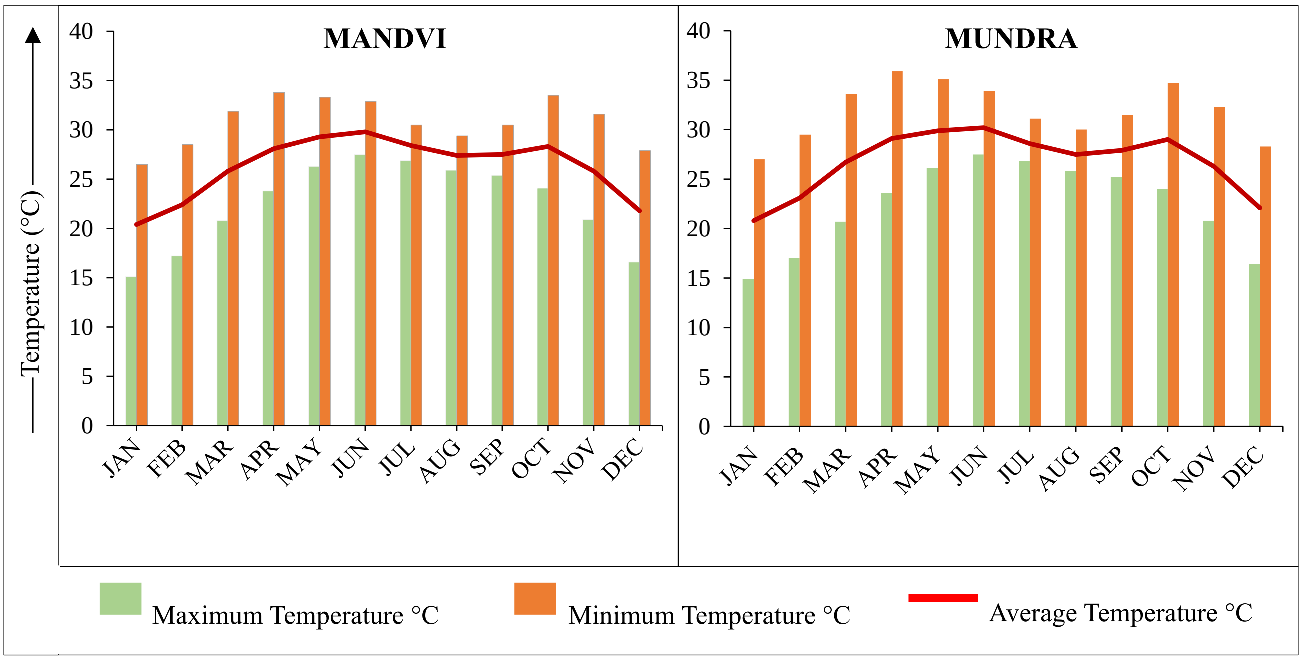


Figure 3.2.6.1: Monthly temperature of Mandvi and Mundra talukas from 1991 to 2021. (*Source: Climate-Data – Base Data; Figure Prepared by the Author*)

Based on the above figure, the region experiences high average temperatures throughout the year. In Mandvi, average monthly temperatures range from 20.4°C in January to 29.8°C in June, while in Mundra, temperatures vary between 20.8°C (January) and 30.2°C (June). The hottest months are typically April and May. The maximum temperatures can reach up to 35.9°C in Mundra and 33.8°C in Mandvi in month of April. The coldest conditions occur during December and January. The minimum temperatures can drop to 14.9°C in Mundra and 15.1°C in Mandvi in the month of January. Despite being close to the sea, the region experiences a wide annual thermal range, which is typical characteristic of semi-arid zones in northwest India.

Rainfall:

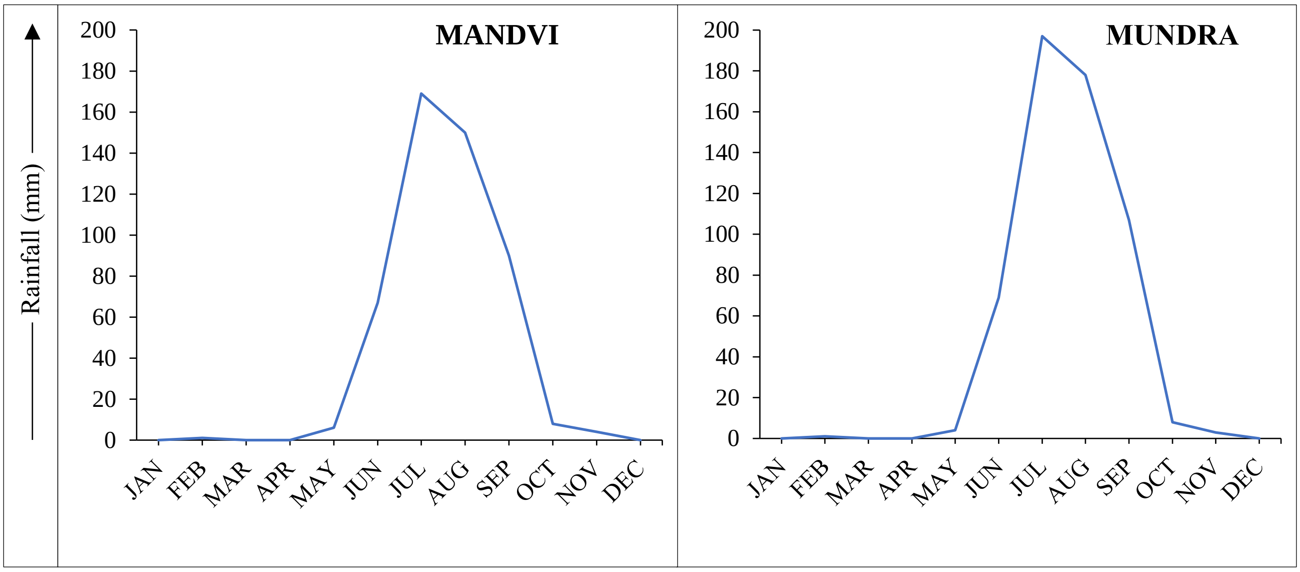


Figure 3.2.6.2: Monthly rainfall of Mandvi and Mundra talukas from 1991 to 2021. (*Source: Climate-Data – Base Data; Figure Prepared by the Author*)

Rainfall in the study area is highly seasonal, with the southwest monsoon (June to September) accounting for more than 85% of the total annual rainfall. In Mandvi taluka the wettest months are July (169 mm) and August (150 mm) and in Mundra taluka slightly higher rainfall is recorded with 197 mm in July and 178 mm in August. The other months of the year remains largely dry, with no significant rainfall from January to April and again in December. October and November experience only minor precipitation, typically below 10 mm in both talukas. This influence of seasonal rainfall, combined with high evaporation shapes the arid and moisture-deficit conditions that prevail for most of the year.

Humidity:

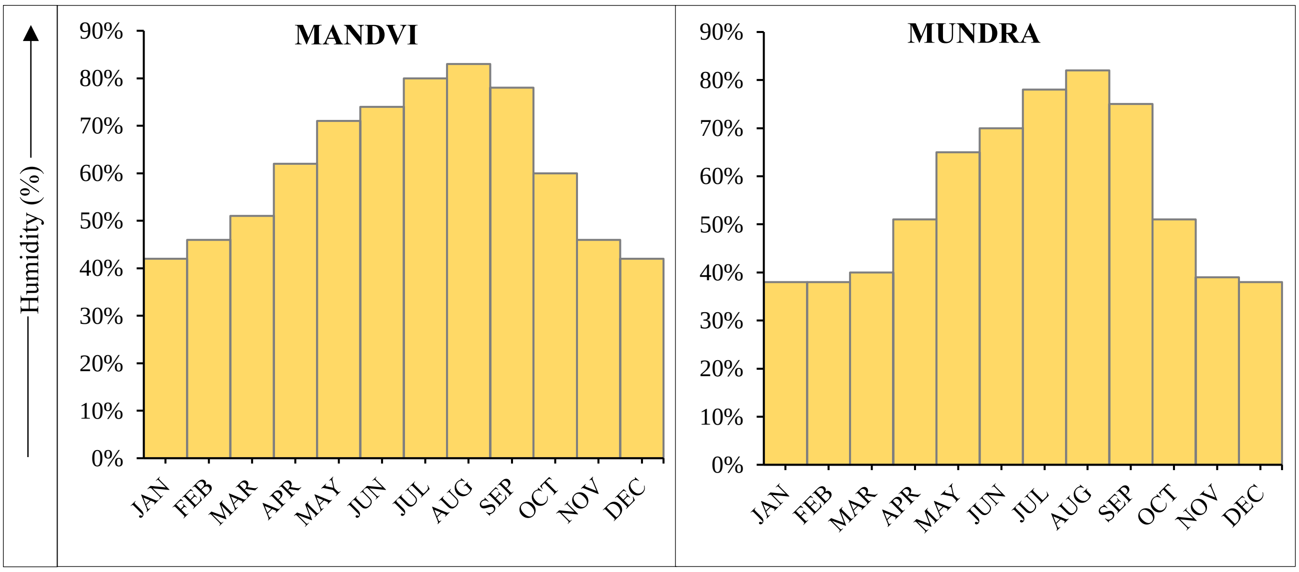


Figure 3.2.6.3: Monthly humidity of Mandvi and Mundra talukas from 1991 to 2021. (*Source: Climate-Data – Base Data; Figure Prepared by the Author*)

Humidity levels follow the same seasonal rhythm as precipitation. In Mandvi, humidity rises from 42% in January to 83% in August whereas in Mundra, it increases from 38% in January to 82% in August. These high humidity levels during the monsoon enhance the perception of discomfort despite slightly moderated temperatures. During the dry season humidity drops significantly which leads to dry and dusty surface conditions that may accelerate wind-driven coastal erosion.

Wind speed:

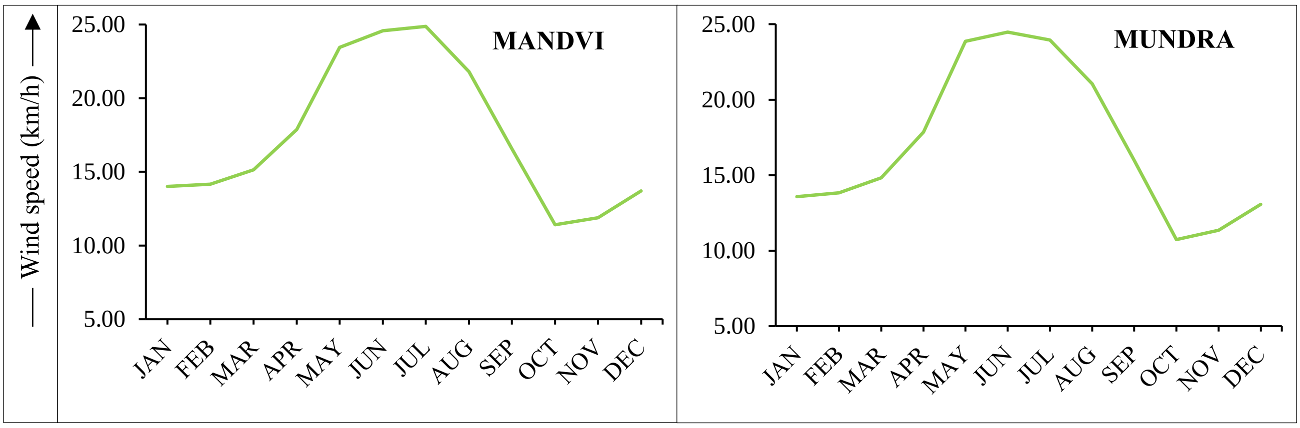


Figure 3.2.6.4: Monthly wind speed of Mandvi and Mundra talukas from 1991 to 2021. (*Source: Climate-Data – Base Data; Figure Prepared by the Author*)

Wind speed is an important climatic parameter, especially when it shapes coastal landforms and influences sediment transport. In both Mandvi and Mundra, the strongest winds are experienced during the pre-monsoon and monsoon periods (May to July), with average speeds of 24 km/h. In Mandvi wind speed reaches up to 24.87 km/h in July whereas in Mundra it goes up to 24.47 km/h in June. The lowest wind speeds occur during October and November, with speeds dropping to 10 km/h to13 km/h. It shows post-monsoonal atmospheric stability. These moderate wind conditions near the coastal area, particularly during May to July play a crucial role in shaping coastal sediment redistribution and erosion patterns along the shoreline.

Wind direction:

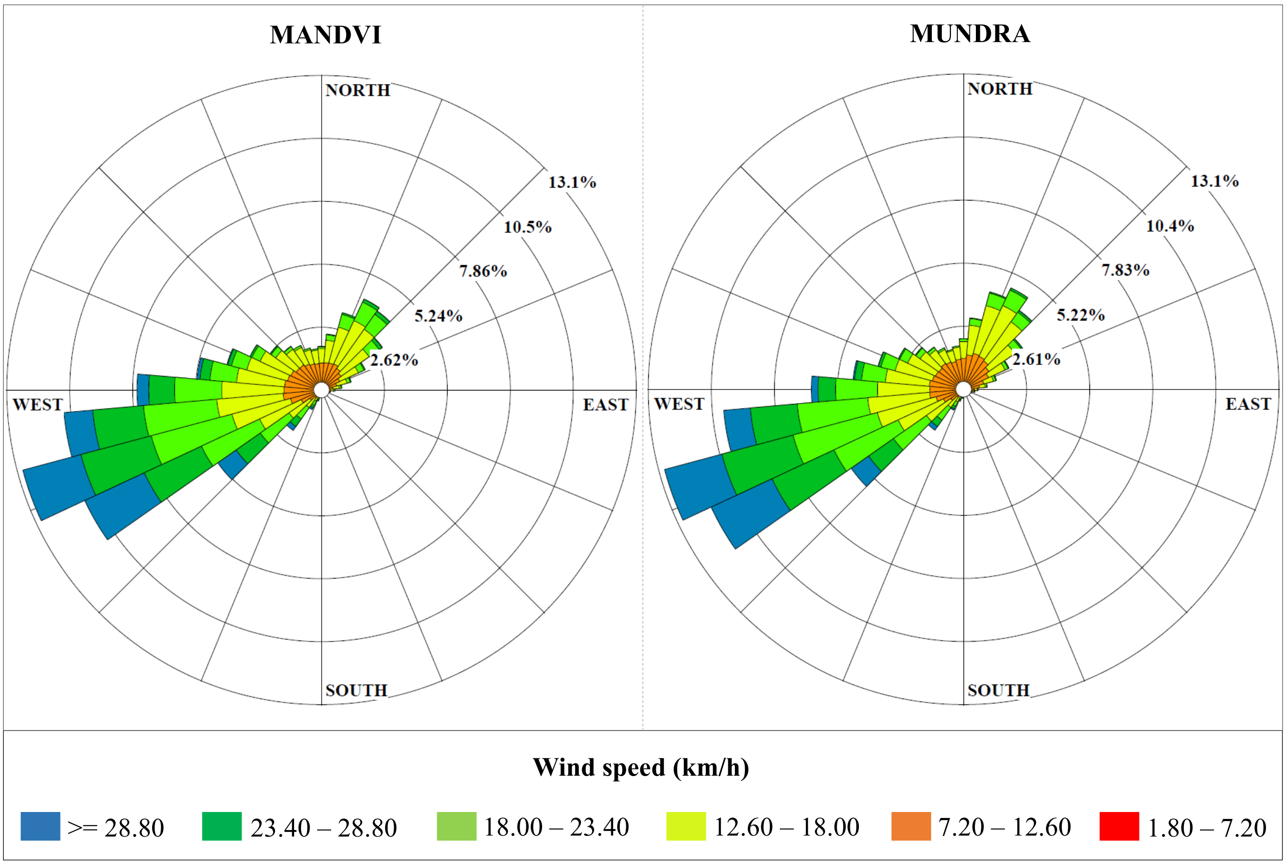


Figure 3.2.6.5: Wind Rose Diagrams of Mandvi and Mundra Based on Hourly Wind Data (2001–2024). (*Source: NASA POWER (DAV) – Base Data; Figure Prepared by the Author*)

The above wind rose diagrams are generated for Mandvi and Mundra talukas using hourly data from NASA POWER (2001 to 2024) which show that the predominant wind directions are from the southwest (SW) to west-southwest (WSW). These directions are most frequent during the monsoon season (June to September) and are aligned with the southwest monsoonal flow from the Arabian Sea. In the post-monsoon period (from October to November), change in the wind pattern can be observed with a gradual shift toward north (N) and north-east (NE) directions. The wind speed in these directions is week. The recorded average wind speed is 17.21 km/h in Mandvi and 16.81 km/h in Mundra, with wind speeds increasing up to 24 km/h which is common during monsoon months.

