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Spatio-temporal assessment of climate variability and its influence on mangrove ecosystem dynamics along the bapatla coast, Andhra Pradesh (1996-2026)

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Abstract

Mangroves are very crucial and important ecosystems that protect coastal areas; however, they can be vulnerable to climate fluctuations and anthropogenic activities. The current research analysed the changes in climate factors, namely, the amount of rainfall and temperature, and the mangrove cover in the Bapatla coastal panchayat, Andhra Pradesh, over 30 years (1996-2026). First of all, the current study utilised the time series of decadal statistical patterns of mangrove cover to explore its spatial variations with the annual trends of climate factors. Furthermore, the study employed the Normalised Difference Vegetation Index (NDVI) to estimate the percentage of mangrove vegetation in the research site based on decadal spatial mapping and annual time series analysis consistent with the Global Mangrove Watch. The current research found that the NDVI of mangroves demonstrated a significant long-term positive tendency ($p\text{-value} < 0.05$) with a high strength ($R^2 = 0.7003$), ranging from 110 km² in 1996 to a peak of 170 km² around 2023 and a sudden decrease to 130 km² in 2026. On the other hand, the annual variation of rainfall and temperature was nearly chaotic, with insignificant long-term trends ($p\text{-value} = R^2 = 0.0393$ and 0.0087). Moreover, the spatial analysis revealed that the growth of mangroves was mainly observed along the coast of Nizampatnam, Karlapalem, and Repalle, whereas a small area was noted in Chinaganjam. Meanwhile, there were no mangroves in the internal and northern mandals. Overall, the current study concluded that the growth of mangroves is more likely associated with favourable climate conditions over multiple years rather than a linear long-term trend, and the recent decline was probably triggered by the deviation of temperature and rainfall.

Keywords: Mangrove ecosystems, NDVI, climate variability, remote sensing, Bapatla coast, coastal vegetation dynamics

1. Introduction

Mangrove Forests are highly productive and dynamic ecosystems that provide a wide range of goods and services to coastal tropical and subtropical communities, such as shoreline protection and stabilization, nutrient cycling and retention, and significant carbon stocks, offering carbon sequestration and storage capacities, and playing an important role in climate change mitigation (Spalding *et al.*, 2010; Atwood *et al.*, 2017; Donato *et al.*, 2011) [3, 5, 16]. They are located mainly in tidal flats, estuaries, lagoons, deltas, and other sheltered coastal saline landforms (Alongi, 2009) [1]. Mangrove health depends upon temperature, rainfall, freshwater availability, tides, salinity, sedimentation, and wave action, making them highly sensitive to climate change, which determines mangrove distribution, structure, and function (Gilman *et al.*, 2008; Ward *et al.*, 2016) [7, 19]. Temperature changes may affect plant physiology and productivity and promote species invasion; moreover, sea-level rise can cause mangroves to migrate inland or seaward or become permanently submerged (Lovelock *et al.*, 2015; Saintilan *et al.*, 2020) [13, 15]. Therefore, to understand regional forest responses and adaptations, the analysis of climate variability both short- and long-term is critical. Recent studies highlight that anthropogenic activities have converted significant mangrove areas to other land cover types (Valiela *et al.*, 2001; Polidoro *et al.*, 2010) [14, 18]. Indeed, the net change in mangrove distribution has been inconsistent throughout the continent since the 1990s (Hamilton & Casey, 2016; Goldberg *et al.*, 2020) [9, 10]. Global Mangrove Watch allows for analysing land cover changes at a continental scale from 1996 to 2021 (Bunting *et al.*, 2022) [4]. If year-over-year analysis shows inter-annual variability, a decade-scale assessment reveals patterns of change across different study sites.

Indian mangroves, especially those located along the eastern coast and found in estuaries and deltas, are highly diverse, widespread, and threatened by natural (cyclones, erosion, silting) and anthropogenic disturbances (Forest Survey of India, 2023) ^[6]. Their status needs to be evaluated using Earth observation data. Andhra Pradesh, India's East Coast state, is recognised for its large-scale mangrove forests under seasonal climatic variations (rainfall, cyclones, and droughts).

The region around Bapatla is a low-lying coastal tract exposed to natural and human-induced environmental changes that might influence land cover. For instance, natural climate variability may increase biomass production through rising temperatures, impact the number of canopies, and promote saline water intrusion during cyclones and droughts. At the same time, monsoon floods may lead to increased freshwater discharge and silting affecting estuarine forest ecosystems. Moreover, long-term evaluation highlights that vegetation cover changes on both a decadal and inter-annual scale determine forest response to climatic variability.

Therefore, earth observation methods are necessary to detect the associations between environmental/climate factors and forest cover changes. Normalised Difference Vegetation Index (NDVI) is a valuable indicator to assess trends in mangrove forests since remote sensing technologies, such as Landsat or Sentinel-2 satellites, allow for quantifying vegetation cover at different dates (Landsat's temporal resolution is appropriate for a decadal-scale assessment while Sentinel-2's high-resolution is optimal for small-scale mangrove mapping).

The comparison of vegetation indices with climate data will highlight the possible relationships. Overall, remote sensing technologies and GIS can provide a comprehensive understanding of the relationship between climate change and mangrove forest cover changes (Kuenzer *et al.*, 2011; Thomas *et al.*, 2017) ^[12, 17]. The long-term assessment of mangrove forests is crucial because their distribution ranges from year to year, showing both gains and losses over time (Goldberg *et al.*, 2020) ^[9]. The analysis of inter-annual and decadal changes in mangrove forest cover in India's East Coast and its association with climate variability highlights possible mechanisms in the Bapatla region, which will further help to identify the climate change impact.

