

Assessing Climate Change Vulnerability in Coastal Ecosystems Using Remote Sensing

Dr. Jayant Awasthy¹, Dr. Anita Nigam², Praveen Balasaheb Gandugade³, Aniruddha Purohit⁴, Pooja Mailsamy⁵
and Chandan Kumar⁶

¹Professor, Department of Civil Engineering, Acropolis Institute of Technology and Research, Indore, Madhya Pradesh, INDIA.

²Assistant Professor, Department of Geography, D. B. S. College, Kanpur, Uttar Pradesh, INDIA.

³Assistant Professor, Department of Physics, Shivraj College, Gadhinglaj, Kolhapur – 416502, Maharashtra, INDIA.

⁴Assistant Professor, Department of Physics, Rajarambapu Paramount Academy (RIT), Rajaramnagar, Ishwarpur – 415414, Maharashtra, INDIA.

⁵Assistant Professor, BMS College of Architecture, Design & Planning, INDIA.

⁶Department of Civil Engineering, Government Engineering College Banka, Bihar Engineering University, Patna – 800001, Bihar, INDIA.

¹Corresponding Author: jayantawasthy@acropolis.in



www.jrasb.com || Vol. 5 No. 1 (2026): February Issue

Received: 23-01-2026

Revised: 26-01-2026

Accepted: 30-01-2026

ABSTRACT

Coastal ecosystems are among the most economically active and ecologically important in the world, biodiversity, climate control, shoreline protection, and millions of livelihoods of people on the planet. Nevertheless, the complex effects of climate change, such as rise in sea level, frequency and intensity of extreme weather events and ocean warming, salinity intrusion, coastal erosion as well as habitat degradation are increasingly threatening these ecosystems. The vulnerability of the coastal ecosystems is thus becoming a key scientific and policy issue. Conventional methods of vulnerability measurement, relying on the efforts of field survey and local observation, are usually constrained in their spatial domain, temporal coverage, availability, and monetary aspect. In this regard, remote sensing technology offers a viable, scaled, and scientifically sound substitute to the tracking and assessment of effects of climate change on coastal infrastructure.

This paper discusses how multi-source remote sensing data can be used to determine the vulnerability to climate change in coastal ecosystems using a combined spatial and temporal analysis system. Optical, radar and elevation based satellite data is used to follow indicators of critical vulnerability such as shoreline processes, vegetation condition, land cover changes and inundation. This research establishes both progressive environmental changes and instances of sudden disturbance by the use of the long-term satellite archives to enable a holistic view of the ecosystem exposure and sensitivity. The methods of measuring ecosystem responses to climatic stressors include advanced image processing techniques, spectral indices, change detection techniques, and geographic information system (GIS)-based modeling.

The paper also establishes a complex vulnerability model that is founded on the generally agreeable dimensions of exposure and sensitivity, and adaptive capacity. These elements are spatially modeled to find regions of high risk in coastal setting which can be applied in conservation planning, disaster risk reduction and climate adaptation measures. The results show that remote sensing does not only increase the accuracy and efficiency of vulnerability assessment, but also contributes to sound-based policymaking by providing timely and objective data on large and often inaccessible coastal areas. Conclusively, the study highlights how remote sensing is of crucial importance in enhancing climate resilience and sustainable governance of coastal ecosystems in a world that is rapidly changing in terms of environmental change.

Keywords- Coastal ecosystems, Climate change vulnerability, Remote sensing, Shoreline dynamics, Vegetation health, Inundation risk, GIS-based modeling

I. INTRODUCTION

The coastal ecosystems create an interactive boundary between the land and sea and are essential in the preservation of ecological balance and well being of man[1]. These ecosystems which are mangroves, salt marshes, coral reefs, seagrass beds, beaches, and estuaries, are known to offer very important ecosystem services like stability of the shoreline, carbon, nutrient cycling, fisheries support, storm surge, and coastal flood mitigation. Although coastal ecosystems are important, they are some of the most susceptible to climatic changes because they are relatively low, they are close to the ocean, as well as they are exposed to severe climatic conditions.