Seasonal characteristics of climate in Mandvi and Mundra talukas:

During winter (December to February) the both talukas experience mild temperatures with monthly averages ranging from 20.4°C to 23.1°C and minimum temperatures dropping around 14.9°C. Humidity remains low (38% to 46%) with low wind speeds (from 13 km/h to 14 km/h). Rainfall is virtually absent in winter season which results into cool and dry conditions.

In the pre-monsoon season (March to May) temperatures rise rapidly, reaching monthly maximums of 33.6°C to 35.9°C. Humidity gradually increases (40% to71%) as the region approaches to the monsoon. Wind speeds start to increase from 13 km/h to 24 km/h in May, while rainfall remains negligible. These create hot and dry conditions with gradually increasing surface winds.

Monsoon (June to August), the wet season, with the highest rainfall recorded in July (169 mm to 197 mm) and August (150 mm to178 mm). Humidity also increases at 80% to 83% with moderate to high wind speeds (20 km/h to 28 km/h). Temperatures moderate slightly, with averages between 27.0°C and 30.0°C due to increased cloud cover and precipitation.

During post-monsoon (September to November) temperatures begin to decline with an average between 24.0°C and 29.0°C and humidity also falls around 70% to 40 %. Rainfall drops sharply with only minor showers (3 mm to 8 mm) with a decreasing wind speed. These result in more stable atmospheric conditions and a transition into the winter season.

These climatic characteristics play a critical role in shaping the environmental and geomorphological features of the study area. It also shapes the coastal areas of the Mandvi-Mundra region.

3.2.7 Tidal influence in Mandvi and Mundra talukas

As per Mahapatra et al., 2015 tidal energy and variation significantly affect low-lying coastal areas in Gujrat district, especially when combined with wave height and slope. This study used a GIS-based Coastal Vulnerability Index (CVI) and considered tidal range as one of the core parameters in assessing vulnerability. The report, ICMAM-PD, 2001 shows that how tidal inundation is a threat to mangrove belts in Mandvi–Mundra. The degradation of these buffers increases vulnerability to tides and storm surges which further increase the coastal erosion. This is why understanding the influence of tides is very important in coastal erosion analysis.

The daily tidal data for the year 2024 are generated using WXtide32, a publicly available tidal prediction software. From the daily tidal data (two high tide and two low tides for each day) the highest high tide and lowest low tide value are considered to analyse tidal influence in Mandvi-Mundra region.

Table 3.2.7: Average tidal data of Mandvi–Mundra region.

Month	Average high tide (m)	Average low tide (m)	Average tidal range (m)
January	5.6	1.08	4.52
February	5.57	1.15	4.42
March	5.50	1.11	4.39
April	5.58	1.15	4.43
May	5.65	1.18	4.47
June	5.66	1.05	4.61
July	5.59	1.19	4.40
August	5.55	1.12	4.43
September	5.52	1.28	4.24
October	5.53	1.10	4.43
November	5.56	1.02	4.54
December	5.61	0.96	4.65

(*Source: WXtide32, tidal prediction software – Base Data; Table compiled by the Author*)

The average tidal data table are computed from the daily tidal dataset of 2024. As per the data table the average high tide height is near about 5.5 m throughout the whole year, 2024 while the average low tide height is 1.1 m throughout the whole year, 2024. The average tidal range throughout the whole year, 2024 is 4.4 m. The highest average high tide height can be observed in June (5.66 m) while the lowest average low tide height can be observed in December (0.96 m). Tidal range peaks in June (4.61 m) and December (4.65 m), indicating stronger tidal action during early monsoon onset and early winter months. Lowest tidal range is observed in September (4.24 m), coinciding with the late monsoon season and higher river discharge, potentially reducing the difference between high and low tide levels.

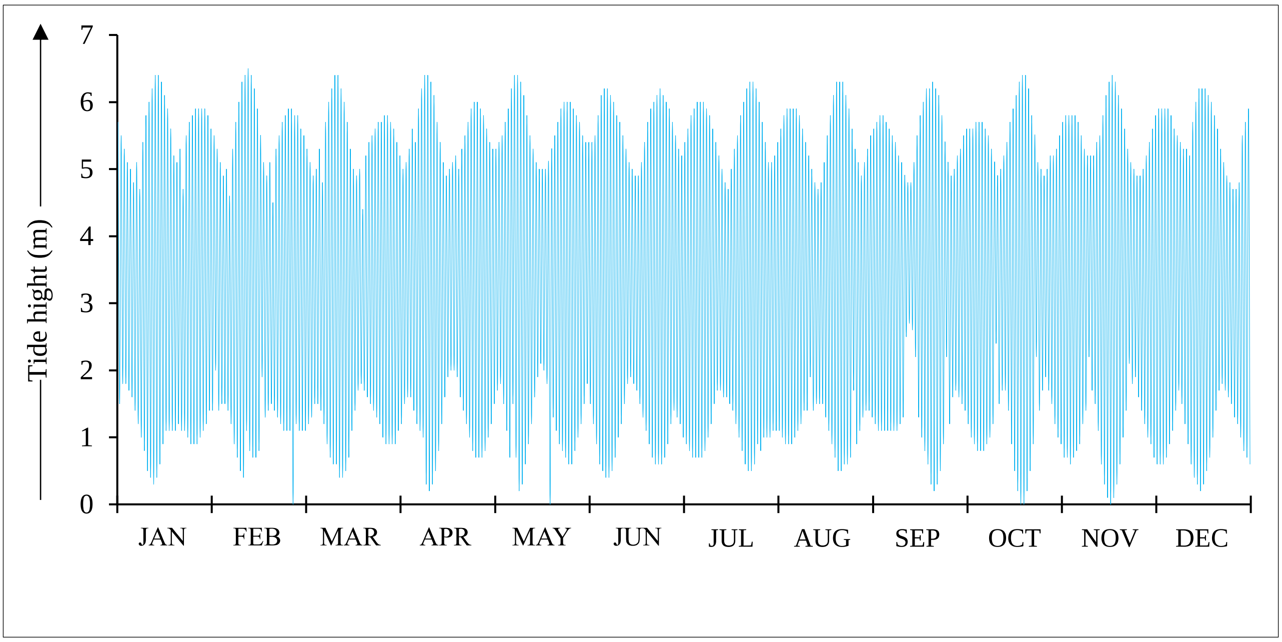


Figure 3.2.7.1: Daily highest high tide height and lowest low tide height for the year 2024 in Mandvi-Mundra region. (*Source: WXtide32, tidal prediction software – Base Data; Figure Prepared by the Author*)

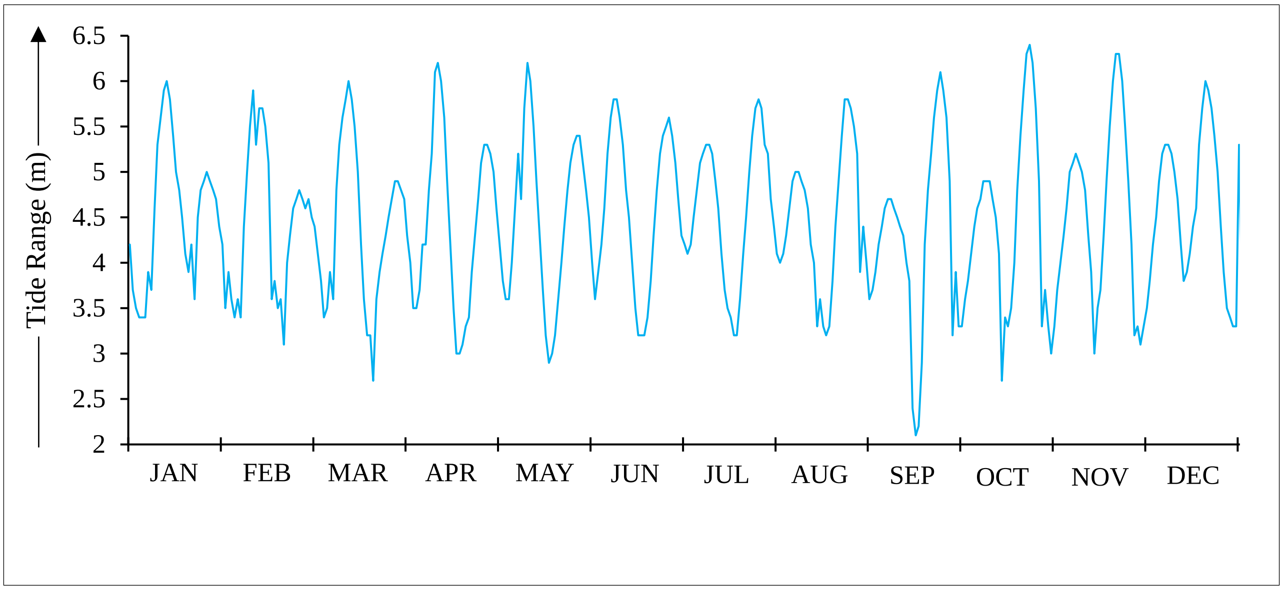


Figure 3.2.7.2: Daily tidal range for the year 2024 in Mandvi-Mundra region. (*Source: WXtide32, tidal prediction software – Base Data; Figure Prepared by the Author*)

Tides play a crucial role in shaping the dynamic coastal environment of the Mandvi–Mundra region. Based on daily tidal data for the entire year of 2024, a semi-diurnal tidal pattern, with two high tides and two low tides occurring each day can be observed.

3.2.8 Biotic elements of Mandvi and Mundra talukas

The various living components of an ecosystem are often regarded as essential indicators of environmental health. Mandvi and Mundra, situated in western India along the Gulf of Kachchh are recognized for their biodiversity though they are located in a semi-arid zone. Several studies have been conducted to document the floral and faunal wealth of these talukas. Here, findings from multiple sources have been simplified and compiled to present a clear overview on biodiversity of Mandvi and Mundra.

Floral composition of Mandvi taluka:

Forest and wild flora: A total of 145 plant species belonging to 117 genera and 51 families have been recorded from Mandvi forest areas (Malsatar & Mehta, 2019). Among these, trees were represented by 53 species, shrubs by 32 species, herbs by 46 species and climbers by 14 species. The majority of the recorded plants were phanerophytes followed by therophytes. Species such as *Acacia nilotica*, *Azadirachta indica* and *Butea monosperma* were frequently encountered. An ecological assessment of the Gulf of Kachchh further indicated that the Mandvi taluka supports dense (2.57 km^2) and sparse (7.34 km^2) mangrove cover along with over 169 km^2 of mudflats (ICMAM-PD, 2002).

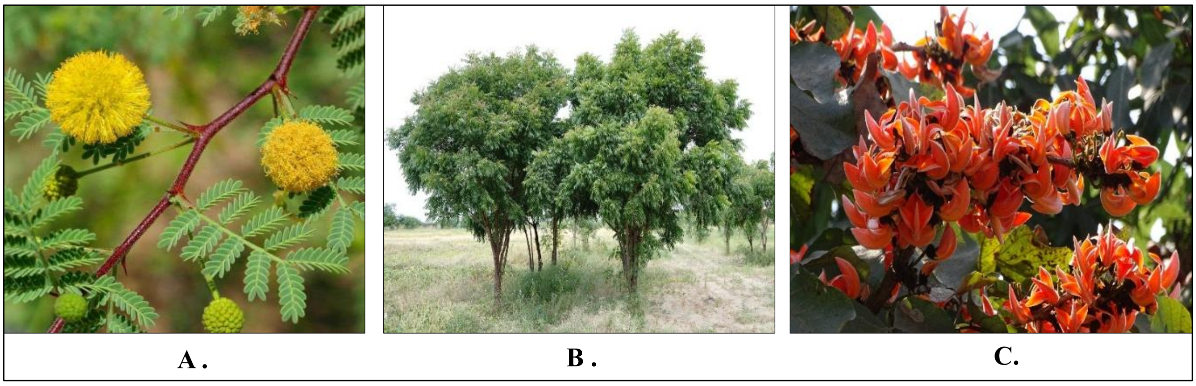


Figure 3.2.8.1: Major forest and wild flora of Mandvi taluka: **A.** *Acacia nilotica* (deshibavl), **B.** *Azadirachta indica* (limado), **C.** *Butea monosperma* (khakhro). (*Source: India Biodiversity Portal*)

Urban flora: Urban flora has also been documented in various public and institutional areas. A total of 71 plant species were reported from campuses such as Government Science College and ITI Mandvi (Kachhot et al., 2019). The most common families identified in urban areas included Fabaceae and Poaceae.

Sacred groves: Traditional sacred groves in Mandvi have been preserved through community practices and cultural beliefs. A total of 14 sacred groves were reported where native trees like *Ficus religiosa*, *Prosopis cineraria* and *Ziziphus nummularia* have been traditionally protected (Gadhavi & Mehta, 2019). These areas serve as biodiversity reservoirs and reflect the close relationship between ecological conservation and cultural heritage.

Figure 3.2.8.2: Sacred groves in Mandvi taluka: **A.** Yaa sultanshah pir dargah sacred grove, **B.** Ganga maa and Avad maa sacred grove. (*Source: Gadhavi& Mehta, 2019*).

Halophytes and mangroves: Mangrove and halophyte vegetation have been commonly found in the coastal areas of Mandvi. *Avicennia marina* has been identified as the dominant mangrove species while *Suaeda nudiflora* has been frequently observed as a salt-tolerant halophyte (Vyas et al., 2018). These plants are adapted to saline conditions and contribute to coastal stability. These ecosystems serve as nursery habitats for molluscs, fishes and other marine organisms.

A. B.

Figure 3.2.8.3: Coastal flora of Mandvi taluka: **A.** *Suaeda nudiflora*, **B.** *Avicennia marina*. (*Source: Earthpedia*)

Faunal composition of Mandvi taluka:

Marine and intertidal fauna: A study was conducted in which 43 species of intertidal organisms were recorded which includes molluscs, crustaceans and polychaetes (Pandya et al., 2021). Species such as *Umbonium vestiarium*, *Cerithidea cingulata* and *Dotilla* sp. were documented. The diversity was found to be lower at the Mandvi beach which happened due to increasing tourist activity.

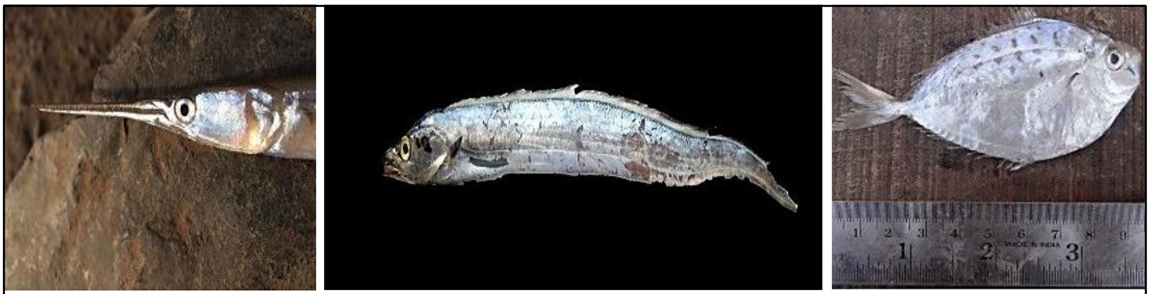
A. B.

Figure 3.2.8.4: Marine fauna of Mandvi beach: **A.** *Umbonium vestiarium*, **B.** *Cerithidea cingulata*. (*Source: Biolib.cz*)

Macrobenthic ecology: A total of 42 taxa of macrobenthic organisms were observed in a separate study (Thivakaran & Kundu, 2011). Seasonal variations in their density and distribution were noted. Crustaceans and polychaetes were found to be the dominant groups.

Ichthyofauna and coastal marine ecosystem: A detailed study of the ichthyofaunal diversity at Mandvi and Jakhau coasts revealed a total of 96 marine fish species out of which 77 species were observed at Mandvi alone (Sidat et al., 2021). These species belonged to 20 orders and 47 families with Carangidae being the most dominant family. Several species were classified under conservation categories such as vulnerable, endangered and critically endangered. Additionally, the presence of

Deveximentum indicium was recorded for the first time in the Gulf of Kachchh which highlights the ecological importance of the Mandvi coast.