Mangroves' ecosystem services such as shoreline protection, breeding and nursery grounds for commercial

fish and shellfish, improving water quality, serving as carbon sinks, and decreasing erosion make them highly important for coastal communities (Donato *et al.*, 2011; Alongi, 2014) ^[2, 5]. Their current and future status is closely related to the state and resilience of mangrove forests. Therefore, a long-term assessment of their dynamic changes is critical to understanding their response to climate change. This study aims to analyse long-term climate trends and their impact on mangrove forests in the study area, investigating potential relationships between climate variability and forest cover changes. The research will employ NDVI data for the 1996-2026 period to evaluate vegetation cover trends, applying remote sensing and GIS to study the relationship between climate change and mangrove forests along the Bapatla coast.

The study area was selected because of the high diversity of mangrove forests, high exposure to climate change, and the availability of remote sensing data for the study area. Decadal analysis of the climate and NDVI trends will be used to identify patterns of climate change and mangrove forest cover dynamics for the past three decades (following the Global Mangrove Watch initiative, 1996-2021; Bunting *et al.*, 2022) ^[4].

2. Data and Methodology

2.1 Data

The current work utilises satellite imagery and climatic datasets that are appropriate for long-term mangrove monitoring. In particular, Landsat Collection 2 Level-2 Surface Reflectance data from Landsat 5, Landsat 7, Landsat 8, and Landsat 9 sensors were applied to extract mangrove information.

For mangrove baseline/reference data, Global Mangrove Forests were used, which define the mangrove analysis area. The former was used as an input layer for training the random forest classifier, whereas the latter was utilised to determine the extent of mangrove cover throughout the study region. In addition, CHIRPS v3 daily precipitation data and ERA5-Land daily aggregated data were employed to characterise the annual amount of rainfall and temperature, respectively.

Sl. No.	Component	Dataset	Purpose
1	Mangrove Mapping	Landsat 5 (L2 SR)	Historical Mangrove Extraction
		Landsat 7 (L2 SR)	Mangrove Extraction
		Landsat 8 (L2 SR)	Mangrove Extraction
		Landsat 9 (L2 SR)	Recent Mangrove Extraction
2	Mangrove Reference	Mangrove Forests	Baseline/Reference Zone
3	Rainfall	CHIRPS (Daily)	Annual Precipitation Variability
4	Temperature	ERA5-Land (Daily)	Temperature Variability

2.2 Methodology

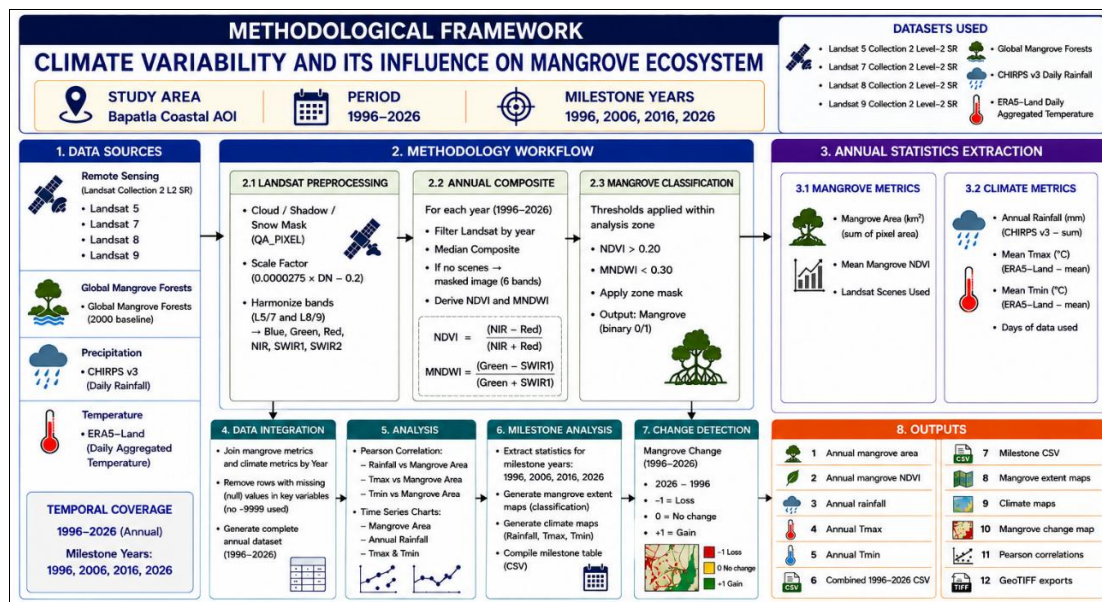


Fig 1: Methodological Framework

The current research has employed remote sensing and geospatial technologies to demonstrate the spatial and temporal distribution patterns of mangroves and their relationship with climate conditions on the Bapatla coast. The work has utilised the temporal variability of mangroves and climate to understand how climate change can affect vegetation cover and the status of the mangrove forest from 1996 to 2025. The study employs Landsat remote sensing data and climate data, including CHIRPS rainfall and ERA5-Land temperature. The extent of mangroves was determined using vegetation and water indices from annual Landsat composite data, while inter-annual variability in rainfall and temperature was quantified using climate data. The processed data were combined and analysed as a function of time to establish a relationship between the climate conditions and the status of the mangrove forest.

Objectives of the Study

1. To study the status of mangrove cover in Bapatla coast (1996–2026).
2. To examine the pattern of rainfall and temperature during 1996–2026.
3. To understand the association between climatic factors and mangrove cover.