The issue of climate change presents direct and indirect risks to the coastal systems. Increased sea level causes coastal flooding, intrusion of sea waters, and habitat destruction, and rising sea surface temperatures cause coral bleaching and species redistribution. Increased storms and cyclones speed up the erosion process and destruction of the natural coastal defenses. Moreover, climate change plays with other human impacts like urbanization, industrialization, tourism, and aquaculture that adds to the degradation of the ecosystem. It is vital to know the area of these impacts as well as the extent of magnitude to formulate mitigation and adaptation measures.

To measure climate change vulnerability, one must have extensive data on the exposure of the ecosystems to the hazards, their sensitivity to the changes in the environment and their adaptability or recovery capacity. Traditional methods of assessment frequently use field observations and social-ecological surveys, the value of which is confined to the need to record massive and long-term alterations[2]. The solution to these limitations is remote sensing, which can be used to monitor the coastal environments both spatially and over a long period.

Coastal monitoring has been transformed by the latest development of satellite technology such as high-resolution optical imagery, synthetic aperture radar (SAR) and satellite altimetry. Such instruments enable scientists to identify the subtle shifts in land cover, shoreline location, vegetation status and inundation patterns at a higher accuracy. Remote sensing data can be a very strong framework of assessing the vulnerability of climate change in coastal ecosystems when incorporated with the GIS and the spatial modeling techniques. This research will use the technologies to create a methodical and repeatable manner of assessing of coastal vulnerability and assisting in sustainable management of the coastal areas.

II. LITERATURE REVIEW

Climate change has been known to pose a threat to the wellbeing of coastal ecosystems, and environmental

and geospatial studies have strongly reported on this vulnerability. The main conceptualization of vulnerability used in vulnerability assessments is as a product of exposure, sensitivity and adapting capacity, which the Intergovernmental Panel on Climate Change (IPCC) uses. Exposure describes the scale and the amount of the occurrence of climatic stressors, sensitivity describes the level to which the ecosystems react to these stressors, and adaptive capacity describes the capability of the systems to endure, recuperate or adapt.

Initial research on coastal vulnerability was based mostly on earth studies and archives to determine a change in the shoreline, frequency of flooding and loss of habitat. Although these approaches were useful in giving insight into local scales, they did not cover space and time to comprehend the coastal processes on a large scale[3]. With the advent of satellite remote sensing, it became much easier to observe the coastal environments, since one was in a position to observe uniformly through space and time.

The satellite information found in optical satellites e.g. Landsat and Sentinel-2 has been highly utilized in evaluating any change in land cover, vegetation structure and movement along the coastlines. The normal vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) have been found to be useful in the tracking of mangrove health, salt marsh productivity and recovery after disturbance[4]. The time-series studies over a long period of time show slow-paced ecosystem degradation that is associated with rising sea-level and enhancing salinity stress levels.

A significant area of coastal remote sensing studies is on shoreline change. Methods used in extracting shoreline locations using multi-temporal imagery have included spectral water indices, edge detection algorithms as well as object-based image analysis. Such tools as the Digital Shoreline Analysis System (DSAS) have become a common means of estimating the velocity of erosion and accretion as a way to obtain quantitative data about the instability of the coastline.

priority has been given to radar remote sensing, especially Synthetic Aperture Radar (SAR), which has been found to be able to operate through the cloud cover and also performs in all weather conditions. The data acquired by Sentinel-1 SAR have been successfully utilized to map the changes in coastal flooding, wetland areas and surface roughness. The radar backscatter variations are quite effective in detecting the patterns of inundation as well as the alteration of the vegetation structure in mangrove forest.

DEMs based on satellite missions e.g., SRTM and ICESat have made possible evaluations of elevation dependent vulnerability. Sea-level rise is particularly vulnerable to low-lying coastal regions and elevation-based models have assisted in determining areas vulnerable to either permanent or temporary permanent

floods. DEMs are useful in exposure analysis when they are used together with tidal and storm surge models. The recent literature indicates the relevance of incorporating the multi-sensor remote sensing data alongside the GIS-based vulnerability frameworks. Increasing research uses machine learning algorithms to assess land cover and predictive models, including the Random Forest and Support Vector Machines. With such achievements, there are still challenges such as the inability to resolve some forms of data, uncertainty in the weighting of vulnerability indicators, and wanton ground validation[5]. The literature, nevertheless, is always in favor of remote sensing as a very important instrument of gauging and managing the vulnerability of climate change on the coastal ecosystem.