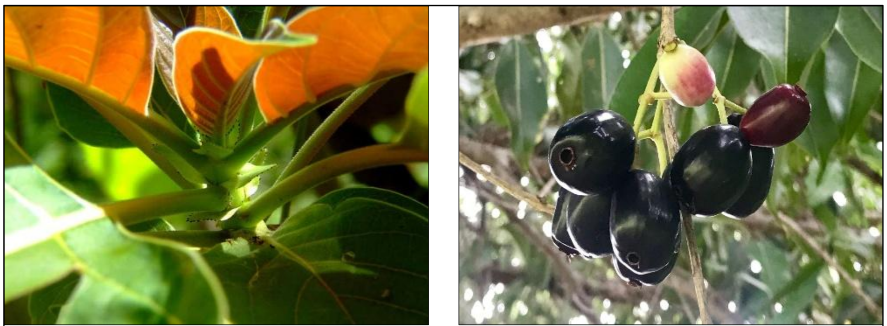
A. B. C.

Figure 3.2.8.5: Ichthyofaunal diversity at Mandvi coast: **A.** *Strongylura strongylura*, **B.** *Lepturacanthus savala*, **C.** *Deveximentum indicium*. (*Source*: *Sidat et al., 2021*)

The biodiversity of Mandvi was seen to be under threat from human activities such as tourism and urban expansion. Lower diversity and biomass in certain areas indicated signs of ecological stress (Pandya et al., 2021). The biodiversity of Mandvi includes a wide variety of plant and animal life supported by forest, urban, sacred and marine ecosystems. The unique ecological and cultural elements which are found in this region highlight the need for more focused conservation strategies.

Floral composition of Mundra taluka:

Forest and wild flora: The wild flora of Mundra is mainly found in small forest patches and in sacred groves protected by local communities. In total, 32 sacred groves were documented in 18 villages of Mundra. These groves covered about 12.8 hectares and contained 16 different tree species (Malsatar & Mehta, 2023). Trees such as *Ficus benghalensis, Azadirachta indica*, *Syzygium cumini* and *Prosopis cineraria* were most commonly found. Although thick forests are not seen in Mundra, patches of tropical thorn forest have been reported in earlier studies (Malsatar & Mehta, 2019). These dryland species have been adapted to survive in low-moisture and high-salinity conditions.



A. B.

Figure 3.2.8.6: Wild flora of Mundra taluka: **A.** *Ficus benghalensis* (vad), **B.** *Syzygium cumini* (jambu). (*Source: Earthpedia*)

Mangroves and halophytes: Along the coast of Mundra, important mangrove patches can be observed. These are mostly made up of the species *Avicennia marina* which is known to tolerate very high salt levels (Gujarat Ecology Society, 2002). Other mangrove species like *Rhizophora mucronata* and *Ceriops tagal* have been recorded as vulnerable whereas *Aegiceras corniculatum* has been considered endangered in the area. The mangroves are usually short in height and grow in patchy stands because of grazing and past overuse. In some places, halophytic plants such as *Salicornia brachiata* have also been seen. These plants have adapted to grow in salty soil and help prevent erosion of the mudflats (Panda, 2007).

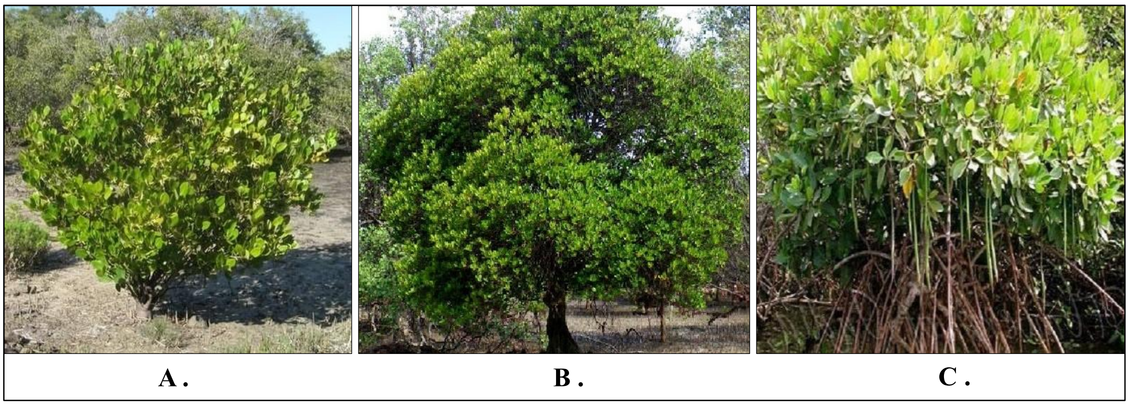


Figure 3.2.8.7: Mangroves along Mundra coast: **A.** *Aegiceras corniculatum*, **B.** *Ceriops tagal*, **C.** *Rhizophora mucronata*. (*Source: Forestrypedia*)

Faunal composition of Mundra taluka:

Marine and intertidal biodiversity: The marine life around Mundra has been supported by the presence of rich mudflats, mangroves and even coral patches. Macrobenthic organisms such as molluscs, polychaetes and crustaceans have been recorded from the intertidal zone. A total of 42 taxa were reported in a study carried out at three coastal sites including Mundra. Crustaceans made up the largest group while molluscs and polychaetes followed in number (Thivakaran & Kundu, 2011). Seasonal changes in density were also observed.

Live coral reefs have been found off the coast of Mundra during surveys conducted between 1999 and 2000. These reefs were found to cover nearly 8 km^2 and were home to corals like Tubastraea, Favia and soft corals such as Dendronephthya (Gujarat Ecology Society, 2002). Associated species included sea urchins, sponges, sea cucumbers and different algae. This habitat provides support to fish breeding and it is important for marine biodiversity.

In the marine zone, sea turtles have been seen nesting on the coast of Mundra. Mainly Olive ridley turtles have been reported and their nesting is believed to be affected by port development and other human activities in the coastal area(Santha, 2014).

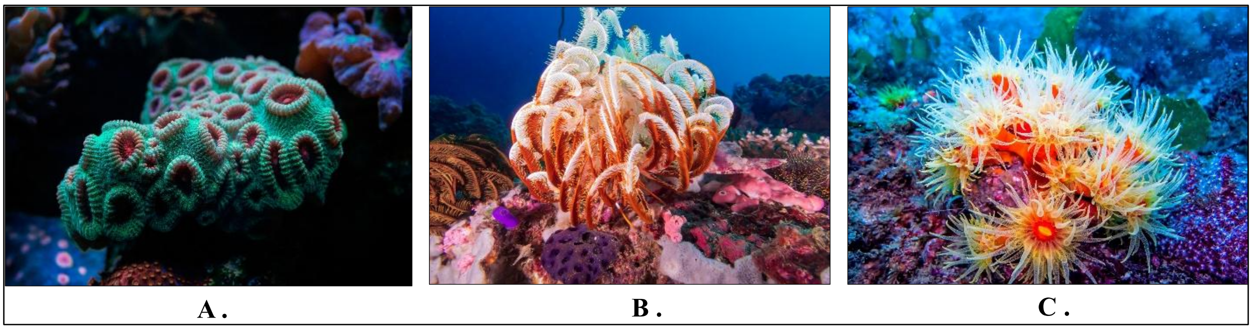


Figure 3.2.8.8: Corals around Mundra coast: **A.** Favia, **B.** Dendronephthya, **C.** Tubastraea. (*Source: Earthpedia*)

Avifaunal Diversity: Several species found in and around Mundra have been classified as threatened. Among them, the *Ardeotis nigriceps* and the *Sypheotides indica* are of special concern. These birds depend on grassland habitats that are becoming rare in Kachchh (Rahmani, 2012). Although these species are not coastal. Their presence near Mundra shows the ecological importance of the larger landscape. Migratory birds like flamingos and pelicans are also commonly seen in the wetland and saltpan areas of Mundra coast.

Figure 3.2.8.9: Avifaunal species around Mundra: **A.** *Ardeotis nigriceps*, **B.** *Sypheotides indica*. (*Source: India Biodiversity Portal, eBird*)

Mundra has experienced major changes in the last two decades because of port development, industrial growth and coastal infrastructure projects. Many of the natural mangrove trees have been cut or buried under reclaimed land. Studies have shown that almost 22.6% of mangrove trees in the area were removed during earlier years (Panda, 2007). Tidal flow has been blocked in some areas by sea walls. This has led to drying of mangrove roots and further degradation of the habitat.

Fishing communities like the Wagher have reported a decline in fish catch. Coral reefs and mudflats have been threatened by dredging, pollution and increased boat traffic. Conservation steps like replanting mangroves, creating buffer zones and setting up marine protected areas can be suggested. It has also been recommended that local knowledge should be included in decision-making and in this way community-based resource management will be helpful for protection of Mundra's biodiversity.

3.3 Human Environment

The human environment of Mandvi and Mundra talukas has been shaped by the interaction between natural resources and human activities. Over the past few decades these talukas have experienced population growth, expansion of settlements and the development of industries and infrastructure. These have significantly changed the socio-economic landscape of the region. These talukas include both rural and urban areas with growing towns such as Mandvi and Mundra towns situated along the coast. The demographic characteristics, socio-economic conditions and land use practices reflect the relationship between people and the coastal environment.

3.3.1 Demographic profile of Mandvi and Mundra talukas

The demographic profile offers a comprehensive understanding of the population structure in both Mandvi and Mundra talukas. This includes key indicators such as population distribution, caste composition, religious composition, sex ratio, literacy rate and language. These variables help in understanding the human environment and planning for future developmental needs.

Rural-urban composition:

Table 3.3.4.1: Rural–urban population composition in Mandvi and Mundra talukas.

Sl. No.	Indicator	MANDVI			MUNDRA		
		Total	Rural	Urban	Total	Rural	Urban
1	**Area in km^2**	1406.17	1391.28	14.89	888.15	867.4	20.75
2	**Inhabited villages**	92	92	-	59	59	-
3	**Uninhabited villages**	2	2	-	3	3	-
4	**Number of statutory towns**	1	-	1	-	-	-
5	**Number of census towns**	-	-	-	1	-	1
6	**Number of house-holds**	41854	31508	10346	34832	30454	4378
7	**Total population**	203373	151997	51376	153219	132881	20338
8	**Population density**	145	109	3450	173	153	980

(*Source: District Census Handbook Kachchh 2011 PART-XII-A– Base Data; Table compiled by the Author*)

As per the District Census Handbook Kachchh 2011 (Part XII-A), Mandvi taluka covers a geographical area of 1406.17 km^2 while Mundra extends over 888.15 km^2. Both talukas are primarily rural with only a small portion of urban settlements (14.89 km^2 urban area in Mandvi and 20.75 km^2 in Mundra taluk).

In Mandvi, the total population is 2,03,373, of which 1,51,997 (75%) resided in rural areas and 51,376 (25%) resided in the statutory town of Mandvi taluka. The population density of Mandvi taluka is 145 persons/km^2 but in the urban part, it rose sharply to 3450 persons/km^2 which reflects the compactness of urban space.

Mundra has a total population of 1,53,219 with 1,32,881 (87%) living in rural areas and 20,338 (13%) in the census town of Mundra taluka. The population density in Mundra is higher overall (173 persons/km^2) than in Mandvi with 980 persons/km^2 in the urban region.

Mandvi has 92 inhabited villages while Mundra has 59 inhabited villages. In addition, a few uninhabited villages are reported in both talukas. The number of households in Mandvi taluka is 41,854 among which 10,346 are urban households whereas Mundra has 34,832 households with 4,378 urban households.

Notably, the presence of one statutory town in Mandvi taluka named, Mandvi town and one census town in Mundra taluka called, Mundra town highlights the ongoing urban transition in both areas. Both towns are situated near the coastal area of the talukas.

Caste composition:

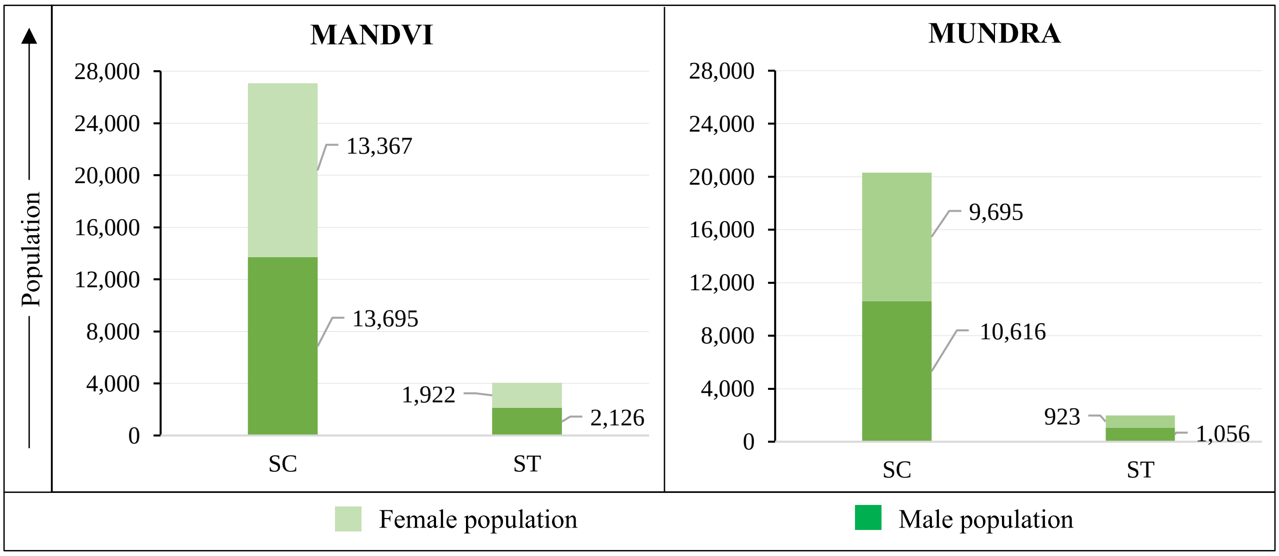


Figure 3.3.1.1: Caste population of Mandvi and Mundra talukas. (*Source: District Census Handbook Kachchh 2011 PART-XII-A– Base Data; Figure compiled by the Author*).

The caste composition of both Mandvi and Mundra talukas reflects the presence of marginalized communities, particularly the Scheduled Castes (SC) and Scheduled Tribes (ST). In Mandvi, the SC population stands at 27,062 which is almost equally divided between males (13,695) and females (13,367). The ST population in the taluka is comparatively lower which is 4,048. This is also almost equally distributed between males (2,126) and females (1,922).

In Mundra taluka, the Scheduled Caste population is 20,311 with 10,616 males and 9,695 females. The Scheduled Tribe population here is 1,979 including 1,056 males and 923 females. These figures indicate that SC population form a more significant proportion of the population in both talukas compared to ST population.

Religious Composition:

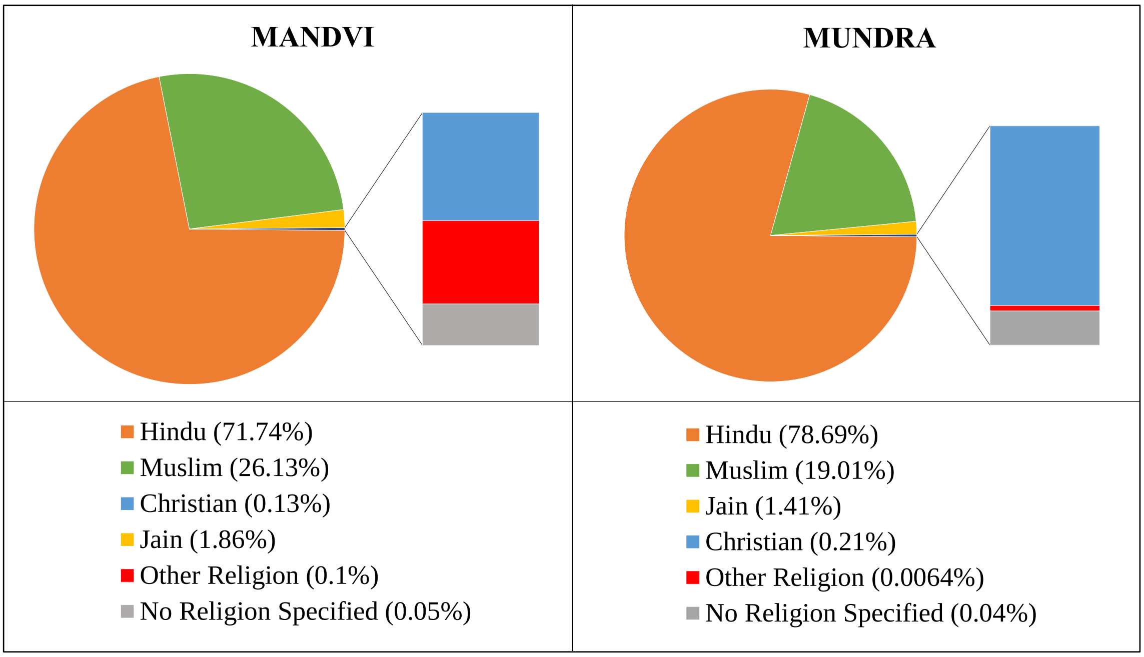


Figure 3.3.1.2: Religion wise population of Mandvi and Mundra talukas. (*Source: District Census Handbook Kachchh 2011 PART-XII-A– Base Data; Figure compiled by the Author*).