3. Study Area

The study area falls under the Bapatla coastal belt of Andhra Pradesh, India. It is a coastal zone surrounding the Bay of Bengal. Hence, the geographical location covers latitudes 15°45'N–16°00'N and longitudes 80°15'E – 80°45'E (Fig. 2), extending from the Bay of Bengal to the interior parts of the province. The study area comprises coastal and near-coastal mandals such as Chinaganjam, Karamchedu, Chirala, Vetapalem, Bapatla, Karlapalem, Pittalavanipalem, Nizampatnam, Nagaram, and Repalle. The physiography of the study region consists of agricultural land, settlements, coastal swamps, estuarine, and shoreline habitats as the main land cover utilisation. It is a key coastal ecological region that interacts with the Bay of Bengal and is exposed to climate variability and change, cyclones, floods, coastal erosion, and salinity-freshwater regimes.

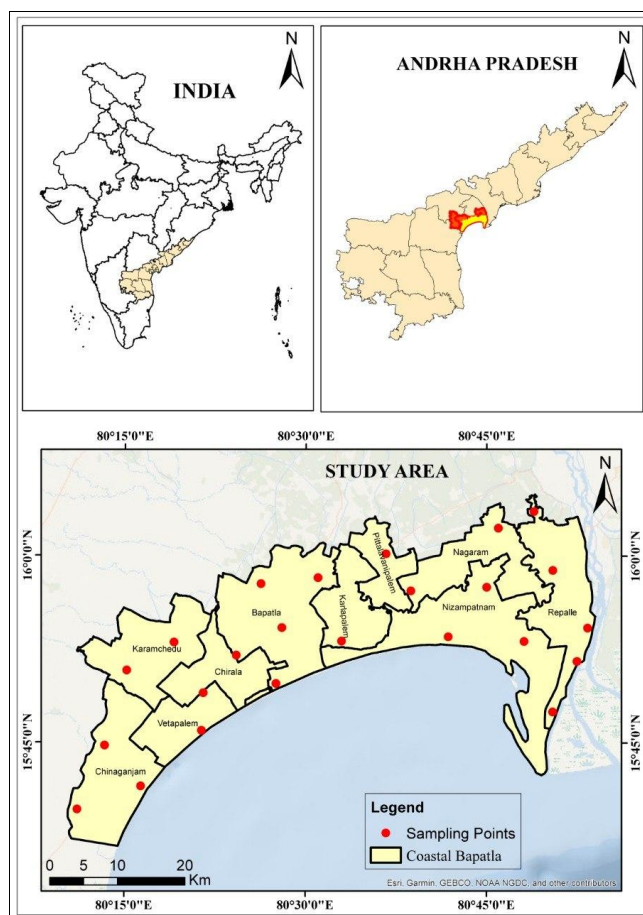


Fig 2: Location Map of the Study Area

The study area falls under the coastal plains of Andhra Pradesh. It consists of low-lying land with flat landscapes sloping gently towards the Bay of Bengal. The coast is formed by riverine, marine, and fluvial processes, ranging from alluvial plains, sandy coasts, swamps, drainage, and estuarine inland and coastal water bodies. Agricultural lands and rural settlements dominate the inland regions, while the coastal parts are found to have sandy beaches, environments, and ecosystems. The study area experiences a tropical maritime climate with extreme temperatures that

range from hot summers to winters, and a long rainy season. The rainfall is derived from South-West and North-East monsoon flows. Consequently, the climate variables considered for the study comprised annual and seasonal rainfall, maximum and minimum temperatures, mean temperature, temperature and rainfall anomalies, rainy days, extreme rainfall events, and cyclones to evaluate their impacts on coastal ecology and vegetation. The coastal belt of Bapatla hosts a considerable number of villages and towns engaged in agriculture, fisheries, aquaculture, and allied activities. It is a heavily populated region, with the selected coastal and near-coastal mandals recorded with a total population of 784000 people according to the 2011 census. Private organisations, agricultural activities, trading, and other human developments thrive in this region. Among the mandals, Chirala and Bapatla are considered hotspots for population density, whereas Nizampatnam, Repalle, Vetapalem, Nagaram, Karlapalem, and Pittalavanipalem record high rural and coastal settlements. Coastal regions are anthropogenically influenced by

population growth, agricultural lands, aquaculture, and human developments, and consequent impacts are expected on coastal ecology. Thus, population distribution is an essential parameter for analysing the relationship between climate variability, land use/land cover, and the coastal environment in the study area.

4. Result and Discussion

The Results and Discussion contains temporal and spatial analysis of climate variables (rainfall, temperature) and mangrove cover in the Bapatla Coastal Panchayat between 1996 and 2026, using decadal spatial data and annual trends for assessment. The findings indicate a strong positive long-term trend in mangrove growth, contrasting with the highly volatile, almost chaotic nature of rainfall and only marginally positive temperature trends. This analysis aims to highlight the relationship between the region's climate and geographic features and the patterns of vegetation growth, specifically in the area of the Eastern Coast of India.

