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ASSESSMENT OF THE IMPACT OF SEA LEVEL RISE ON SHORELINE DYNAMICS OF SANDY COAST ON THE EAST COAST OF INDIA

Umamaheswari M[12*], Ramana Murthy MV[1], Saravanan R[2], and Kankara RS[1]

[1]*National Centre for Coastal Research (NCCR), NIOT campus, Pallikaranai, Chennai, Tamil Nadu, India - 600 100*

[2]*Centre for Water Resources, Department of Civil Engineering, Anna University, Chennai, Tamil Nadu, India-600 025*

Abstract: Coastal zones are among the most highly developed regions in the world, and play a crucial role economically and environmentally. Sea-level rise and changes in wave dynamics are expected to cause shoreline retreat along open sandy coasts. This study evaluates the potential shoreline response to sea-level rise (SLR) through numerical wave modeling and an empirical shoreline recession model. The wave conditions were simulated using the MIKE 21 Spectral Wave (SW) module for the period 1970–2020, and the model outputs were validated against observed data from two locations, Chennai and Puducherry. In the study region, the average H_s, T_m, and D_m were varying 0.96 m, 6.24 s, and 112° (E-SE), respectively. The Depth of Closure (DoC) was estimated using the Hallermeier (1978) method based on mean wave conditions. Future shoreline recession was assessed using the Bruun rule, considering sea-level rise projections for 2100 under the IPCC SSP2-4.5 and SSP5-8.5 scenarios. Beach profiles were generated by integrating measured bathymetric with topographic data. Based on the modeled wave data, the Depth of Closure (DoC) was estimated to be approximately 5 m. The results indicate that, the shoreline retreat was observed along the sandy beach on the Chennai coast, approximately 17 m and 26 m under the SSP2-4.5 and SSP5-8.5 scenarios, respectively. The present study provides a first-order assessment of potential shoreline retreat along the open sandy coast. This integrated framework provides valuable insights for coastal managers and policymakers to support the development of adaptive strategies for climate-resilient shoreline management.

Keywords: sea level rise, Bruun rule, sandy beach, shoreline retreat, depth of closure, wave modeling

Introduction

Coastal regions worldwide are increasingly affected by accelerating sea-level rise. Rising mean sea levels contribute significantly to the retreat of unprotected coastlines (Bruun, 1962). Sandy shorelines are highly dynamic and prone to erosion due to sea-level rise, shifts in wave climate, and human interventions (Ranasinghe, 2016). Assessing the response of shorelines to sea-level rise is essential for sustainable coastal planning, hazard mitigation, and the development of resilient climate adaptation measures.

An estimated rise of approximately 0.20 m in global mean sea level occurred during the 20th century, driven predominantly by thermal expansion of the oceans and melting of glaciers and ice sheets (IPCC, 2021). Sea-level rise is increasingly impacting low-lying coastal zones globally, leading to enhanced shoreline erosion, and more frequent flooding, particularly in urban coastal environments (Nicholls & Cazenave, 2010). Climate change is also expected to change wave dynamics and storm surge, which

*Corresponding Author's Email: * *umamaheswari@nccr.gov.in*

are key drivers of coastal morphology. Widely used empirical approaches, such as the Bruun rule, offer a practical framework for assessing shoreline retreat associated with projected sea-level rise by relating beach profile adjustment and landward shoreline translation to rising sea levels (Bruun, 1962). When integrated with wave climate changes, these methods enable researchers to assess and quantify potential long-term shoreline Changes.

The eastern coast of India, including Chennai, has experienced significant shoreline variability in recent decades due to both natural coastal processes and human-induced interventions (Kankara et al., 2018). The main objectives of the research are (i) to hindcast long-term wave climate using numerical wave modeling, and (ii) to project shoreline retreat for the SSP2-4.5 and SSP5-8.5 scenarios for the year 2100. This study integrates hindcast wave modeling with the Bruun rule to evaluate potential shoreline retreat along the Chennai coast under two different scenarios (SSP2-4.5 and SSP5-8.5). The findings aim to provide actionable insights for coastal planners, managers, and policymakers to support the implementation of adaptive measures that enhance resilience to long-term erosion hazards.

Study Area

The study area is focused on the Chennai coast, located along the Tamil Nadu in the Bay of Bengal region. The study investigates an integral part of the Chennai coast, Palavakkam beach (80.265°E and 12.964°N) (Fig. 1). Palavakkam beach lies between Thiruvanmiyur and Neelankarai beaches and is known for its vast sandy beach and gentle wave activity. “The east coast of India is characterized by three distinct seasons: pre-monsoon (February–May), the southwest (SW) monsoon (June–September), and the northeast (NE) monsoon (October–January)” (Glejin et al., 2013). The region experiences significant wind and wave activity associated with the northeast monsoon, which contributes substantially to sediment transport and seasonal beach changes. The local sea level rise is projected to be 0.69 m (SSP5-8.5) by 2100 (IPCC, 2021). The sea is observed to be calm in the pre-monsoon, and extreme events are prevalent during the southwest and northeast monsoon seasons.