The population of both Mandvi and Mundra talukas is religiously diverse though the main religion, practiced by maximum people in these talukas is Hinduism. In Mandvi Taluka, the Hindu population is approximately 71.74% of the total, followed by Muslims (26.13%), Jains (1.86%) and a very small percentage of Christians (0.13%) and other religions (0.1%).

In contrast, Mundra Taluka shows a slightly higher proportion of Hindus which is 78.69% of total, while the Muslim community covers 19.01%. The presence of Jains (1.41%), Christians (0.21%) and others (0.01%) is relatively limited.

This composition reflects the broader cultural and religious diversity of the Mandvi-Mundra region with Hinduism being the dominant faith in both talukas.

Sex ratio:

Table 3.3.12.2: Sex ratio in Mandvi and Mundra talukas.

Sl. No.	Indicators	MANDVI			MUNDRA		
		Persons	Males	Females	Persons	Males	Females
1	**Total population in all age group**	203373	103983	99390	153219	89871	63348
2	**Sex ratio for all age group**	956			705		
3	**Total population in 0-6 age group**	27256	14114	13142	21623	11206	10417
4	**Sex ratio for 0-6 age group**	931			930		

(*Source: District Census Handbook Kachchh 2011 PART-XII-A– Base Data; Table compiled by the Author*)

The sex ratio of Mandvi taluka has been recorded at 956 females per 1000 males which indicates a relatively balanced demographic composition. In contrast, Mundra taluka shows a significantly lower sex ratio of 705 females per 1000 males which highlights a sharp gender imbalance.

Among the 0–6 age group, the sex ratio in Mandvi stands at 931 while Mundra reflects a slightly lower value of 930. These figures suggest that even in the younger population the gender disparity continues especially in Mundra. This demographic trend may require attention for future planning and gender focused welfare programs to decrease the gender disparity.

Literacy rate:

Table 3.3.19.3: Literacy rate in Mandvi and Mundra talukas.

Sl. No.	Indicators	Mandvi			Mundra		
		Persons	Males	Females	Persons	Males	Females
1	**Number of literates**	132274	74801	57473	101793	66815	34978
2	**Number of illiterates**	71099	29182	41917	51426	23056	28370
3	**Literacy rate (%)**	75.11	83.23	66.64	77.35	84.94	66.08
4	**Gap in male-female literacy rate**	16.59			18.86		

(*Source: District Census Handbook Kachchh 2011 PART-XII-A– Base Data; Table compiled by the Author*)

A significant variation has been observed in literacy levels between Mandvi and Mundra talukas. In Mandvi, the overall literacy rate stands at 75.11% with male literacy recorded at 83.23% and female literacy at 66.64% which shows a gender literacy gap of 16.59%. In contrast, Mundra taluka has a slightly higher overall literacy rate of 77.35% with males at 84.94% and females at 66.08% which reflects a wider gap of 18.86% between genders. While both talukas show similar trends of male-dominated literacy, the gap in Mundra indicates greater disparity in terms of literacy. Female literacy in both regions remains significantly lower than male literacy which suggests persistent gender-based educational inequality.

Linguistic composition:

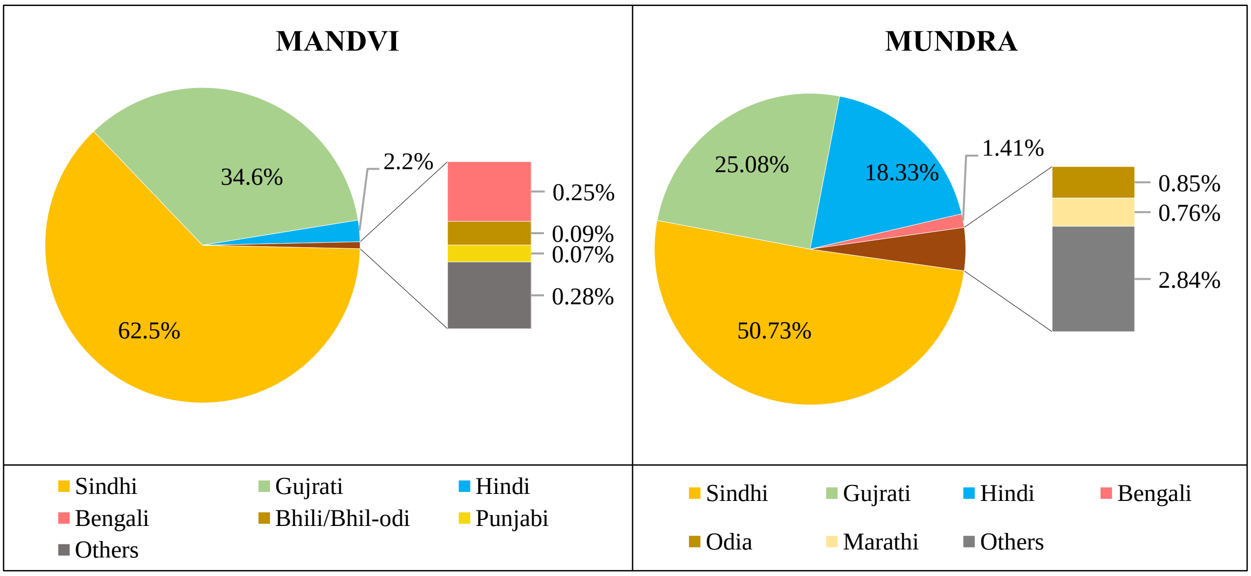


Figure 3.3.1.3: Linguistic composition of Mandvi and Mundra talukas. (*Source: District Census Handbook Kachchh 2011 PART-XII-A– Base Data; Figure compiled by the Author*)

The language distribution in Mandvi and Mundra Talukas shows regional diversity. In Mandvi, the most spoken mother tongue is Sindhi (62.5%), followed by Gujarati (34.6%) and Hindi (2.2%). Other minor language groups include Bengali, Bhili, Punjabi and Others. In Mundra, Sindhi (50.73%) and Gujarati (25.08%) are again the two leading languages, while Hindi (18.33%) is also significant in Mundra taluka. Smaller numbers of people speak Bengali, Odia, Marathi and Others.

The data shows that while both talukas share a similar linguistic base dominated by Sindhi and Gujarati, Mundra shows a slightly higher share of speakers from eastern and central Indian language groups, due to recent labour migrations connected to industrial and port-based employment. This linguistic variety has contributed to a vibrant socio-cultural environment in both talukas which show their importance as coastal settlements with regional economic significance. This distribution reflects both regional identity and migration-related diversity across both talukas.

Population growth rate of Mandvi and Mundra towns:

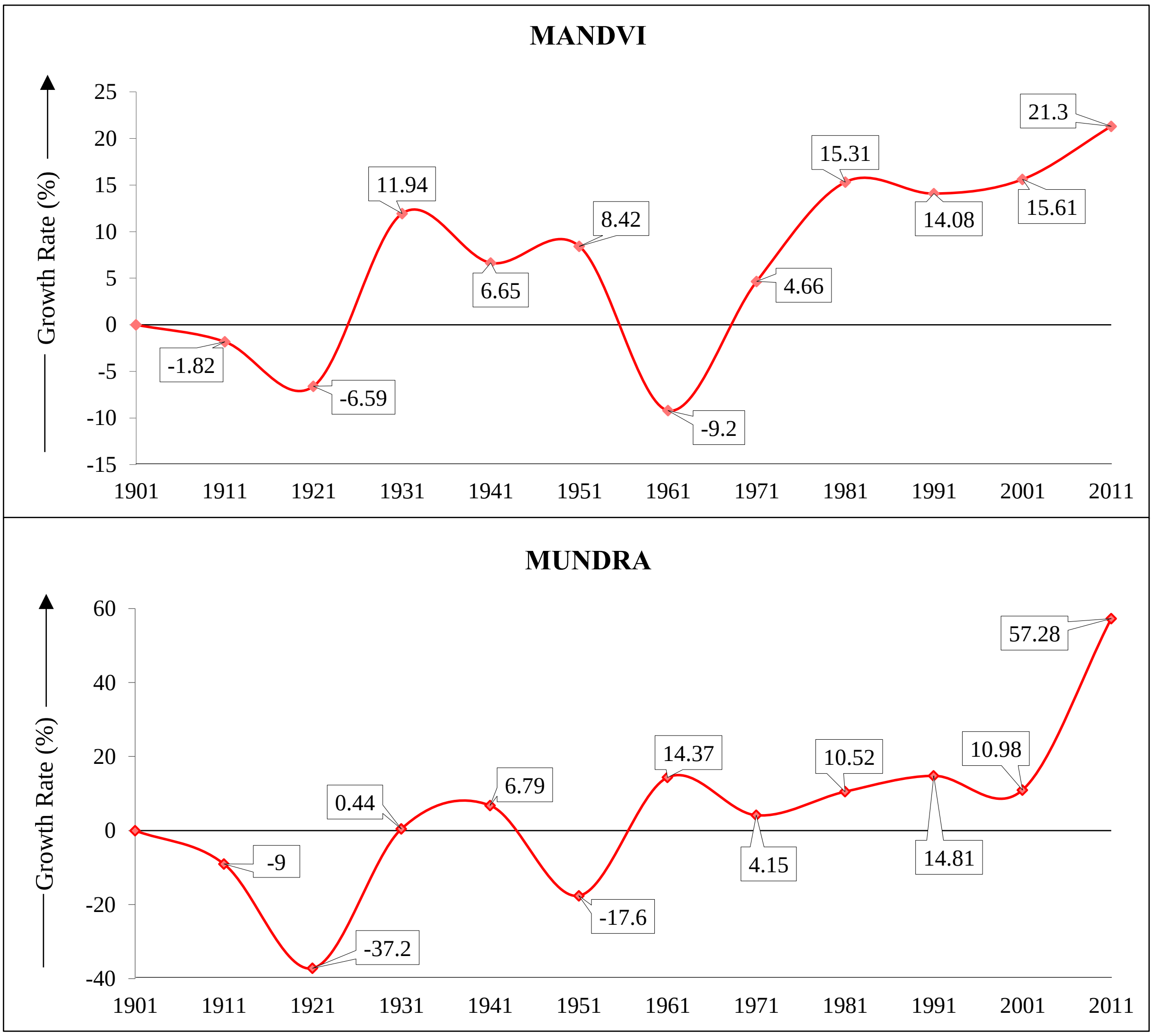


Figure 3.3.1.4: Population growth rate of Mandvi town and Mundra town. (*Source: District Census Handbook Kachchh 2010 PART-XII-A & B; District Census Handbook Kachchh 2011 PART-XII-A–Base Data; Figure compiled by the Author*)

The historical population growth of Mandvi town and Mundra town between from census year 1901 to census year 2011 shows significant demographic transitions shaped by urban dynamics, port activities and economic changes in coastal Kachchh.

In Mandvi town, the population increased from 24,683 in 1901 to 51,376 in 2011. The early decades witnessed fluctuations, including declines in 1911 (-1.82%), 1921 (-6.59%) and 1961 (-9.2%). However, from the 1980s onward the town experienced consistent growth. Which is prominent during 2001 (15.61%) and 2011 (21.3%) which suggests improvements in civic infrastructure, trade connectivity and port establishment.

On the other hand, Mundra town showed a more volatile growth trajectory. Its population decreased sharply in 1921 (-37.2%) and 1951 (-17.6%). However, a demographic shift began after 1961, with an extraordinary growth rate of 57.28% in 2011. This dramatic rise can be attributed to the rapid industrial development around Mundra Port, which transformed the town into a major economic hub which attracts workforce migration and urban expansion. The contrasting trends show the relatively stable but gradual urban growth in Mandvi town and the industrial boom-led massive growth in Mundra town particularly in the last two census years.

3.3.2 Economic profile of Mandvi and Mundra talukas

The economic structure of Mandvi and Mundra talukas has been shaped by a combination of traditional livelihoods and growing industrial activities. While Mandvi has historically depended on shipbuilding, fishing, agriculture and small-scale trade, Mundra has experienced significant transformation due to industrialization and port-based development. In both talukas, the workforce is distributed across primary, secondary and tertiary sectors which reflects regional variations in resources and development. The economic profile focuses on workforce composition, major industries and livelihood and transport linkages that contribute to the economic landscape of the region.

Workforce composition:

Table 3.3.2.1: Workforce composition in Mandvi and Mundra taluk.

Sl. No.	Indicators	MANDVI			MUNDRA		
		Persons	Males	Females	Persons	Males	Females
1	**Total workers**	80082	59566	20516	69603	60612	8991
2	**Non-workers**	123291	44417	78874	83616	29259	54357
3	**Marginal workers**	12512	3748	8764	5041	2258	2783
4	**Main workers**	67570	55818	11752	64562	58354	6208
5	**Category of workers**						
5.i	**Cultivators**	11943	9377	2566	6920	5966	954
5.ii	**Agricultural labourers**	23680	13595	10085	9393	6253	3140
5.iii	**Household industry workers**	1472	579	893	929	260	669
5.iv	**Other workers**	42987	36015	6972	52361	48133	4228

(*Source: District Census Handbook Kachchh 2011 PART-XII-A – Base Data; Table compiled by the Author*)

The distribution of workers in both Mandvi and Mundra talukas reflects a mixture of traditional and modern occupational patterns. In Mandvi, a total of 80,082 individuals are engaged as workers, while

69,603 individuals are recorded as workers in Mundra taluka. A higher male participation rate is observed in both areas while female workforce contribution is significantly lower especially in Mundra.

Out of the total workforce, the main workers are 67,570 in Mandvi and 64,562 in Mundra. Marginal workers, who are engaged in seasonal or short-term employment are recorded at 12,512 in Mandvi and 5,041 in Mundra.

When categorized by occupation, Mandvi shows a higher reliance on agricultural labourers (23,680) and cultivators (11,943) which includes the persistence of primary sector activities. In contrast, though Mundra has a lower number of cultivators and agricultural workers but it has a considerably higher number of "other workers" (52,361). This reflects the impact of port-based activities, industrial zones and service sector employment in the region.

Female workers are primarily involved in marginal activities and agricultural labour. Mandvi has 10,085 female agricultural labourers, while Mundra has 3,140. The share of household industry workers is minimal in both regions with only 1,472 in Mandvi and 929 in Mundra.

Overall, the economic activities in Mandvi remain anchored in agriculture while Mundra shows signs of transition towards a diversified and industrially influenced economy.