III. OBJECTIVES

- To discover remote sensing products that could be used to assess the coastal vulnerability.
- To come up with a methodological framework that combines both satellite data and spatial analysis.
- To measure the change of the important indicators of shoreline position, vegetation health and land cover.
- To suggest vulnerability indices to manage the coastal ecosystem.

IV. STUDY AREA

This is an example of a mosaic of natural habitats and anthropogenic landscapes that are in a typical low-lying coastal ecosystem[6]. The area has mangrove forests, sandy beaches, estuaries, tidal flats and near shore waters meaning that it is very sensitive to climatic and oceanographic variations. The climate in the coastal zone is the tropical or subtropical climate with well-defined wet and dry seasons, which affect the processes in hydrology and vegetation. The geography of the research location is mostly flat with the heights not exceeding ten meters above the mean sea level. This low elevation will be prone to sea-level rise, tidal flooding, storm surge, and saltwater intrusion. The river systems flow to the coastal zone bringing with them nutrients and sediments but also raising the risk of floods during rain-induced occurrences of excess[7]. Due to interactions of freshwater inflows with marine processes, the existing environmental conditions become dynamic and highly susceptible to climate variations.

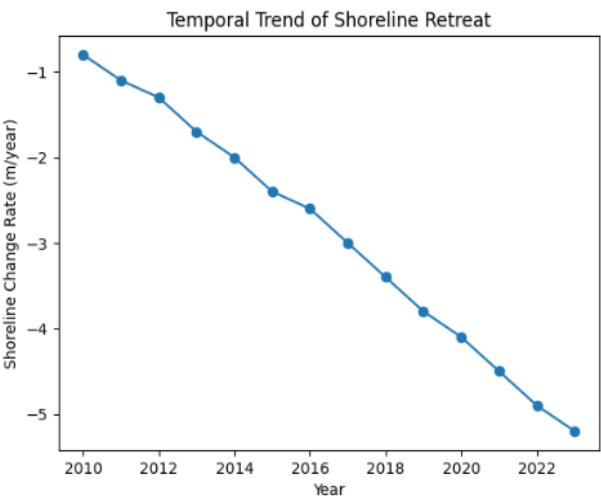


Figure 1. Temporal Trend of Shoreline Retreat

There is a lot of pressure on the study area as a result of human activities. Coastal communities, ports, aquaculture farms, and tourist infrastructures have grown at a high rate at the costs of the natural habitats. The clearing of mangroves, land reclamation, and natural urbanization decrease the natural sustainability of the coastline ecosystems and enhance climate-related hazards[8]. The combination of climate and human-created vulnerability is best evaluated in the region due to these man-made forces.

The study region was chosen because of the satellite data that has been recorded over a long period, climate-related effects, and ecological importance. Its varied habitat condition is the reason that it is possible to compare the vulnerability of this structure across various coastal environments. This knowledge on coastal patterns of vulnerability in such a representative coastal environment has lessons that can be applied in other like regions around the world and in the creation of scalable remote sensing based assessment systems[9].

V. DATA AND METHODOLOGY

In this work, the researcher is using an integrated remote sensing and GIS-based research approach to measure climate change vulnerability in coastal ecosystems. To obtain a full assessment of vulnerability indicators, there are a variety of satellite datasets that capture the degree of biophysical changes in time and space.

5.1 Data Sources

Data Type	Sensor/Platform	Purpose
Optical imagery	Landsat 8 OLI	Long-term vegetation and land cover change

High-resolution imagery	Sentinel-2 MSI	Detailed shoreline and habitat mapping
Radar imagery	Sentinel-1 SAR	Detection of flooding and structural change
DEM	SRTM/AW3D30	Elevation and inundation potential
Sea-level data	Satellite altimetry	Trends in sea-level change

Multi-temporal optical satellite images of Landsat 8 Operational Land Imager (OLI) and Sentinel-2 MultiSpectral Instrument (MSI) are the principal sources of data to be used in land cover mapping, vegetation analysis, and shoreline detection. These datasets provide moderate or high spatial resolution and long term continuity hence they are useful in the trend analysis. Sentinel-1 Synthetic Aperture Radar (SAR) data images are applied in mapping the inundation and extent of wetlands especially in places that have persistent cloud cover. Topography Digital elevation data that are available through the Shuttle Radar Topography Mission (SRTM) are utilized to examine the exposure to sea-level rise based on elevation.