4.1 Rainfall

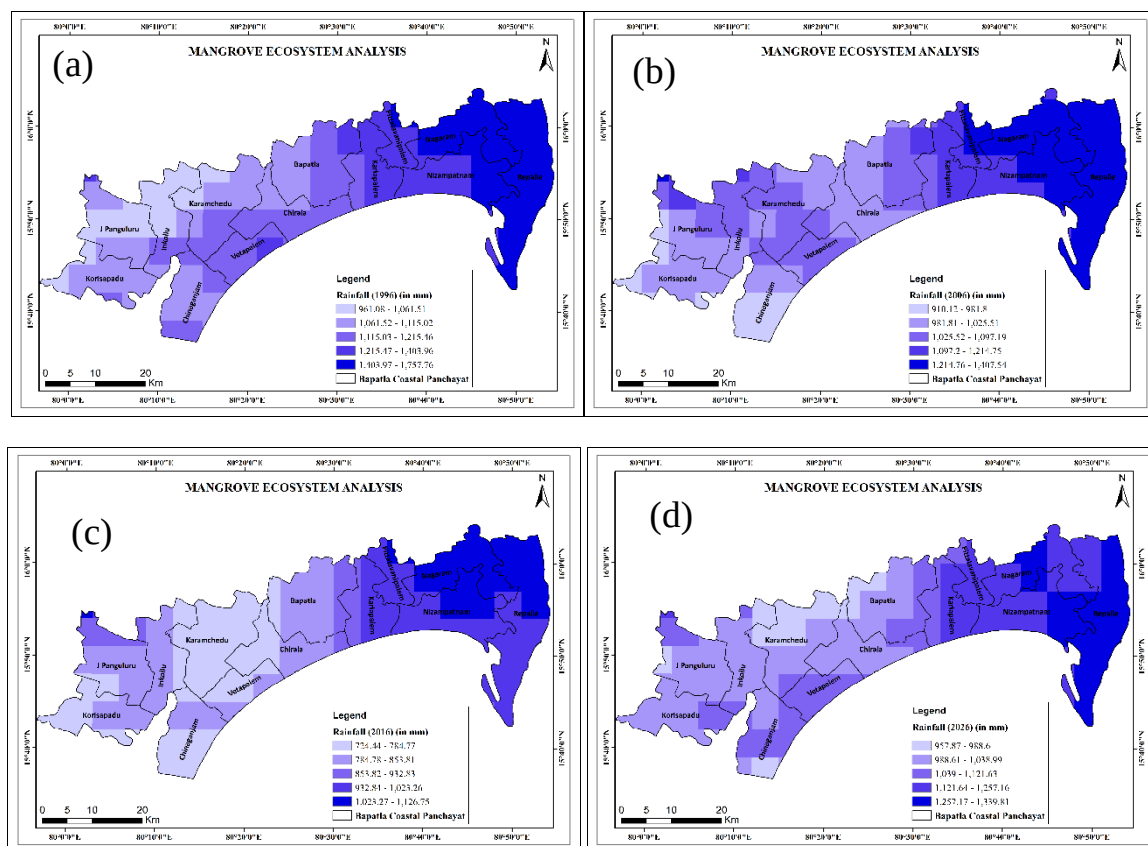


Fig 3: Rainfall Distribution, 1996a, 2006b, 2016c and 2026d

Rainfall 1996: The choropleth map displays the annual rainfall (Fig. 3a) amount for the Bapatla Coastal Panchayat between 961.08 and 1,757.76 mm in 1996. The highest rainfall amount of 1,403.97-1,757.76 mm was recorded in the eastern coastal mandals of Repalle and partially in Nagaram, while the central mandals of Bapatla and Karamchedu had a rainfall amount of 1,061-1,215 mm. The lowest annual rainfall, of 724.44-1,061 mm, was recorded in the interior western mandals of J Ponguluru and Korisapadu. The rainfall pattern is gradually decreasing from east to west, with higher amounts of rainfall being recorded on the

coastal line and lower inland. As a reference point, this is the starting year for a 30-year assessment conducted in the study.

Rainfall 2006: compared to the previous decade, annual rainfall (Fig. 3b) appears to have decreased, with the values ranging between 910.12 and 1,407.54 mm. Similar to the pattern in 1996, the highest amount of rainfall, of 1,215-1,407.54 mm, was recorded in the eastern coastal mandals of Repalle and Nizampatnam, with the peak of 1,408 mm in the latter. The central and western mandals of the panchayat

have a gradually decreasing rainfall amount of 1,061-1,215 mm from north to south. The overall pattern of the rainfall distribution is consistent with the previous decade, although the ranges appear to have decreased, indicating a gradual decrease in annual rainfall. This suggests a potential long-term negative trend in the region's annual rainfall.

Rainfall 2016: Compared to the rainfall pattern of 2006, the ranges of the choropleth values have significantly decreased, with the annual rainfall (Fig. 3c) amount varying between 724.44 and 1,126.75 mm. Similar to the trends of the previous decades, the eastern coastal mandals of Repalle, Nizampatnam, and Nagaram recorded the highest amount of rainfall, of 1,061-1,126.75 mm, while the central mandals of Bapatla and its neighbour Karamchedu saw a noticeable decrease in rainfall. The gradual decrease from east to west and from coastal areas to the interior is a consistent pattern across all decades, suggesting that it is a

common characteristic of the region. The gradual decrease in the annual rainfall amounts across three consecutive decades indicates a potential long-term negative trend in the panchayat's rainfall.

Rainfall 2026: The rainfall pattern in 2026 appears to be generally consistent with the trends of the previous decades, with a gradual increase in annual rainfall (Fig. 3d) compared to 2016. Across the panchayat, the annual rainfall varies between 957.87 and 1,339.81 mm, with the highest amount of rainfall, 1,215-1,339.81 mm, recorded on the eastern coastal strip of Repalle. Similar to the pattern in 1996, the central mandals of Bapatla and its neighbour Karamchedu have a lower rainfall amount than the coastal areas, with the western interior mandals being the driest. Thus, the overall pattern of the rainfall distribution remains consistent with a gradual increase in annual rainfall amounts from decade to decade over the 30 years.