Industries and livelihoods:

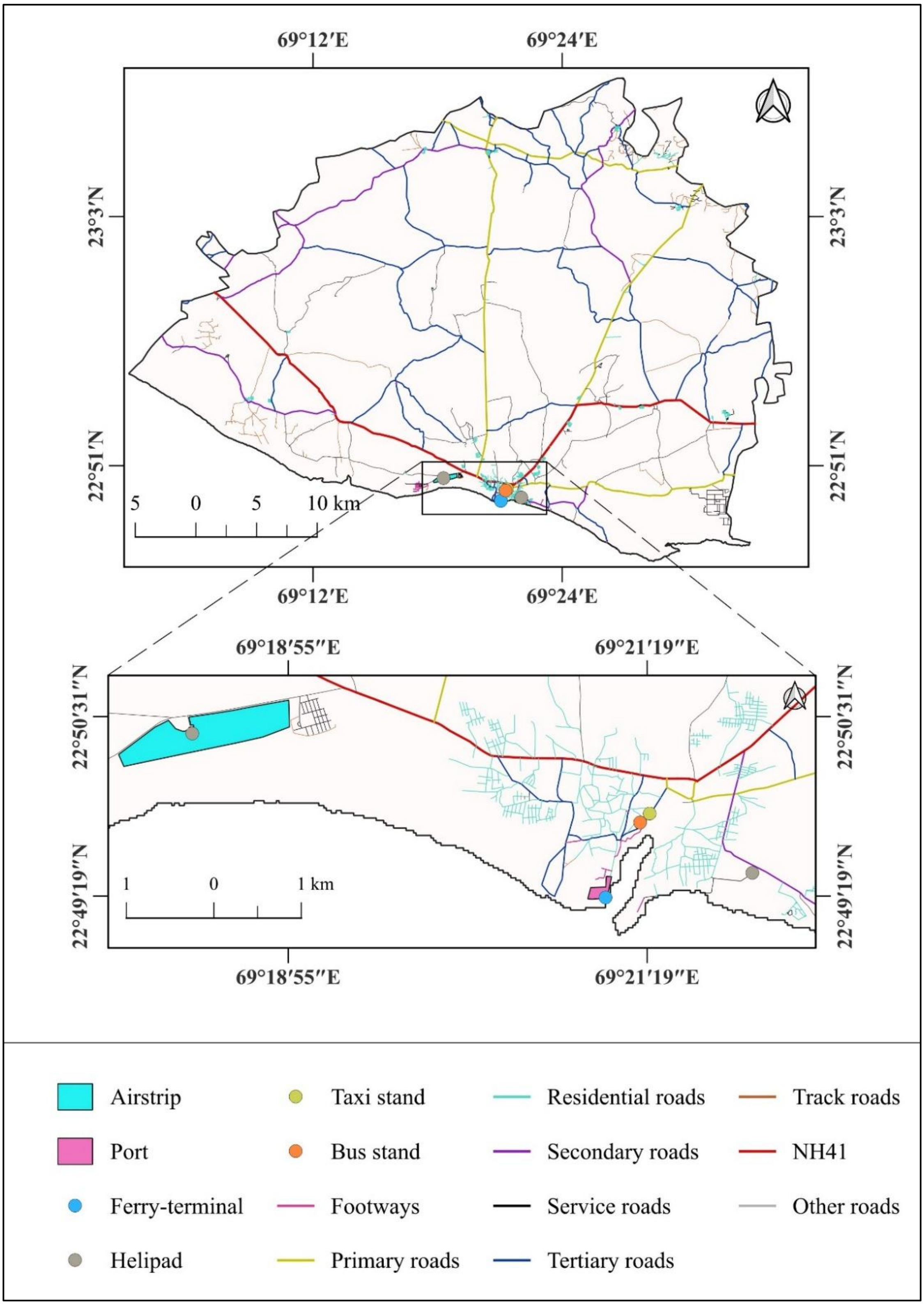
The economic profile of both Mandvi and Mundra towns is influenced by region-specific small and medium-scale industries. These industries have developed in response to local resource availability, traditional skills of individuals and market linkages.

As per, District Census Handbook Kachchh, 2011 in Mandvi town, industrial activities have primarily revolved around the processing of edible oil, the production of cement bricks and the utilization of mineral resources. The Mandvi taluka is also famous for its very old shipbuilding industries which are local in nature.

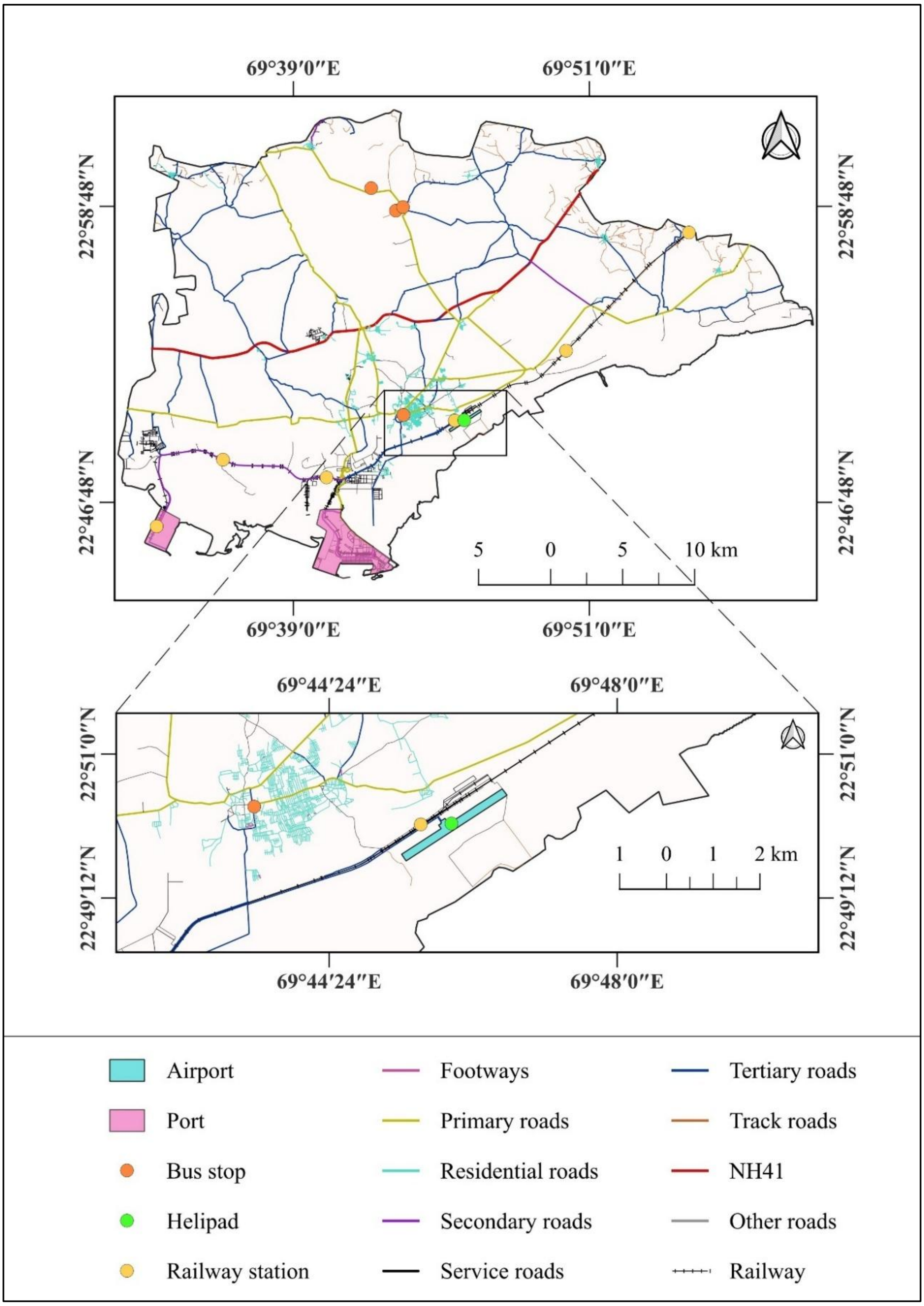
On the other hand, the Mundra town has gained its identity as a centre of traditional textile printing, particularly the renowned Ajrakh, Batique and Bandhani art forms. These crafts have not only supported household-level production but also attracted attention for their cultural and commercial value. Additionally, salt production is a significant industrial activity in the coastal and low-lying areas of Mundra. The fisheries sector also plays a crucial role in the local economy (District Census Handbook Kachchh, 2011).

Transportation and connectivity:

Transport network is an essential part of human environment in a region. The more stable transport and connectivity indicate toward more development of infrastructure which results into population growth and urban area spreading. The Mandvi and Mundra talukas' transport network maps are represented below.



Map 3.3.2.1: Transportation and connectivity of Mandvi taluka. (*Source: Open Street Map dataset – Base data; Map Prepared by the Author*).



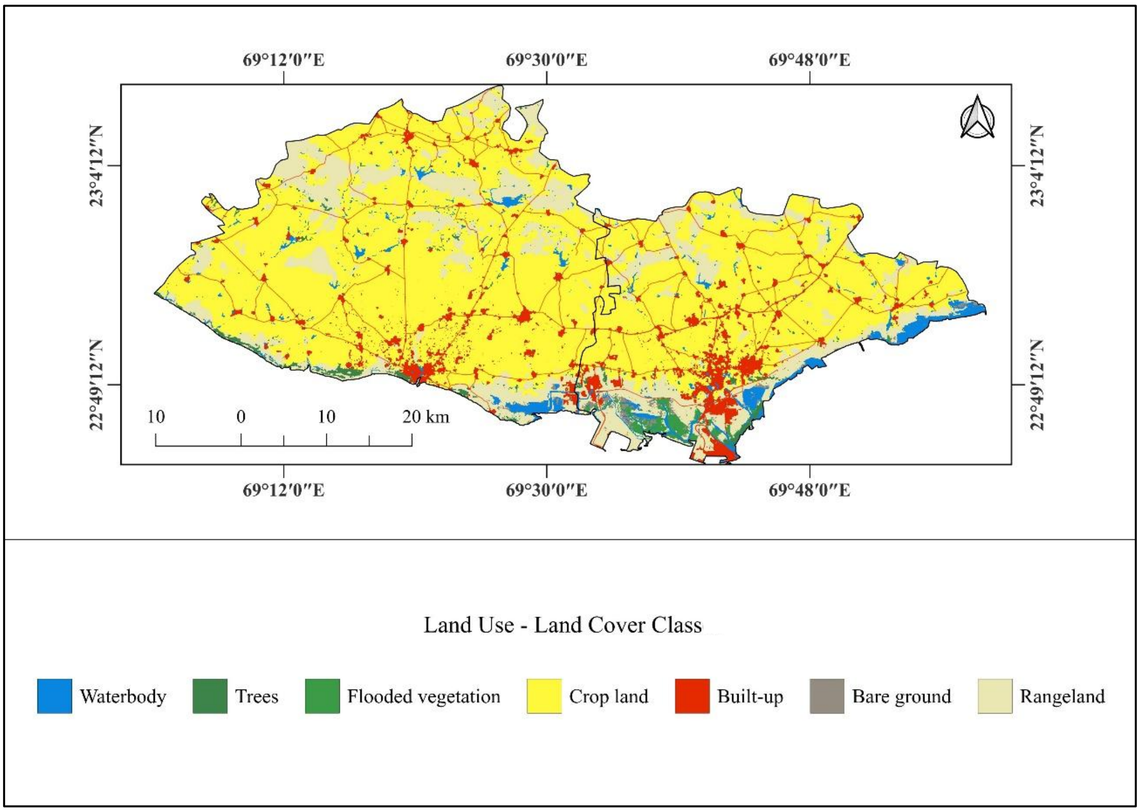
Map (*Source: Open Street Map dataset – Base data; Map Prepared by the Author*).

The transportation infrastructure in Mandvi and Mundra Talukas shows both similarities and little differences which is shaped by geography, urban development and economic activities. In Mandvi Taluka, the transport network is moderately developed with state highways and major district roads serving as the primary means of connectivity. The primary roads connect Mandvi town to major nearby centers like Bhuj and coastal villages. Village roads penetrate the interior regions which enable access to agricultural zones and small-scale industrial units. However, in some remote rural areas, connectivity remains limited. In contrast, Mundra Taluka exhibits a well-developed and dense transportation network, significantly influenced by the presence of the Mundra Port, a major private cargo port in India. The taluka is connected through a combination of highways and rail lines which support both passenger and freight movement. Rail connectivity further boosts Mundra’s role in national and international trade as it connects Mundra with other part of the Gujrat state.

In both talukas, the national highway 41 (NH-41) plays a central role in connectivity. It links Mandvi and Mundra towns to Gandhidham and Kandla, facilitating trade, passenger movement and supply chains. This highway forms the primary route for both domestic logistics and regional access.

Both talukas have ports and airport but Mundra is one step ahead in terms of port for industrial needs and airport which much larger and busier than the airstrip present in Mandvi taluka. While Mandvi's transport system is more aligned with traditional needs and small-town commerce, Mundra's network reflects its growing industrial status and port-based urban centre.

3.3.3 Land use - land cover (LULC) of Mandvi and Mundra talukas



Map 3.3.3: LULC (2024) map of Mandvi and Mundra talukas. (*Source: Esri Land Cover - ArcGIS Living Atlas (2024), Sentinel-2 satellite imagery – Base data; Map Prepared by the Author*)

The Land use - land cover (LULC) analysis for the year 2024 has been conducted for the combined geographical extent of Mandvi and Mundra talukas. The area calculations reflect the total land surface of both talukas together which is approximately 2361.68 km².

Table 3.3.3: LULC classes and area coverage in Mandvi and Mundra talukas.

LULC Class	**Area in km^2**	**Percentage %**
Water body	84.16	3.56
Trees	26.87	1.14
Flooded vegetation	19.38	0.82
Crop land	1629.26	68.99
Built-up	138.19	5.85
Bare ground	15.72	0.67
Range land	448.11	18.97
Total	2361.68	100

(*Source: Esri Land Cover - ArcGIS Living Atlas (2024), Sentinel-2 satellite imagery – Base data; Table Prepared by the Author*)

The Mandvi-Mundra region is predominantly agricultural, with crop land covering 68.99% (1629.26 km²) of the total area. This extensive coverage shows the reliance on farming as a primary land use. Range Land which includes open grazing lands and scrub areas covers 18.97% (448.11 km²) which indicates the presence of semi-natural landscapes. Built-up areas occupy around 5.85% (138.19 km²), largely clustered around the urban centers of Mandvi and Mundra. These areas reflect moderate levels of urban development and associated infrastructure. Water bodies make up 3.56% (84.16 km²) consisting of natural and artificial sources such as rivers, tanks and reservoirs. Vegetation land cover includes trees (1.14%) and flooded vegetation (0.82%), covering 26.87 km² and 19.38 km² respectively. These are primarily found in floodplains and low-lying areas. Bare Ground, covers up to 0.67% (15.72 km²) which represents temporarily exposed soils.

This spatial pattern of land use reflects a diverse rural-urban variety, where agriculture is major part, while urbanization and industrial activities are gradually shaping the land cover especially near coastal and infrastructural corridors.

The detailed examination of the physical and human environment of Mandvi and Mundra talukas has provided a detailed understanding of the study area. The Mandvi-Mundra region shows a dynamic coastal landscape which is shaped by geomorphological and geological variations, tidal forces and semi-arid climatic conditions. Human aspects such as demographic structure, economic activities and land use patterns reveal growing urbanization and industrial development with traditional livelihoods.

CHAPTER 4: RESULT AND DISCUSSION

4.1 Shoreline Change Analysis of Mandvi and Mundra Talukas

Shoreline change analysis has been done to understand the long-term coastal dynamics of Mandvi and Mundra talukas over the past three decades. This analysis helps to identify areas undergoing erosion or accretion and to provide future planning and mitigation strategies. For this purpose, multi-temporal Landsat satellite images from the years 1994, 2004, 2014 and 2024 were used. The High Tide Line (HTL) was considered the main shoreline proxy to ensure consistency in the delineation process.