5.2 Data Preprocessing

Radiometric calibration of all satellite images as well as atmospheric correction is performed so as to make consistency across time. Cloud masking algorithms are used to process optical images in order to eliminate the contamination of clouds and shadows. The datasets are aligned with the help of geometric correction and co-registration. The radar images undergo speckle filtration and radiometric calibration as well as terrain correction to improve the ability of these images to be interpreted.

5.3. The classification of land cover and habitat mapping.

Supervised classification methods are used to categorize land covers into mangroves, water bodies, built-up areas, agricultural land, and barren surfaces. Supervised classification such as Random Forest algorithms are used to classify land covers in relation to the specified categories. The sampling of training samples will be done using visual interpretation and available land use maps. Confusion matrices and kappa statistics are used to determine the accuracy of classification.

5.4 Shoreline Change Detection

The spectral water indices like the Normalized Difference Water Index (NDWI) are used to extract positions of the shorelines. GIS-based tools are used to analyze the multi-temporal shoreline vectors to determine the erosion and accretion rates. These measurements are important measures of exposure to the coastal processes.

This module is designed to evaluate vegetation health following the guidelines of the Australian Bureau of Statistics (2009).<|human|>5.5 Vegetation Health Assessment This module will help to assess vegetation

health in accordance with the Australian Bureau of Statistics (2009).

The NDVI time-series analysis is used to analyze the health and productivity of vegetation. The NDVI values are studied to detect trends which are indicative of long-term stress or degradation in an area as a result of salinity intrusion, long time inundation or temperature deviations.

5.6 Analysis of Inundation and Elevation.

During extreme events, the flooded zones are also detected by using SAR image and the low areas that are prone to permanent or episodic flooding are detected with the help of DEMs. Overlay analysis combines the elevation data, land cover data and flood frequency data to determine the spatial exposure[10].

5.7 Vulnerability Index Development.

A composite vulnerability index is developed by taking an amalgamation of exposure, sensitivity and adaptive capacity indicators. The indicators are all normalized and weighted according to the expert judgment and literature search. Bases on the resultant vulnerability maps, high-risk zones can be realized and assisted in special management interventions.

VI. RESULTS

The findings of this work provide an inclusive spatial and temporal evaluation of the vulnerability of climate change in coastal ecosystems with multi-source remote sensing data. The combination of optical, radar, and elevation data offers the analysis of both slow environmental changes and disturbances. The results are structured based on the main signs of vulnerability such as shoreline dynamics and changes in vegetation, habitat change, and flood-prone areas[11]. A combination of these findings indicates a definite exposure, sensitivity and environmental stress in the coastal environment.

6.1 Shoreline Dynamics

Dynamics of the shoreline form one of the most visible and serious evidence of the effects of climate change on coastal ecosystems. The review of multi-temporal satellite data during the last decade indicates that there is a significant loss of shoreline in most areas of the study site. With coastline extraction methods that are grounded on spectrophotometers of water indices and GIS, which are utilized in detecting changes, an observation was made that a number of coastal areas are experiencing rates of erosion more than multiple meters per annum. These values are much higher than the historical averages given in previous research indicating a rise in the speed of coastal degradation.

The area-level distribution of shoreline change is disproportionate in that it is a result of the complicated interaction of natural forces and human activities. Exposure coastlines especially that with no natural protective features like mangroves or dunes records the highest erosion rates. Conversely, locations where the mangrove belts are intact as well as in places of sediment

deposition exhibit comparatively smaller erosion or some local accretion. This spatial variability highlights the need of the ecosystem-based coastal protection systems[13].

Temporal analysis has shown that the shoreline retreat is closely related to extreme weather conditions such as cyclones, storm surges and high-energy wave conditions. The position of the shorelines shifts abruptly to landward, and the satellite images recorded before and after the significant storm events indicate the power of episodic disturbances in the rapid change of the coast. Also tidal variations and seasonal monsoon cycles also have an effect on short-term shoreline changes, but the long run trends always show net erosion.