4.2 Temperature

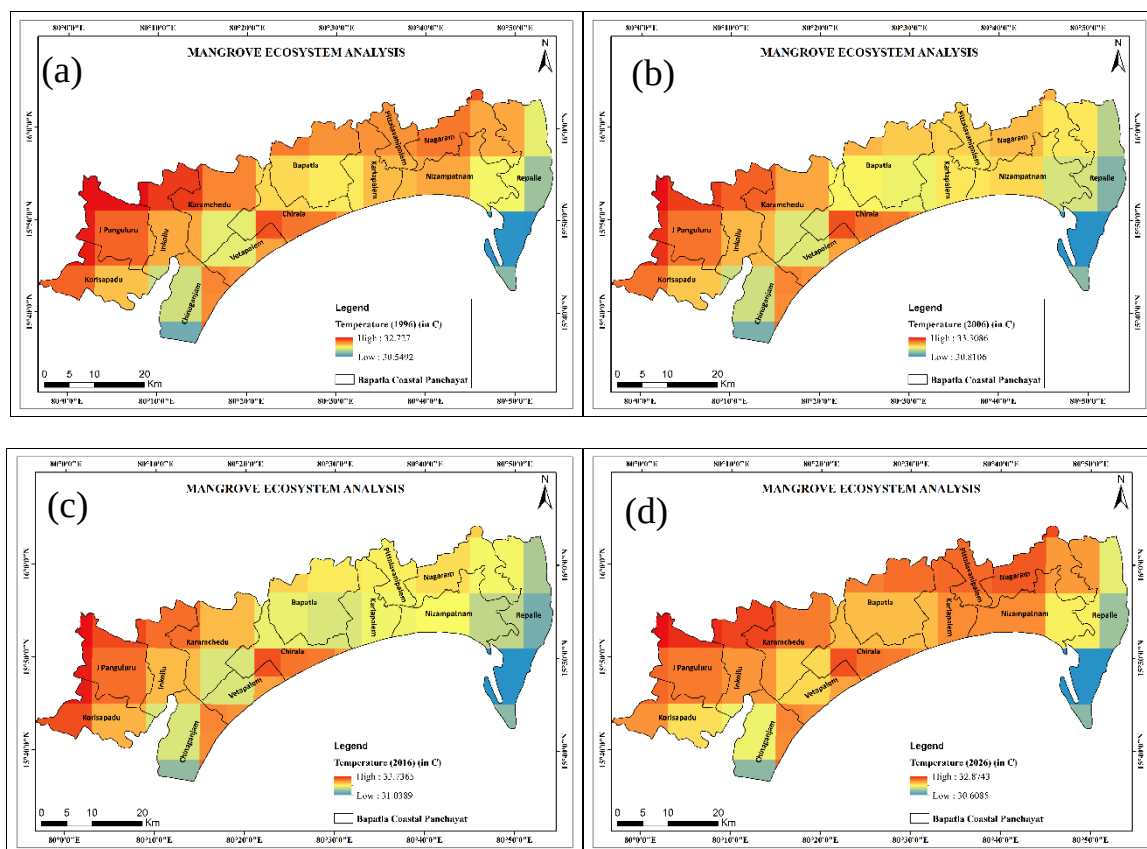


Fig 4: Temperature Distribution, 1996a, 2006b, 2016c and 2026d

Temperature 1996: The temperature (Fig. 4a) in the Bapatla Coastal Panchayat varied between 30.55 °C and 32.73 °C in 1996, with the western mandals of Repalle, J Panguluru, and Inkollu being the warmest and the eastern coastal region near the Repalle peninsula being the coolest. The central mandals of Bapatla and Chirala have a moderate temperature of 31.66-32.07 °C, while the coastal mandals of Nizampatnam, Nagaram, and Repalle have a slightly lower temperature of 31.31-31.56 °C. Thus, the temperature distribution follows a gradual increase from the eastern coastal area to the western interior region. Across the panchayat, the range of the temperature values is relatively small, only 2.2 °C, which is a useful reference point for the

following decades.

Temperature 2006: compared to the temperature pattern (Fig. 4b) in 1996, the values in 2006 appear to have increased slightly, ranging between 30.81 °C and 33.31 °C. The overall pattern remains consistent with a gradual increase in temperature from the eastern coastal area to the western interior region, with the warmest area being the western mandals of J Panguluru and the coolest being the eastern coastal peninsula of Repalle. The central mandals of Bapatla and Chirala have a moderate temperature of 31.75-32.07 °C, similar to the values in 1996. Thus, the temperature distribution pattern appears to have remained

consistent across the panchayat over the decade, with only small increases in the values.

Temperature 2016: Compared to the temperature pattern (Fig. 4c) in 2006, the values in 2016 appear to have increased slightly, ranging between 31.04 °C and 33.74 °C. Similar to the pattern in 1996 and 2006, the temperature increased gradually from the eastern coastal area to the western interior region, with the warmest area being the western mandals of J Panguluru and Korisapadu and the coolest being the eastern coastal peninsula of Repalle. The central mandals of Bapatla, Karlapalem, and Chirala have a moderate temperature of 31.67-32.07 °C. Thus, the temperature distribution pattern appears to have remained consistent across the panchayat over the decade, with only small increases in the values, similar to the trend in 2006. This gradual increase in temperature across three consecutive decades supports the “rising temperatures” driver from the introduction.