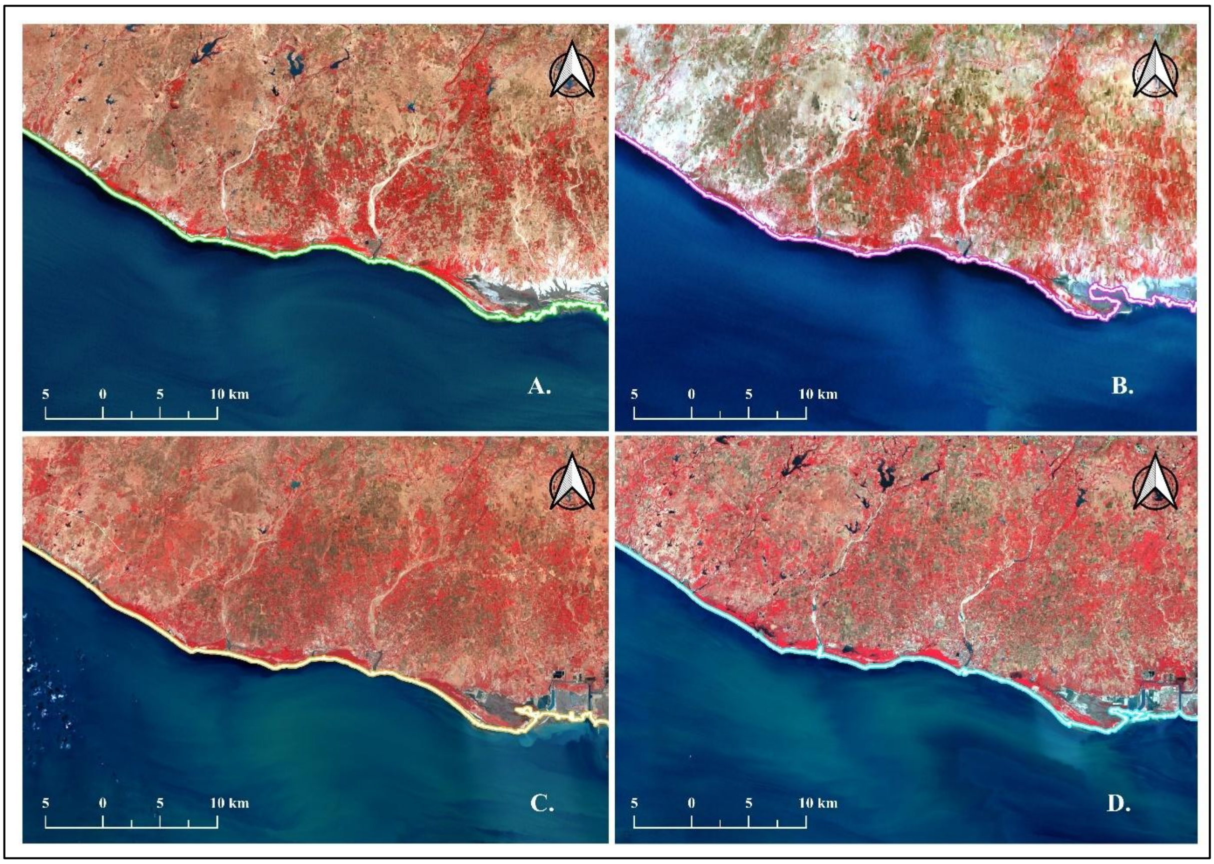
Using the Digital Shoreline Analysis System (DSAS) software and QGIS, various statistical parameters like Net Shoreline Movement (NSM), End Point Rate (EPR) and Weighted Linear Regression (WLR) were generated. These metrics were then interpreted to describe the spatial and temporal patterns of shoreline change in the study area.

4.1.1 Coastline mapping by using Landsat data (1994–2024)

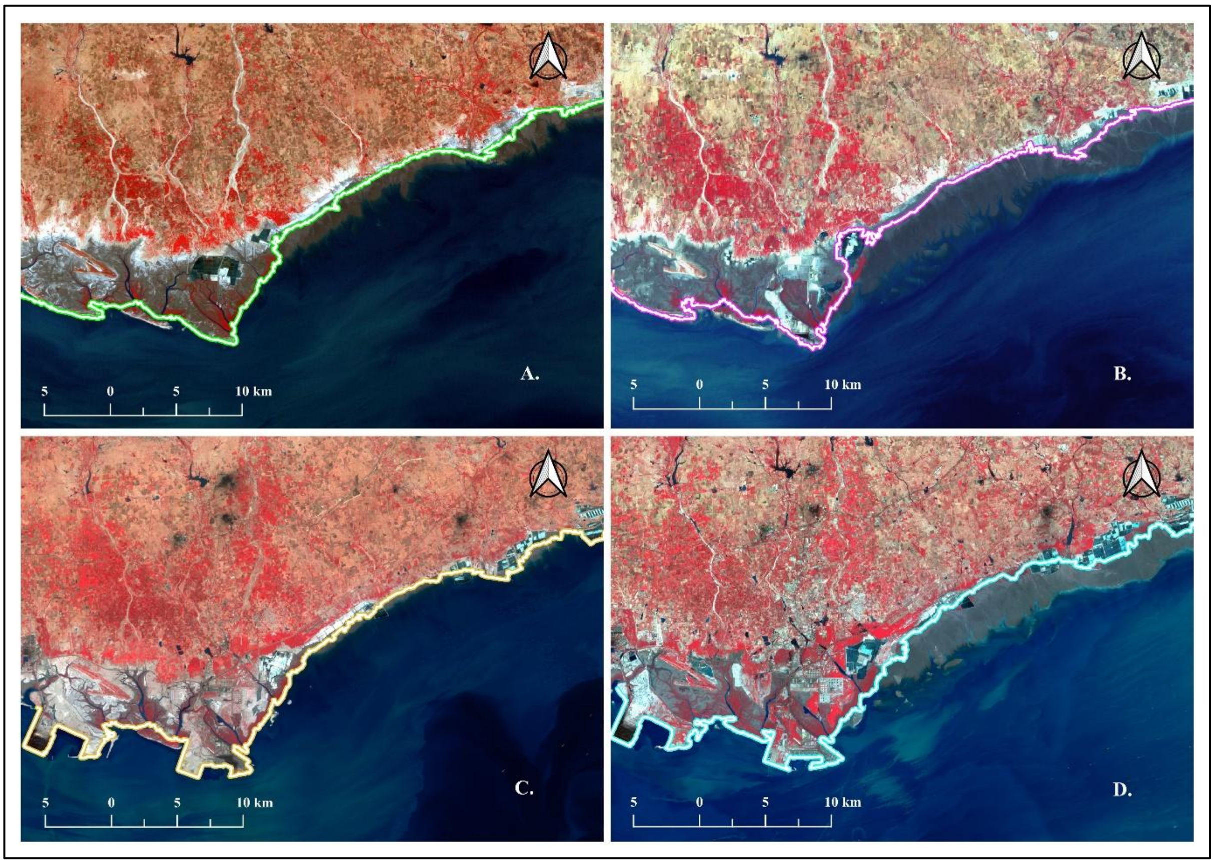
To understand the long-term coastal dynamics of the Mandvi and Mundra talukas, coastlines for the years 1994, 2004, 2014 and 2024 were delineated using multi-temporal Landsat satellite imagery. These satellite images were carefully selected based on cloud-free conditions and availability near high tide timings to minimize tidal variability. The delineation of shoreline features was done through manual digitization of the HTL using visual interpretation in QGIS. A standardized symbology and scale were applied throughout the process to reduce interpretation bias. Each year's shoreline was mapped separately for Mandvi and Mundra talukas.

The digitized shoreline layers were then used to prepare detailed maps that reflect the positional changes in coastline over the 30-year study period. The maps of shorelines are generated differently for both talukas.

These mapped shorelines were then further used as input in the Digital Shoreline Analysis System (DSAS) to calculate quantitative shoreline change metrics, including Net Shoreline Movement (NSM), End Point Rate (EPR) and Weighted Linear Regression (WLR). The results of this statistical shoreline change analysis are presented in the next section.



Map 4.1.1.1: Shoreline map of Mandvi taluka: A.1994, B.2004, C.2014, D.2024 (*Source: USGS.gov Earth Explorer, Landsat imagery – Base data; Map Prepared by the Author*)



Map 4.1.1.2: Shoreline map of Mundra taluka: A.1994, B.2004, C.2014, D.2024 (*Source: USGS.gov Earth Explorer, Landsat imagery – Base data; Map Prepared by the Author*)

4.1.2 Erosion-accretion variation for Mandvi taluka (1994–2024)

The shoreline change analysis for Mandvi taluka has been carried out over a thirty-year period divided into three decadal intervals: 1994–2004, 2004–2014 and 2014–2024. The coastline of this taluka has undergone both erosion and accretion in different periods which indicates the dynamic nature of the coastal system.

The area-wise analysis of total erosion and accretion was derived from digitized shoreline polygons for each time period. These values provide a clear picture of how the coastal morphology of Mandvi has shifted over time.

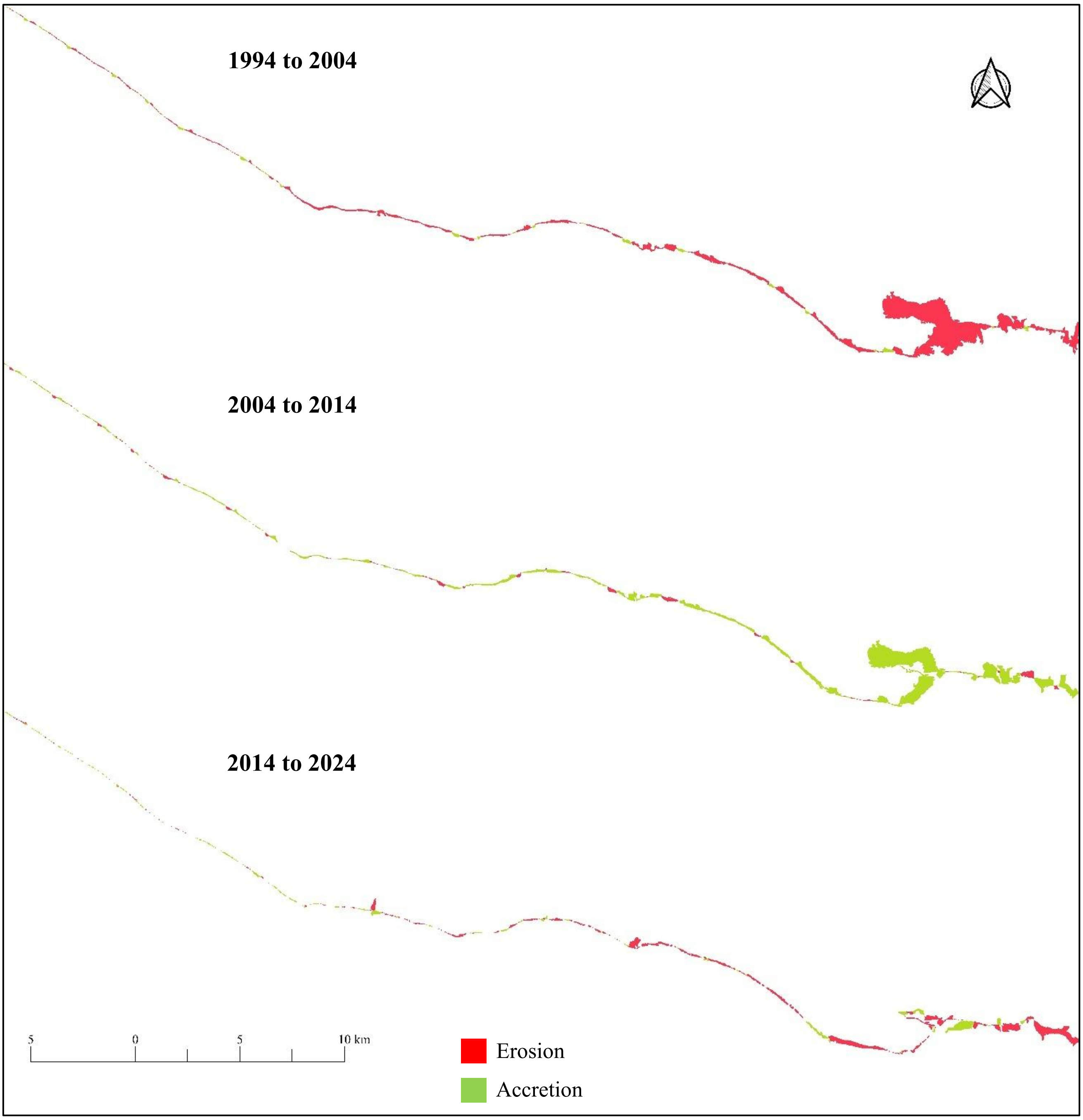
Table 4.1.2: Area-wise change in Mandvi taluka.

Year interval	Total erosion (km^2)	Total accretion (km^2)
1994 to 2004	9.89	0.4
2004 to 2014	0.6	7.37
2014 to 2024	2.88	0.95

(*Source: Landsat images from 1994 to 2024 – Base Data; Table compiled by the Author*)

This, 1994 to 2004 decade recorded the highest erosion in the Mandvi coastline with a total loss of 9.89 km^2 of land. In contrast accretion was negligible at only 0.4 km^2. The high area under erosion during this period may be indicate to natural processes such as wave action and the absence of strong sedimentation zones and less human activities. A sharp shift in the pattern was observed from 2004 to 2014 with erosion dropping drastically to 0.6 km^2 while accretion increased significantly to 7.37 km^2. This suggests a period of relative coastal stability, possibly due to favourable sediment deposition or human interventions. The trend shifted once again with erosion increasing to 2.88 km^2 and accretion declining to 0.95 km^2 in the last decade (2014 to 2024). This moderate increase in erosion indicating may be there are renewed wave activity or infrastructure expansion that disrupted sediment transport in Mandvi coast.

The fluctuations in erosion and accretion over the decades highlight the dynamic equilibrium of the Mandvi coastline. The severe erosion during the first decade was followed by a recovery phase which again shifted toward mild degradation in the recent decade. These variations can be linked to both natural coastal processes and anthropogenic pressures due to increasing port activities and population pressure and tourism, which serve as important indicators for future coastal zone management.

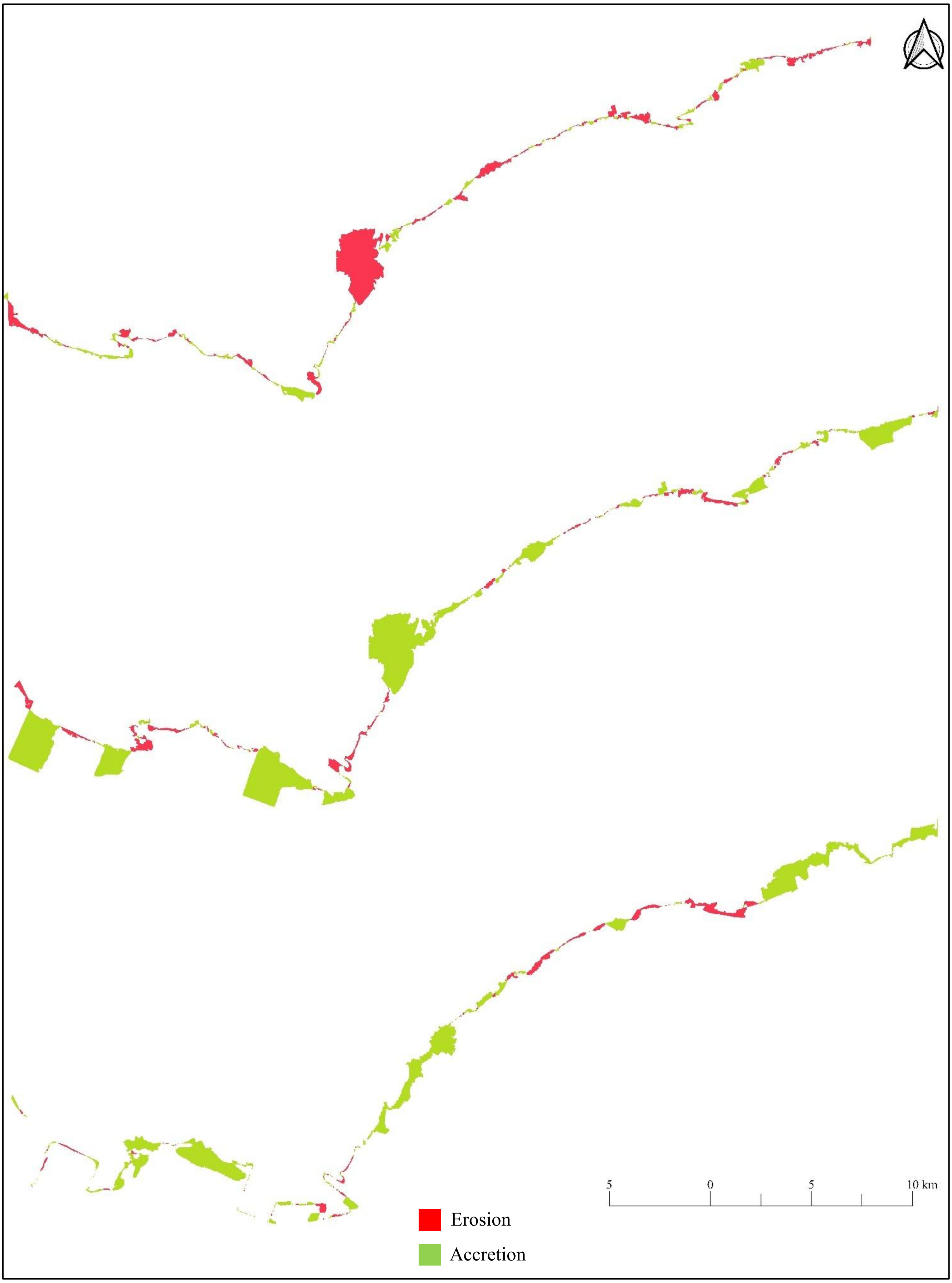


Map 4.1.2: Changing area of Mandvi taluka from 1994 to 2024. (*Source: Landsat imagery – Base data; Map Prepared by the Author*)

4.1.3 Erosion–accretion variation for Mundra taluka (1994–2024)

Shoreline change analysis for Mundra Taluka was conducted using Landsat-derived coastlines for the years 1994, 2004, 2014 and 2024. The entire coastal stretch was evaluated in terms of total erosion and accretion area for each decade to assess the spatial and temporal patterns of shoreline movement.