Anthropogenic factors also contribute to instability of the coastline. The processes of building coastal areas, sand mining, building of ports, and clearing natural vegetation interfere with the processes of sediment transport and decrease the strength of the coastal systems. Evidence of remote sensing reveals that regions with high human activity register faster shoreline withdrawal than relatively undisturbed regions[15]. The results are highlighting the compounding effect of climate change and the anthropogenic pressures on the coastal morphology.

In general, the analysis of the shoreline dynamics shows that the research site is experiencing a dramatic physical change, which directly affects the integrity of the ecosystem, safety of infrastructure and human lives. The trends that were noted show that there is a high level of exposure to risks associated with climate and that there is a need to ensure that adaptive coastal management plans are implemented as soon as possible.

6.2 Vegetation Trends

Vegetation health and distribution are the most sensitive indicators of ecosystem to climate change. Mangroves, salt marshes and seagrasses found in coastal areas are very crucial in stabilizing the shoreline, absorbing waves and sustaining bio life in the coastal area. The analysis on the NDVI as a multi-year period indicates a severe loss of vegetation vigor especially in areas where mangroves are concentrated.

The time-series analysis of NDVI demonstrates the average vegetation index values have a steep downward trend, which reflects a decrease in photosynthetic activity and biomass. Although it is clear that seasonal changes exist, i.e. natural growth cycles and climatic changes; the long-term trend denotes a consistent stress to the ecosystem. Previously dense and healthy mangrove cover areas have been recorded to have patchy vegetation and lower density of canopy cover.

Extended flooding that comes with the rise in sea level is one of the primary points that contribute to vegetation loss. Remote sensing information shows that low tidal mangrove regions are experiencing more time and occurrence of tidal floods which make root systems to face oxygen stress and hence low plant productivity. Further stress on vegetation is caused by salinity intrusion which is predetermined by the increase in sea level and

decreased inflow of freshwater, especially in estuarine environments.

Vegetation degradation is also caused by extreme weather events. The physical impacts of the cyclonic storms to the vegetation are uprooting, defoliation, and deposition of sediment. The values of NDVI at the time of significant storm occurrences are characterized by steep drops with partial recovery in some regions being witnessed over the next few months. Repeated disturbances however restrain the ability of vegetation to recuperate completely causing a cumulative degradation[20].

Vegetation loss is directly related to anthropogenic activities such as deforestation, aquaculture and infrastructure development. Confidential satellite images indicate that the deforestation of mangroves to build shrimp farms and other developmental activities in coastal areas has greatly diminished the vegetation in various areas. These activities do not only reduce the ecosystem services, but also predispose to climatic impacts due to the loss of natural protection barriers.

The loss of coastal vegetation has very extensive ecological and socio-economic consequences. The disappearance of mangroves leads to the decrease of carbon sequestration and erosion of the shoreline and jeopardizes fisheries that rely on mangroves habitat. The vegetation patterns identified in this research emphasize the sensitive character of ecosystem and decreased ability to adapt, which supports the necessity of implementation of the specific conservation and restoration strategies.

6.3 Habitat Transformation

The change of land cover and habitat is one of the most important aspects of the coastal vulnerability that is mirrored by the environmental change and the human presence. Multi-temporal satellite imagery is classified under supervision and the results show that there are considerable changes in land cover composition through the period of study. The natural ecosystems like marshlands, mangrove, and tidal flats have reduced and the poor land, the aquaculture ponds, and the cities have increased[22].

The analysis of transition matrices suggests that the percentage of natural habitats has been shifted to anthropogenic land use by a significant percentage. This is especially true of the marshlands and mangrove forests, which have been replaced by aquaculture farms and urban areas. These transformations are usually irreversible and lead to permanent absenteeism of ecosystem functions.

The geographical distribution of habitat change is closely associated with accessibility and economical activity. Regions around roads, ports and settlements have been found to experience the most land cover change implying that the development pressures are contributing greatly to the loss of habitats. Data on remote sensing demonstrate the discontinuous landscapes with the natural habitats left more and more isolated, making them less ecologically connected and resilient.