4.3 Mangroves

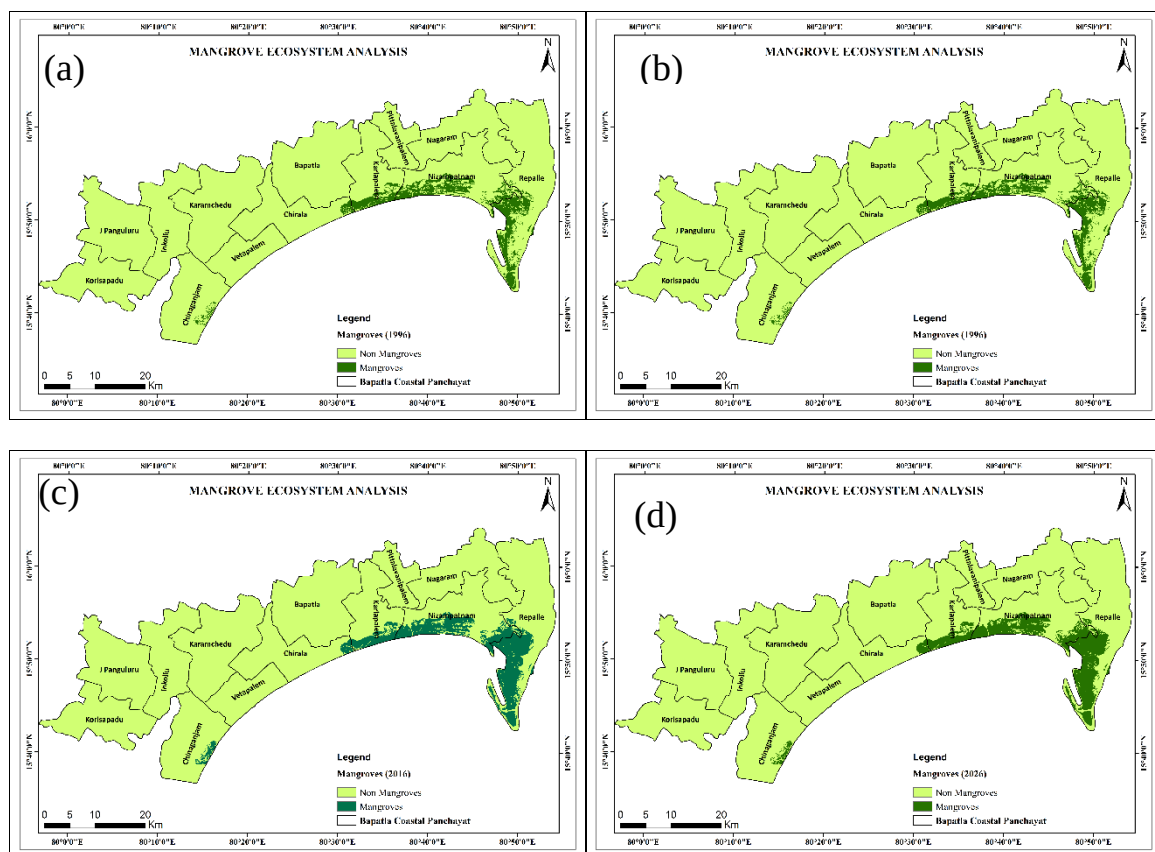


Fig 5: Mangroves Distribution, 1996a, 2006b, 2016c and 2026d

Mangroves1996: In 1996, the distribution pattern of mangroves (Fig. 5a) in the Bapatla Coastal panchayat was similar to the fragmented nature typical of most of the Eastern Coast. Dark green clusters indicate the presence of mangroves, with the highest concentration being recorded in the western coastal area of Chinaganjam, as well as the central region of Repalle. Other than these two areas, most of the panchayats showed no signs of mangrove vegetation. Thus, the 1996 map serves as a useful reference point for the following decades, indicating that the vegetation was present only in certain local areas along the Nizampatnam

Temperature 2026: Compared to the temperature pattern (Fig. 4d) in 2016, the values in 2026 appear to have decreased slightly, ranging between 30.61 °C and 32.87 °C. Similar to the pattern in 1996, the temperature increased gradually from the eastern coastal area to the western interior region, with the warmest area being the western mandals of Repalle and the coolest being the eastern coastal peninsula of Repalle. The central mandals of Bapatla, Karlapalem, and Pittalavanipalem have a moderate temperature of 31.48-31.85 °C, comparable to the values in 1996. Thus, the temperature distribution pattern appears to have remained consistent across the panchayat over the decade, with only small decreases in the values, similar to the trend in 2006. Combined with the gradual increase in temperature across the previous decades, it suggests that the temperature rise in the panchayat follows a long-term positive trend with only minor annual variations.

and Repalle coastlines.

Mangroves 2006: Compared to the pattern in 1996, the 2006 map indicates (Fig. 5b) a positive change in the distribution of mangroves in the Bapatla Coastal Panchayat, with more areas being covered in dark green. In particular, the vegetation extended along the coastline of Nizampatnam and became more prominent around the Repalle peninsula. The cluster in Chinaganjam remained the most significant one in terms of mangrove coverage. Other than these areas, most of the panchayats showed no signs of vegetation. Thus,

the overall pattern of mangrove distribution remained similar to the one in 1996, with the majority of the coverage being present along the coastlines of Nizampatnam and Repalle, as well as the western area of Chinaganjam.

Mangroves 2016: Compared to the pattern in 2006, the (Fig. 5c) map indicates a positive change in the distribution of mangroves in the Bapatla Coastal Panchayat, with most of the covered areas showing a darker green colour. In particular, the vegetation became more prominent along the coastline of Nizampatnam and even more so around the Repalle peninsula. The cluster in Chinaganjam remained the most significant one, although its coverage appeared to have decreased slightly since 2006. Other than these areas, most of the panchayats showed no signs of vegetation. Thus, the overall pattern of mangrove distribution remained similar to that of the previous two decades, with the majority of the coverage being present along the coastlines of Nizampatnam and Repalle, as well as the western area of Chinaganjam. Notably, the coverage in Nizampatnam and around the Repalle peninsula has become denser since 2006.