Unlike Mandvi, where erosion was the dominant trend in the first decade, Mundra showed a mixed pattern with both significant erosion and accretion occurring at various locations. This variation is possibly influenced by extensive port development activities, mudflat sediment dynamics and the presence of aquaculture environments.



Map 4.1.3: Changing area of Mundra taluka from 1994 to 2024. (*Source: Landsat imagery – Base data; Map Prepared by the Author*)

Table 4.1.3: Area-wise change in Mundra taluka.

Year interval	Total erosion (km^2)	Total accretion (km^2)
1994 to 2004	10.46	2.68
2004 to 2014	2.7	24.03
2014 to 2024	2.05	13.44

(*Source: Landsat images from 1994 to 2024 – Base Data; Table compiled by the Author*)

1994 to 2004, This decade recorded the highest erosion for Mundra at 10.46 km², along with 2.68 km² of accretion. The erosion might have been driven by natural coastal retreat. A substantial shift occurred between 2004 to 2014, with erosion reducing to 2.7 km² and accretion increasing sharply to 24.03 km². This is indicating a period of shoreline stabilization and emergence of ports and industries in Mundra coastal region. The most recent decade (2014 to 2024) showed further reduction in erosion to 2.05 km², while accretion continued strongly at 13.44 km². This phase reflects a continuing trend of shoreline advancement, especially near ports, industrial areas and aquaculture areas.

4.1.4 Zone-wise shoreline shifting rate of both talukas from 1994 to 2024

Table 4.1.4: Zone-wise shoreline shifting in Mandvi and Mundra talukas.

Taluka	Zone	Year (1994 to 2004)			Year (2004 to 2014)			Year (2014 to 2024)			Year (1994 to 2024)		
		Mean rate of change (m/yr.)	Net change of shoreline along transects (km)	Status	Mean rate of change (m/yr.)	Net change of shoreline along transects (km)	Status	Mean rate of change (m/yr.)	Net change of shoreline along transects (km)	Status	Mean rate of change (m/yr.)	Net change of shoreline along transects (km)	Status
Mandvi	I	-2.10	-4.72	Erosion	1.08	0.24	Accretion	1.61	3.61	Accretion	0.09	-0.09	Erosion
	II	-5.84	-12.86	Erosion	4.52	9.88	Accretion	-2.62	-5.74	Erosion	-0.95	-13.05	Erosion
	III	-5.03	-8.40	Erosion	3.53	7.24	Accretion	-5.10	-11.30	Erosion	-5.75	-56.48	Erosion
Mundra	I	-5.50	-5.50	Erosion	17.02	16.21	Accretion	18.21	30.09	Accretion	18.19	45.45	Accretion
	II	-1.56	-0.92	Erosion	16.49	9.66	Accretion	75.74	48.07	Accretion	24.88	47.69	Accretion
	III	6.58	5.47	Accretion	70.16	50.13	Accretion	18.47	23.07	Accretion	26.51	47.04	Accretion
	IV	-45.32	-94.71	Erosion	42.55	80.22	Accretion	21.66	45.17	Accretion	11.49	47.05	Accretion
	V	-2.74	-5.53	Erosion	12.61	25.28	Accretion	21.86	48.00	Accretion	10.38	61.99	Accretion

(*Source: Landsat images from 1994 to 2024 – Base Data; Table compiled by the Author*)

Mandvi Taluka experienced erosion in all three zones over the 30-year period. Although there were short phases of accretion between 2004 and 2014, these were not strong enough to reverse the overall erosional trajectory. The highest long-term erosion was observed in Zone 3, where the shoreline retreated at a rate of (–5.75) m/year, with a net loss of 56.48 km. In contrast, Mundra Taluka showed substantial shoreline advancement in all five zones mainly from 2004 onward. Even Zone 4, which faced extreme erosion of (–45.32) m/year during 1994 to2004 period, it shifted to accretion after 2004 and gained a net 47.05 km of shoreline by 2024.

The average mean rate of change across Mandvi zones ranged from –5.75 m/year to 0.09 m/year, indicating slow to moderate erosion. Meanwhile, Mundra recorded high accretion rates, with Zone 3 averaging 26.51 m/year and Zone 2 reaching up to 24.88 m/year, highlighting aggressive land gain commonly influenced by port development, coastal infrastructure and aquaculture practices.

Over the three decades Mandvi's erosion is most concentrated in Zone 3, likely due to exposure to open wave action and limited sediment supply. Mundra's maximum shoreline gain is seen in Zones 2 and 5, areas possibly benefitting from proximity to port structures, mudflats, etc.

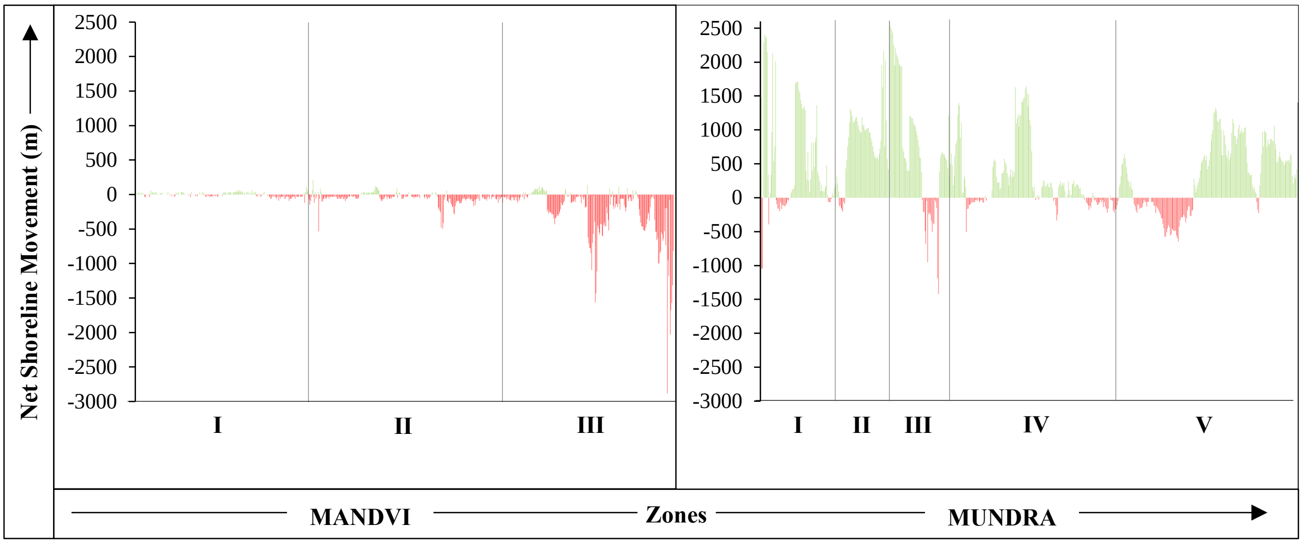


Figure 4.1.4: Net Shoreline Movement (NSM) of different zones of Mandvi and Mundra talukas from 1994 to 2014. (*Source: Landsat images from 1994 to 2024 – Base Data; Figure compiled by the Author*)

The above figure of Net Shoreline Movement (NSM) values across the designated zones of Mandvi (I to III) and Mundra (I to V) for the period 1994 to 2024, is showing positive values (shown in) that represent shoreline advancement (accretion) whereas negative values (in red) indicate shoreline ne retreat (erosion).

In Mandvi taluka, Zone I show mostly neutral NSM values with very slight accretion. Only a few transects cross into the positive range, indicating a relatively stable shoreline with minimal change in the last three decades. Zone II is dominated by negative NSM values, almost beyond (–500) m in several transects which suggests significant erosion. This zone has experienced consistent retreat throughout the period. The Zone III demonstrates the most intense erosion across Mandvi, with several transects showing shoreline retreat between (–1000) m to (–2500) m. This reflects severe coastal degradation in this zone, possibly due to exposure to open sea wave action, lack of vegetation and absence of sediment supply.

In Mundra taluka, Zone I, II and III show widespread positive NSM values, with transects often exceeding 1500 m to 2500 m which indicates strong accretion. This suggests that these areas have experienced significant shoreline advancement, mainly due to port-related construction and mudflat expansion. But some part of the Zone III experienced high erosion up to (– 1500) m, actually this portion is free from human activities. Zone IV contains a mix of accretion and erosion but leans slightly positive overall. Zone V shows moderate but consistent accretion, with most transects displaying NSM values between 500 m and 1000 m, reflecting a stable progradation trend. But the accretion areas under Zone IV and V indicate human interventions commonly in terms of aquaculture practices.

4.1.5 Spatial distribution of erosion and accretion intensity in Mandvi and Mundra talukas

Table 4.1.5: Zone-wise erosion and accretion intensity in Mandvi and Mundra talukas.

Taluk	Zone	Measured Length of Net Change (km)															
		High erosion (> -100 m)				Low erosion (-100 - 0 m)				Low accretion (0 - 100 m)				High accretion (< 100 m)			
		1994 - 2004	2004 - 2014	2014 - 2024	Total	1994 - 2004	2004 - 2014	2014 - 2024	Total	1994 - 2004	2004 - 2014	2014 - 2024	Total	1994 - 2004	2004 - 2014	2014 - 2024	Total
Mandvi	I	8.2	2.2	0.8	11.2	4	0.3	0.9	5.2	8.3	13.6	15.2	37.1	1.8	6.2	4.3	12.3
	II	17.6	3.1	11.9	32.6	0.5	0.3	1.6	2.4	1.8	3	6.2	11	2.1	15.5	3	20.6
	III	13.4	4	14.5	31.9	0	0.3	0.7	1	0.6	2.4	2.9	5.9	2.4	13.9	4	20.3
Mundra	I	3.2	5.6	1.8	10.6	0.3	0	0.7	1	0.9	0.6	7.3	8.8	5.6	3.4	6.6	15.6
	II	2.3	2.4	0.1	4.8	0.2	0.4	0	0.6	1.6	0.9	0.5	3	1.9	2.2	5.7	9.8
	III	2.9	1.9	2.8	7.6	0.3	0.2	0.2	0.7	1.1	0.2	4.5	5.8	3.9	4.9	4.9	13.7
	IV	12.6	5.6	5.4	23.6	0.7	0.3	0.6	1.6	3	1.9	2.5	7.4	4.5	11.1	12.2	27.8
	V	10.8	6.8	6.8	24.4	0.4	0.7	0.2	1.3	3.1	2.5	1.2	6.8	5.8	10.2	13.6	29.6

(*Source: Landsat images from 1994 to 2024 – Base Data; Table compiled by the Author*)

To further understand the spatial extent and intensity of shoreline dynamics the length of the coastline falling under different categories of erosion and accretion has been quantified for each zone in Mandvi and Mundra talukas. The analysis classifies the change into four groups which are, High erosion (> –100 m), Low erosion (–100 m to 0 m), Low accretion (0 m to 100 m) and High accretion (< 100 m).

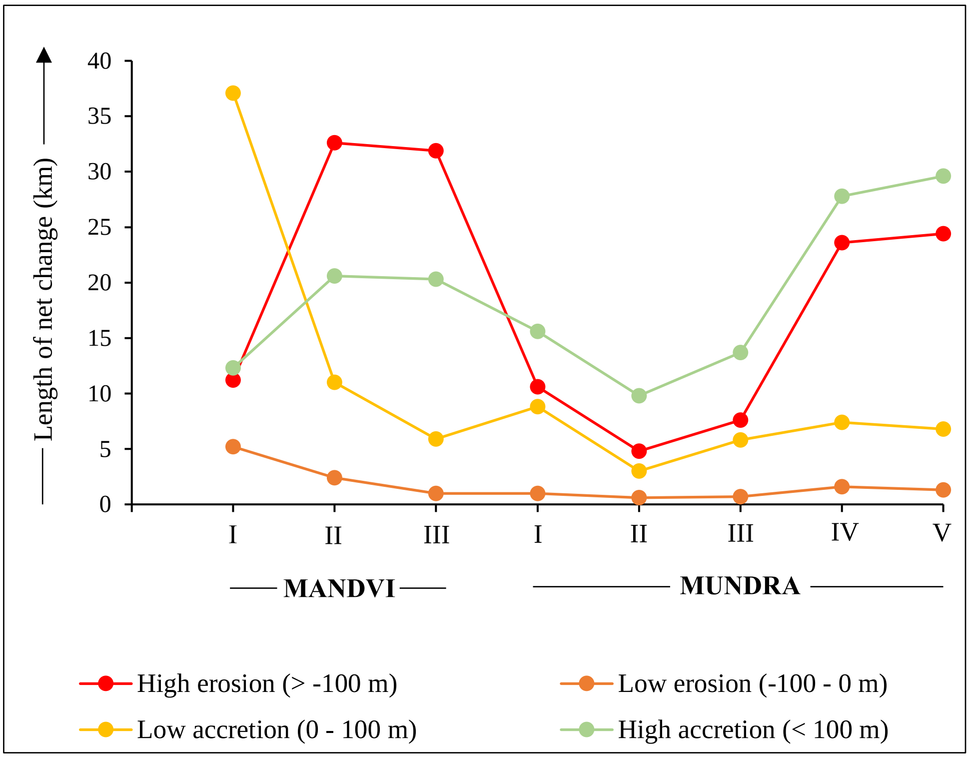


Figure 4.1.5: Length of net shoreline change of different zones of Mandvi and Mundra talukas from 1994 to 2014. (*Source: Landsat images from 1994 to 2024 – Base Data; Figure compiled by the Author*)

Mandvi shows very high length of shoreline retreat along the coast, with Zone II (32.6 km) and Zone III (31.9 km) being the most severely eroded zones. Even Zone I experienced 11.2 km of high erosion. In contrast Mundra, Zones IV (23.6 km) and V (24.4 km) show significant high erosion, but the other three zones (I, II, III) remain comparatively less affected (below 11 km each).

In Mandvi Low erosion is mostly concentrated in Zone I (with 5.2 km long coastal stretch), with Zones II and III having minimal values (2.4 km and 1 km, respectively). Mundra shows lower but more balanced low erosion across all zones, especially in Zone IV (1.6 km) and Zone V (1.3 km).

Mandvi is led by Zone I with 37.1 km of low accretion, far higher than any other zone. Zones II (11 km) and III (5.9 km) also show modest accretion. While Mundra shows a more balanced low accretion trend in all zones, with values ranging from 3 to 8.8 km, particularly in Zone I.

Mundra shows the most impressive figures in high accretion category especially in Zones V (29.6 km), IV (27.8 km) and I (15.6 km). This indicates strong and effective shoreline advancement, due to sediment supply and anthropogenic stabilization (e.g., port expansion, emerging industries near coast). Mandvi does show notable high accretion in Zones II (20.6 km) and III (20.3 km), it mainly happened due to port establishment near the coast of Mandvi after 2010 though erosion still dominates in these zones.

4.1.6 Comparative analysis of both talukas in light of Gujarat's coastal erosion trends

The Gujarat coast is stretching approximately 1,600 km which is nearly 24% of India's total sea coast (largest) and it is recognized as one of the most dynamically active coastal zones in the country. According to Patel et al. (2022), nearly 703.6 km (45.1%) of this coastline has undergone erosion between 1978 and 2020, with ten out of sixteen coastal districts facing various levels of degradation. The Kutch district where more than 300 km long coast falls under high erosion category (> 1 km) (Patel et al., 2022) covers the Mandvi and Mundra talukas. This large-scale pattern of erosion offers an important reference point to evaluate the local shoreline dynamics in Mandvi and Mundra.

The analysis of Mandvi's coastal zones revealed that all three zones are under long-term erosional stress with Zones II and III showing extreme shoreline retreat (more than 30 km of high erosion each between 1994 and 2024). This aligns with the general findings of Gujarat Ecology Commission (2018) and Patel et al. (2022) which noted that Kutch, where Mandvi is located, has one of the highest extents of coastline under high erosion category in Gujrat. The erosion intensity in Mandvi taluka is comparable to districts like Jamnagar and Valsad, which have shown intense erosion (up to 2.5 times increase in Jamnagar from 1998 to 2020). The erosion in Mandvi's Zones II and III shows such long-term degradational trends with minimal recovery, especially in the last decade (2014 to 2024).