The climate change is a direct and indirect factor of habitat change[23]. The rise of the sea level and floods positions some regions inappropriate to traditional land use methods and compel change to aquaculture or abandonment. On the other hand, incapacitated ecosystems cannot sustain climatic stresses; this involves a feedback cycle that increases the rate of loss of habitats.

The changes in habitat have a drastic impact on the biodiversity and ecosystem services. The destruction of wetlands and mangroves decreases fish nursery areas, decreases water quality regulation and exposes them to coastal risks. The findings prove that not only climate change but also habitat degradation contributes to the increase of vulnerability.

These findings provide significance of incorporating land use planning with climate adaptation strategies[24]. The monitoring of habitats with the help of remote sensing can be a good source of information on the rate and cause of change and, therefore, allow an early intervention and making informed decisions.

6.4 Flood-Prone Zones

Another significant type of hazard due to climate is flooding, which impacts the coastal ecosystems and human settlements. This paper will find the spatial patterns and temporal trends of flood-prone areas in the study area by combining the digital elevation models with the Sentinel-1 SAR data. The findings show that there is a marked increase in the size of the territories that are susceptible to episodic and chronic flooding.

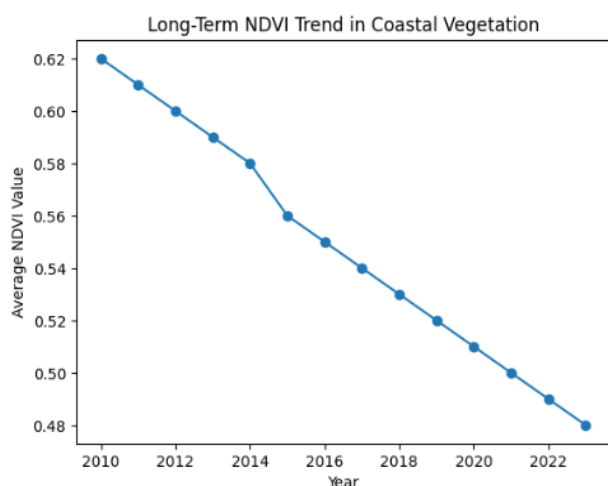


Figure 2. Long-Term NDVI Trend in Coastal Vegetation

Flood monitoring using SAR has shown that low lying coastal flats, estuarine areas, and around river mouths are usually prone to inundation especially during monsoon period and other extreme weather conditions[25]. These high-prone areas have been growing with time, which is in line with the rise of sea levels and intensity of precipitations. Elevation analysis justifies the fact that regions with elevation below critical levels of elevation are highly prone to sustained flooding.

Notably, most areas that have a high ecological value such as mangrove, wetlands, and estuaries overlap with flood-prone areas. Although such ecosystems are naturally suited to infrequent flooding, greater frequency and duration of such occurrences are more than the adaptive capacity of these ecosystems, which then results in stress and habitats deterioration on vegetation. The coincidence between the eco-significance and the flood risk is a key issue that challenges the management of coastal areas.

There are also serious socio-economic consequences of flooding[28]. The remote sensing data states that the rising human settlements and infrastructure in flood-prone areas are becoming more and more intersecting, which is of concern due to displacement, loss of economic, and human security. Informal settlements in low zones are especially prone and do not have sufficient protection infrastructure and resilience.

Combination of SAR and DEM data is particularly useful in flood mapping since radar data allow making accurate detection during cloudy weather conditions and active floods scenarios. These findings show that remote sensing is effective in detecting the hotspots of flood risk and the results can be used to develop early warning systems and adaptive planning.

VII. DISCUSSION

The findings in this paper offer strong proof of growing vulnerability of the coastal ecosystems to climate change. These findings are presented in the context of the overall environmental and management frameworks by observing physical, biological and spatial indicators.

7.1 Implications of Change

These changes in the shoreline recession, vegetation loss, habitat reconfiguration, and flood proliferation are all indicative of the rapid susceptibility of coastal ecosystems to climate change. Erosion of the shoreline also poses a threat to the natural habitats, also to critical infrastructure, such as roads, port, and settlements. Excessive exposure to storm surge and wave action is made worse by the loss of natural buffers, like mangroves, where loss of one leads to greater risk exposure, and so on.