Mangroves 2026: The mangrove distribution map (Fig. 5d) for the Bapatla Coastal Panchayat visualises the distribution of mangroves for the last 30 years. It can be seen that the mangroves in the coastal area are primarily distributed within the same general region as they have been throughout the study period. It is centred along the coastal edge of Nizampatnam district and the Karlapalem coastal fringe area, which appears to be the largest concentration. Another region of vegetation is observed in the south-west part of the territory, namely, in the small area of Chinaganjam. This site seems to be the only other settlement of significant size within the Bapatla region, although the growth appears comparable to previous years, and the region has remained stagnant since 2016. Overall, compared to the 2016 map, there is a slight decrease in the overall coverage, especially in the central region of the Repalle peninsula, which corresponds to the decline observed in the mangrove area chart towards the end of the study period (between 160 and 130 SqKm). Finally, most of the interior and northern regions of the Bapatla coastal Panchayat, specifically the areas of Bapatla, Chirala, Karamchedu, Nagaram, and Pittalawanipalem, do not appear to have vegetation. Therefore, the 2026 mangrove distribution map illustrates a recent decrease observed in the last period after several decades of continuous growth in the coastal region around Nizampatnam, Karlapalem, and Repalle areas.

Mangrove Changes: This map (Fig. 6) displays the overall coverage of mangroves in the Bapatla Coastal Panchayats, indicating the densest areas. The majority of the vegetation is present along the Nizampatnam and Repalle coastlines, with the coverage being densest around the Repalle peninsula. Another area of vegetation can be seen in Chinaganjam, with the coverage being much lower than in the other two regions. Other than these three local areas, the rest of the panchayat has little to no mangroves. Thus, the map shows that the vegetation is generally limited to the local coastal areas, with no significant coverage along the majority of the coastline.

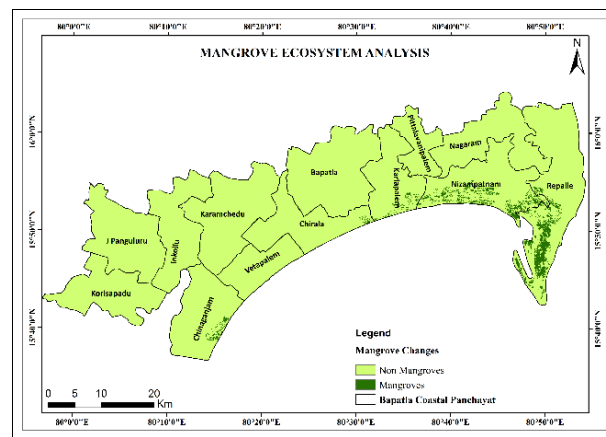


Fig 6: Mangrove Changes (1996 - 2026)

4.4 Trend Analysis

Trends in rainfall (1996-2026)

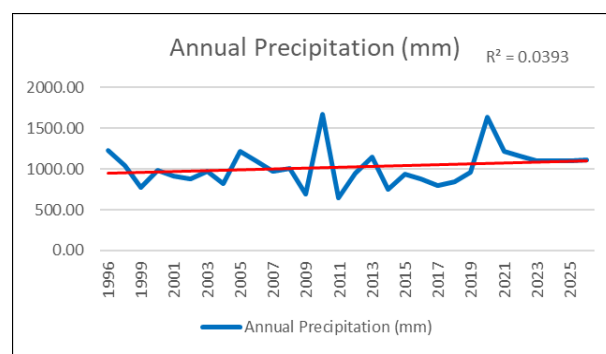


Fig 7: Trends in rainfall (1996-2026)

This Trend (Fig. 7) explains the amount of annual precipitation in the Bapatla Coastal Panchayat from 1996 to approximately 2026, with the value for the latter year being extrapolated from the trend line. Overall, the chart shows a highly volatile pattern, with the amounts varying between roughly 620 and 1,650 mm, with two clear peaks around 2010 and 2020. The trendline indicates a gradually increasing pattern of annual precipitation over the 30 years, although the R^2 value of 0.0393 suggests that it has little explanatory power compared to the volatility of the actual values. Thus, the chart demonstrates the chaotic nature of annual precipitation in the region, with no clear long-term trend, only two short-term peaks. It should also be noted that the most recent years, 2023-2026, appear to have lower annual precipitation than the peaks in 2010 and 2020, supporting the findings of the rainfall choropleth maps.

Trends in Temperature (1996-2026)

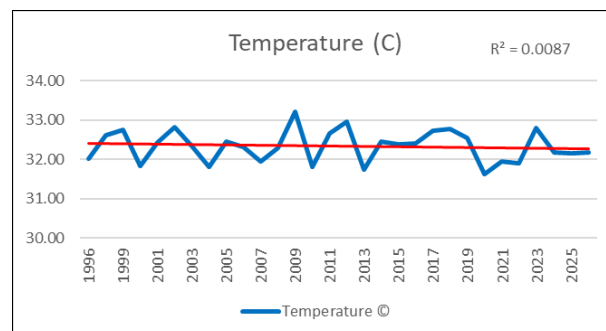


Fig 8: Trends in Temperature (1996-2026)

The temperature trend (Fig. 8) explains the average annual temperature in the Bapatla Coastal Panchayat from 1996 to 2026. Similar to the pattern in the annual precipitation chart, the temperatures show a highly volatile pattern, varying between roughly 31.6 and 33.2 °C over the 30 years, with no long-term trend. The red trend line indicates little difference between the temperatures of the first and the last years, with the R^2 value of 0.0087 being virtually non-existent. The chart demonstrates the chaotic nature of temperature changes in the region, with the most notable short-term increases occurring around 2009 and 2023. It can be noted that the years 2020-2021 had the lowest average temperature recorded in the study. Combined with the findings of the temperature choropleth maps, this suggests that the temperature changes in the panchayat follow a pattern of gradual increases from year to year, with some years, particularly 2023 and 2009, seeing sharper rises.