In contrast to the larger pattern observed across Gujarat, Mundra displays a strongly accretional trend, particularly from 2004 onward. All five zones in Mundra show significant high accretion, with Zones IV and V exhibiting shoreline advancement of 27.8 km and 29.6 km, respectively. This diverges from the broader finding that erosion rates across most coastal districts in Gujarat remained high or increased. The reversal in Mundra's shoreline behaviour can be attributed to extensive industrial development, port construction, coastal infrastructure and aquaculture practices which likely altered sediment transport and wave dynamics and encouraged deposition. Unlike districts like Surat and Valsad, which saw continued erosion into the post-1998 period, Mundra's coast appears as a stabilized and accreting coast, marking it as an outlier within the erosion-dominated Kutch district.

These findings reinforce the argument that while natural erosion is a widespread phenomenon across Gujarat, localized development strategies; like in Mundra can drastically influence coastal behaviour, which creates stability and accretion in coastal zones though there is a larger backdrop of shoreline retreat in the neighbouring taluka, Mandvi.

4.2 Sea Surface Temperature Analysis in Coastal Part of Mandvi and Mundra Talukas

The studies carried out by (Roxy et al., 2020) indicated that the SST in the tropical Indian Ocean underwent rapid warming during 1950 to 2015 and it was observed that the average warming of about 1°C based on SST and also as per the climate model projection, a rise in tropical Indian Ocean SST

by 1.2–1.6°C during the period of 2040 to 2069.The Sea surface temperature (SST) data covering Gulf of Kachchh along the coastal areas of Mandvi and Mundra talukas were collected from KNMI Climate Explorer website and analyzed to study the trends of SST over the period of 50 years from 1974 to 2024. The normalized SST data covering Gulf of Kachchh along the coastal areas of Mandvi and Mundra talukas from 1974 to 2024 are used in further analysis. The analysis indicates that SST shows the gradual increasing trend. in all the three coastal areas in Gujarat state. Gulf of Kachchh shows the increase of SST by 1.63°C over the period of 50 years.

4.2.1 Relationship between Sea Surface Temperature (SST) and Atmospheric CO_2

It was found that Kachchh coast experienced the highest erosion with SST (Sea Surface Temperature) rise and CO_2 emissions identified as contributing factors (Patel et al., 2022). So, it is obvious that the coastal region of Mandvi and Mundra talukas have experienced increasing SST with the increasing amount of atmospheric CO_2 (ppm) both in recent times and past. To analyse that the atmospheric CO_2 data near gulf of Kachchh was collected from World Meteorological Organization. The connection between atmospheric CO_2 and SST was studied to understand how long-term climate change may be influencing the coastal environment of Mandvi and Mundra talukas . Both variables were examined over a period of 50 years, from 1974 to 2024.

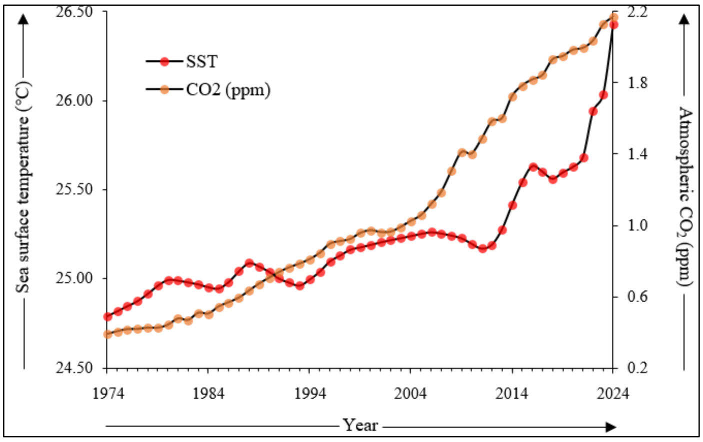


Figure 4.2.1: Time-series plot showing the annual variation of SST (°C) and Atmospheric CO_2 (ppm) from 1974 to 2024. (*Source: KNMI Climate Explorer, World Meteorological Organization – Base Data; Figure compiled by the Author*)

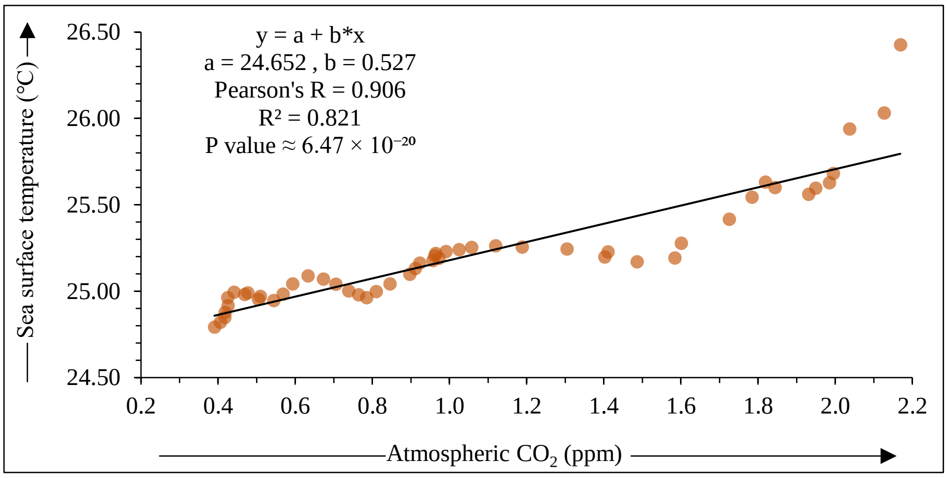


Figure 4.2.2: Correlation between Atmospheric CO_2 (ppm) and Sea Surface Temperature (°C). (*Source: KNMI Climate Explorer, World Meteorological Organization – Base Data; Figure compiled by the Author*)

Both SST and atmospheric CO_2 show a steady upward trend over the 50-year period. While atmospheric CO_2 rises continuously, SST shows similar inflection points, including a moderate rise between 1994 and 2004, a sharper rise after 2008, with spikes after 2015. Both parameters peak around 2024 which indicates a strong temporal alignment.

The Pearson correlation coefficient (R) was calculated as 0.906, which means a very strong positive correlation between SST and atmospheric CO_2. The R^2 value was found to be 0.821, which means around 82% of the changes in SST can be explained by CO_2 levels and the p-value was very small ($\approx 6.47 \times 10^{-20}$), which confirms that the result is statistically meaningful.

From the analysis, it can be concluded that as atmospheric CO_2 levels rise, sea surface temperatures also increase. This suggests that climate change is influencing the coastal environment. In Mandvi, this warming may lead to increased erosion, stronger wave activity and faster shoreline retreat. In Mundra, even though accretion is more common there, rising SST may affect tidal patterns, coastal ecosystems and sediment movement.

4.2.2 Relationship between Sea Surface Temperature (SST) and Annual sunspot activity

The sunspot number is used as an important indicator of solar activity. Sunspots are temporary dark patches on the Sun's surface that are caused by intense magnetic activity. When sunspot numbers are high, the Sun's energy output is slightly increased and more solar radiation is sent toward the Earth. Solar activity follows a regular cycle of about 11 years, known as the solar cycle during which sunspot numbers rise and fall. It has been observed that changes in solar radiation can influence Earth's climate, especially during prolonged periods of low or high sunspot activity. Although the effect of solar activity is smaller compared to greenhouse gases like CO_2 but it can still cause variations in sea surface temperature (SST). The 11-year cycle in sunspot numbers which is strongly related to changes in solar radiation and the variation in sunspot numbers is used as an indicator of variation in solar activity was reported by (Miyahara et al., 2010).

The annual mean sunspot activity or sunspot number data was collected from Solar Influences Data Analysis Centre, from 1974 to 2024 then it has compared with the annual SST data.

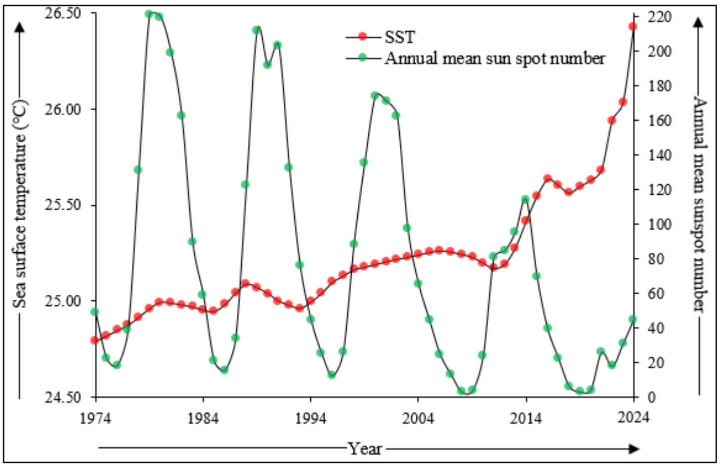


Figure 4.2.3: Time-series plot showing the annual variation of SST (°C) and Annual mean sunspot number from 1974 to 2024. (*Source: KNMI Climate Explorer, Solar Influences Data Analysis Centre – Base Data; Figure compiled by the Author*)

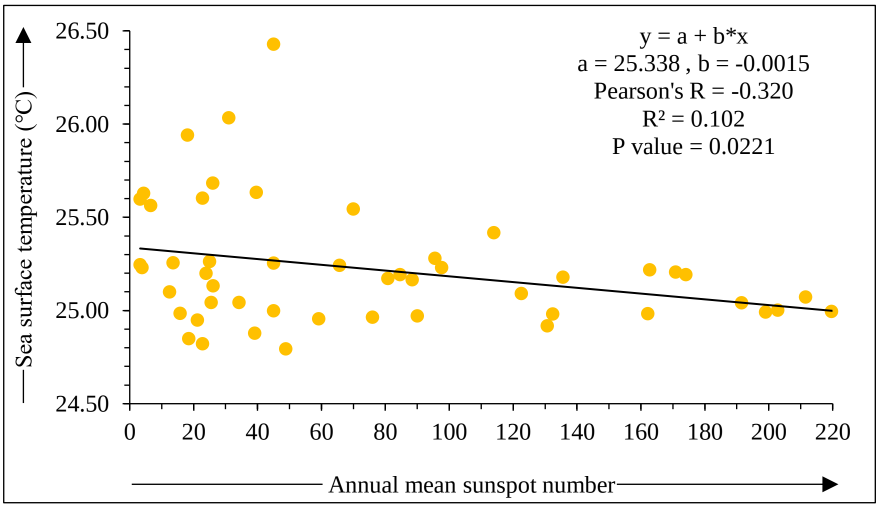


Figure 4.2.4: Correlation between annual variation of SST (°C) and Annual mean sunspot number from 1974 to 2024. (*Source: KNMI Climate Explorer, Solar Influences Data Analysis Centre – Base Data; Figure compiled by the Author*)

The sunspot number fluctuates in a clear cyclical pattern, reflecting the 11-year solar cycle. However, SST shows a steady and more gradual increase over the same period. Peaks in sunspot number (like, around 1980, 1990, 2002 and 2014) do not consistently match peaks in SST. SST appears to continue rising even during periods of low sunspot activity like after 2020.

The Pearson's correlation coefficient (R) = (–0.320) which indicates a weak negative correlation and $R^2 = 0.102$, meaning only about 10% of SST variation is explained by sunspot activity. The p-value ≈ 0.0221 which indicates the result is statistically significant but not strong.

From this analysis, it can be understood that sunspot activity does not have a strong influence on sea surface temperature specially in the Mandvi–Mundra coastal region. Although solar cycles are important for global climate variations but there is no clear link between higher sunspot numbers and SST increase in this regional study of Mandvi and Mundra coasts.

A detailed analysis of shoreline changes along the Mandvi and Mundra coastal zones was carried out using multi-decadal satellite data. The coastline was studied through various indicators such as net shoreline movement (NSM), erosion–accretion classification and shifting rate via WLR (weighted linear rate) analysis for both talukas and all zones under each taluka.

The spatial distribution of high erosion and accretion was also classified for each zone of Mandvi and Mundra coastal region.

Additionally, the role of climatic drivers was examined. A strong positive correlation was observed between atmospheric CO_2 and SST. In contrast sunspot activity showed only a weak correlation with SST.

Overall, the analysis provides important results into the spatio-temporal dynamics of shoreline change and its connection with climatic variability which helped to discuss a foundation for sustainable coastal planning in talukas like Mandvi and Mundra.

CHAPTER 5: CONCLUSIONS

5.2 Major Findings

The shoreline dynamics of Mandvi and Mundra talukas were analyzed using multi-temporal satellite data from 1994 to 2024 and supporting climatic datasets. Several major findings were identified through this work which are,

It was observed that Mandvi's coastline has been affected by high levels of erosion, particularly in Zone II and Zone III, where almost 30 km stretch of the shoreline fall under high erosion category over the years. These areas have experienced both high erosion rates and large spatial exposure to land loss. In contrast, Mundra's coastline showed widespread accretion, especially in Zone IV and Zone V where more than 27 km stretch of shoreline was found to advance seaward.

These high accretion zones of Mundra have been influenced by mainly human-made coastal developments, port emergence (specially in zone I and zone III), industrial activities and aquaculture practices (like in zone V). When the rate of shoreline shifting was analyzed, negative values were found in all zones of Mandvi, confirming ongoing erosion, while positive rates were found in all zones of Mundra, suggesting active shoreline expansion.

A zone-wise classification of the coastal stretch revealed that most of Mandvi's shoreline falls under high erosion, while most of Mundra's falls under accretion. This comparison clearly shows that Mandvi is erosion-dominated while Mundra is accretion-dominated.

The analysis of atmospheric CO_2 and SST (from 1974 to 2024) showed a strong positive correlation ($r = 0.906$), meaning that as CO_2 levels increased, SST also increased. This confirmed that global warming is likely influencing sea surface conditions in Mandvi – Mundra region. The analysis between sunspot activity and SST resulted in a weak negative correlation ($r = -0.320$), showing that sunspot changes have had little impact on SST in the study area. This suggests that solar cycles play a smaller role compared to greenhouse gases.

Overall, it can be concluded that the coastal processes of erosion and accretion in Mandvi and Mundra are being shaped by a combination of natural shoreline dynamics and climate-related changes, especially rising atmospheric CO_2 and SST.

5.2 Recommendations

Based on the findings of this study, the following recommendations are proposed to support better coastal planning and management

Erosion-prone zones in Mandvi, particularly Zones II and III, should be given high priority for protective measures. Natural solutions, such as mangrove restoration and dune stabilization should be considered before using hard infrastructure in these zones.

Coastal planning should adopt a "risk zoning" approach, where infrastructure is restricted in erosion-sensitive areas and encouraged in accreting or stable zones.

In Mundra, where shoreline accretion has occurred, it is advised that ecological changes caused by land gain should be studied further. The long-term impacts of port development, increasing aquaculture practices and altered sedimentation should be monitored.

Some steps can be taken by government in Mandvi to reduce erosion by understanding the reasons of accretions in Mundra taluka.

It is recommended that regular shoreline monitoring using remote sensing and GIS tools should be established. This will allow changes to be tracked in near-real time that helps decision-makers respond quickly to threats.

Coastal development projects should be approved only after considering climate trends, especially sea surface temperature rise and atmospheric CO_2 levels. This will help ensure that new infrastructure is climate-resilient and less CO_2 emission in this region.

It is suggested that community involvement and local awareness programs must be conducted in both talukas. Residents can be encouraged to adopt coast-friendly practices and participate in coastal conservation.

5.3 Limitations

While this study has provided meaningful insights there are several limitations should be acknowledged,

The analysis was based on satellite images from only four years (1994, 2004, 2014 and 2024). As a result, short-term seasonal or annual changes could not be captured.

Field visits were not conducted to validate shoreline movement, which may have introduced minor errors in digitization or interpretation of land–water boundaries.

The data for SST were obtained from global datasets, rather than being directly measured in the Mandvi–Mundra coastal waters. This may have slightly affected the accuracy of correlation results.

Several local factors, such as river discharge, storm surges land-use changes, etc. were not studied in detail. These may also influence shoreline behaviour.

The role of sunspot activity was explored using only correlation analysis, without the use of advanced solar radiation models, which could have provided deeper insights.

Though there are some limitations but the results of this study offer valuable information for understanding and managing shoreline change, understanding the climatic effect on change in shoreline and can be built upon in future research.

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