The loss of vegetation has ripple effect on services to the ecosystem. This decreases coverage of mangrove as it reduces carbon sequestration potential and hence demeans climate mitigation programs. The decreased vegetation health also impacts fisheries productivity and biodiversity endangering food security and livelihood in the coastal communities.

Climate and human pressure are the dynamics that lead to habitat change, which is an indication of a decreased adaptive capacity. Less resilient to climatic stress, fragmented and degraded ecosystems are more prone to a change that is irreversible. Further exposure to a vulnerable situation is highlighted by the growth of

flood prone areas, especially those that are marginalized and reside in low-lying regions.

These results demonstrate an urgent necessity in the integrated coastal management practices, which consider not only the environmental, but also the socio-economic aspects of vulnerability. Such approaches are critical evidence based by remote sensing, which allows providing proactive instead of reactive responses to climate change.

7.2 Strengths and Limitations

Strengths

One of the main strengths of the given research is the use of several remote sensing variables that combine optical, radar, and elevation data sets in order to address various features of coastal vulnerability[29]. The trend analysis is done with long-term satellite archives, which allows one to analyze it on the basis of decadal scales and to increase the accuracy of the results. Spatial analysis made possible through GIS can be extensively used in mapping areas of vulnerability hotspots where desired interventions can be implemented.

Limitations

These strengths notwithstanding, there are a number of weaknesses that have to be admitted. The cover causes variations in quality and availability of optical images especially during monsoon seasons. Although SAR data reduce this problem, radar imagery is restricted in the spatial resolution and interpretation complexity. Besides, there are scarce ground truth data, which limit the classification and vulnerability index validation. In future research, field observations and socio-economic data need to be combined to enhance the accuracy of the assessment.

VIII. RECOMMENDATIONS ON POLICY AND MANAGEMENT

The results of the current study have significant implications on the policy and management of the coasts. Vulnerability maps that are remote sensing-generated must be incorporated in planning to protect the coast as well as land use. By outlining the high-risk areas, the policymakers can focus on those areas to intervene by erosion control or other restoration of habitats and strengthening infrastructure.

Adaptation strategies should be focused on ecosystems, especially mangroves and wetlands restoration and conservation[30]. These ecosystems offer sustainable protection to climate effects at a low cost. The restoration efforts should be done in areas that are detected to be highly vulnerable using the remote sensing analysis.

There should be institutionalization of long-term monitoring programs through satellite data to monitor the change in the environment and to assess management intervention success. Local integration of knowledge and community-based monitoring should be used to complement such programs.

Lastly, the local communities should be actively engaged in the adaptation planning. Resilience to community created by enlightenment, capacity building, and participatory planning promotes the adaptive capacity and makes management approaches socially equitable and sustainable.

IX. CONCLUSION

The study shows that remote sensing is very important in evaluating climate change vulnerability within coastal ecosystems. Having measured changes in shoreline dynamics, vegetation health, changes in habitat, and flood risk, the study has given a complete picture of how coastal systems are adapting to climatic and anthropogenic forces. The findings point to the need to accelerate vulnerability and reduce resilience, with the vitality of adaptive management being pointed out.

Remote sensing has never before provided benefits as far as spatial coverage, time continuity and analytical consistency is concerned. Combined with GIS and vulnerability systems, satellite-based data can be used as potent evidence-based decision-makers. Further investment in remote sensing resources, data availability, and research across disciplines will be necessary to improve the ability to cope with the coastal area in the face of increasing climate change.

REFERENCES

- [1] Alongi, D. M. (2008). Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science*, 76(1), 1–13. <https://doi.org/10.1016/j.ecss.2007.08.024>
- [2] Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., & Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs*, 81(2), 169–193.
- [3] Burkett, V., Suarez, A. G., Bindi, M., Conde, C., Mukerji, R., Prather, M., & St. Clair, A. L. (2014). Point of departure. In *Climate change 2014: Impacts, adaptation, and vulnerability* (pp. 169–194). IPCC.
- [4] Chust, G., Borja, Á., Caballero, A., & Irigoien, X. (2014). Climate change impacts on coastal and pelagic ecosystems. *Oceanography and Marine Biology*, 52, 121–159.
- [5] Cinner, J. E., et al. (2018). Building adaptive capacity to climate change in tropical coastal communities. *Nature Climate Change*, 8(2), 117–123.
- [6] Coppin, P., Jonckheere, I., Nackaerts, K., Muys, B., & Lambin, E. (2004). Digital change detection methods in ecosystem monitoring. *International Journal of Remote Sensing*, 25(9), 1565–1596.
- [7] Cowart, L., Walsh, J. P., Corbett, D. R., & Mallinson, D. J. (2011). Shoreline change and