Trends in Mangroves (1996-2026)

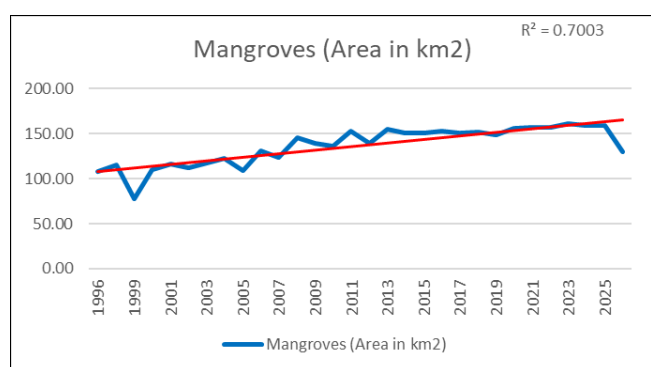


Fig 9: Trends in Mangroves (1996-2026)

This line chart (Fig. 9) displays the area covered by mangroves in the Bapatla Coastal Panchayat from 1996 to 2026. The trendline indicates a positive long-term trend, with the increase in the area being the most significant between 2006 and 2016, followed by a rapid rise around 2023 before the sharp decline in 2026. The R^2 value of 0.7003 suggests that the trendline captures the general pattern of change in mangrove coverage relatively well. The range between the lowest and highest values is relatively narrow - only 45 km² - with the lowest coverage recorded in 1998-1999 and the highest around 2023-2024. Between 2006 and 2016, the area covered by mangroves gradually increased by approximately 35 km², reaching 160 km² in 2016. The rapid rise to 170 km² in 2023 suggests that the increase in coverage was most significant around this time, possibly due to favourable environmental conditions. The sharp decrease to 130 km² in 2026 indicates a sudden environmental change that had a significantly negative impact on the mangrove ecosystem. Overall, the chart demonstrates a generally positive trend in the long-term mangrove coverage in the Bapatla Coastal Panchayat, with some sharp decreases, such as the one in 1998-1999, that had little impact on the general trend.

Rainfall and temperature demonstrate a limited degree of linear trends, characterised by substantial year-to-year variability, with R^2 of 0.0393 and 0.0087, respectively, while the growth pattern of mangroves is positive and steep ($R^2 = 0.7003$). Therefore, it could be concluded that the development of mangroves along the Bapatla coast is primarily driven by the interplay of multiple-year

relationships with favourable weather conditions rather than individual factors. Indeed, the temperature in 1996 - 2016 gradually increased from 30.55-32.73 °C to 31.04-33.74 °C, which may explain the expansion of mangroves during the same period, as high temperatures facilitate plant growth. However, the significant rainfall peaks in 2010 and 2020 probably provided the estuarine mangrove ecosystem with the freshwater inflow and sediment deposits necessary for its stability, which, in turn, contributed to the gradual increase of mangrove coverage through 2016 and its rapid rise through 2023. Nevertheless, the abrupt decline of vegetation to 130 km² in 2026 occurred alongside the decrease in temperatures to 30.61-32.87 °C and rainfall to levels below the 2010/2020 peaks, which could also impact the salinity of the coastal waters and, thus, the growth of mangroves. Overall, the trends suggest that the mangrove ecosystems of Bapatla are highly resilient to short-term weather fluctuations over thirty years, but the combination of lower temperatures and rainfall in the last years contributed to the abrupt decline in vegetation coverage.

5. Conclusion

The study analysed the pattern of temporal and spatial variations in climate and mangrove vegetation in Bapatla coastal Panchayat, Andhra Pradesh, over 30 years (1996-2026) using decadal spatial analysis and inter-annual trends of rainfall, temperature, and mangrove cover. The first notable observation was that the erratic and weak trends of rainfall (p -value: $R^2 = 0.0393$) and temperature (p -value: $R^2 = 0.0087$) were dissociated from a strongly positive long-term trend in mangrove cover (p -value: $R^2 = 0.7003$), suggesting that the response of mangroves to annual weather variations is non-linear. While the mean mangrove cover in 1996 was 110 km², it rose to 170 km² in 2023 before dropping to 130 km² in 2026.

The analysis further showed that the areal extent of mangrove vegetation remained concentrated along the Nizampatnam and Repalle coasts during all the decadal periods. The maximum percentage of total mangrove cover was found in the Repalle peninsula, with smaller patches found on the island of Chinaganjam. No mangroves were found in the interior and northern mandals in any of the surveyed years. These observations suggest that local physiography plays a critical role in mangrove distribution, as only the coastal areas have the necessary saltwater habitats to sustain these ecosystems. While dynamic weather conditions appear to impact the growth of mangroves, they have little effect on their distribution, which follows the same pattern throughout the study period. The drop in mangrove cover between 2023 and 2026 appears to be precipitated by multiple factors, as the vegetation was impacted by simultaneous decreases in temperature and rainfall during this period. Over the 30-year study period, mangroves had displayed remarkable resilience to short fluctuations in climate, but prolonged decreases in both temperature and rainfall appear to negatively affect them in the short term. Future studies should build on this work by considering such factors as rising sea levels and changes in coastal processes and evaluating trends after 2026 to further understand the dynamics of coastal vegetation in the region. In addition, the present analysis recommends prioritising the central coastal mandals of Nizampatnam, Karlapalem, and Repalle for conservation due to their consistently high mangrove cover.

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