- sediment redistribution. *Marine Geology*, 287(1–4), 31–41.
- [8] Donato, D. C., et al. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, 4(5), 293–297.
- [9] Ellison, J. C. (2015). Vulnerability assessment of mangroves to climate change. *Environmental Conservation*, 42(2), 1–12.
- [10] Giri, C., et al. (2011). Status and distribution of mangrove forests of the world using Earth observation satellite data. *Global Ecology and Biogeography*, 20(1), 154–159.
- [11] Guo, H., Wang, L., & Chen, F. (2017). Radar remote sensing for coastal flood monitoring. *Remote Sensing of Environment*, 201, 228–242.
- [12] IPCC. (2021). *Climate change 2021: The physical science basis*. Cambridge University Press.
- [13] Kuenzer, C., Bluemel, A., Gebhardt, S., Quoc, T. V., & Dech, S. (2011). Remote sensing of mangrove ecosystems. *Remote Sensing*, 3(5), 878–928.
- [14] Li, X., Damen, M. C. J., & Ban, Y. (2017). Detecting shoreline changes using satellite imagery. *Remote Sensing*, 9(2), 204.
- [15] McLeod, E., et al. (2016). Assessing vulnerability to climate change in coastal areas. *Marine Policy*, 64, 1–9.
- [16] Nicholls, R. J., & Cazenave, A. (2010). Sea-level rise and its impact on coastal zones. *Science*, 328(5985), 1517–1520.
- [17] Ozesmi, S. L., & Bauer, M. E. (2002). Satellite remote sensing of wetlands. *Wetlands Ecology and Management*, 10, 381–402.
- [18] Rahmstorf, S. (2007). A semi-empirical approach to projecting future sea-level rise. *Science*, 315(5810), 368–370.
- [19] Rogers, K., Saintilan, N., & Copeland, C. (2014). Mangrove and salt marsh dynamics. *Estuarine, Coastal and Shelf Science*, 145, 70–82.
- [20] Satyanarayana, B., et al. (2011). Mangrove mapping using multi-temporal remote sensing data. *Remote Sensing of Environment*, 115(2), 660–671.
- [21] Schumann, G. J. P., Bates, P. D., Horritt, M. S., Matgen, P., & Pappenberger, F. (2009). Progress in integrating remote sensing and flood models. *Progress in Physical Geography*, 33(2), 161–180.
- [22] Small, C., & Nicholls, R. J. (2003). A global analysis of human settlement in coastal zones. *Journal of Coastal Research*, 19(3), 584–599.
- [23] Syvitski, J. P. M., et al. (2009). Sinking deltas due to human activities. *Nature Geoscience*, 2, 681–686.
- [24] Thieler, E. R., Himmelstoss, E. A., Zichichi, J. L., & Ergul, A. (2009). Digital Shoreline Analysis System (DSAS). *U.S. Geological Survey Open-File Report*.
- [25] Turner, B. L., et al. (2003). A framework for vulnerability analysis. *Proceedings of the National Academy of Sciences*, 100(14), 8074–8079.
- [26] Wang, L., & Sousa, W. P. (2016). Disturbance, recovery, and resilience in coastal ecosystems. *Ecology*, 97(8), 2059–2070.
- [27] Wetzel, R. G. (2001). *Limnology: Lake and river ecosystems*. Academic Press.
- [28] Wong, P. P., et al. (2014). Coastal systems and low-lying areas. In *Climate change 2014: Impacts, adaptation, and vulnerability* (pp. 361–409). IPCC.
- [29] Woodroffe, C. D., & Murray-Wallace, C. V. (2012). Sea-level rise and coastal change. *Quaternary Science Reviews*, 54, 1–14.
- [30] Zhu, Z., & Woodcock, C. E. (2014). Continuous change detection using Landsat time series. *Remote Sensing of Environment*, 144, 152–171.