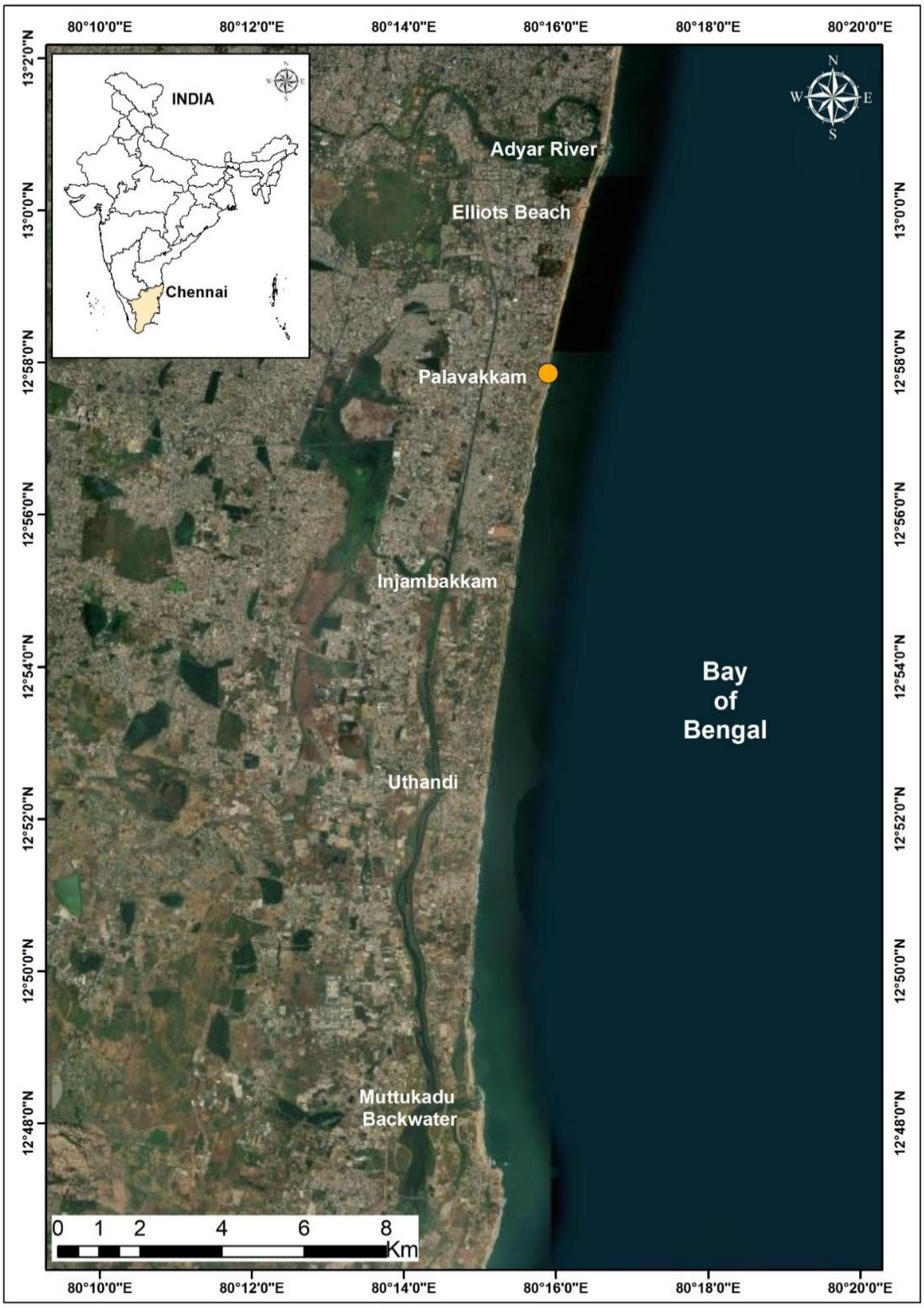

Figure 1: Location map of the study area

Data and Methodology

A. Data Sources

Beach Profile and Bathymetry Data

The beach profiles were collected through field surveys using a Real-Time Kinematic Global Positioning System (RTK-GPS) during December 2024. The bathymetric data were collected in December 2024 using an echo sounder with a grid resolution of 250 m. The cross-shore profiles were generated with combining measured beach profile and bathymetric data extending from the backshore to offshore regions.

Wave data and Sea Level Rise (SLR)

The offshore wave parameters, including significant wave height (H_s), peak wave period (T_p), and mean wave direction (θ), were obtained from ECMWF-ERA5 data, used as offshore boundary conditions for wave modelling. The observed wave data from INCOIS (Indian National Centre for Ocean Information Services) wave rider buoy for Chennai (13.101°N, 80.316°E) and Puducherry (11.926°N, 79.852°E) at 15 m water depth were used for validating the wave model.

Future sea-level rise (SLR) projections were derived from the IPCC Sixth Assessment Report (AR6) based on the Shared Socioeconomic Pathways (SSP) - specifically SSP2-4.5 (moderate emissions) and SSP5-8.5 (high emissions) scenarios for the year 2100.

B. Methodology

In this study, we project shoreline dynamics for 2100, along the Chennai coastline under two SSPs: SSP2 - 4.5 and SSP5- 8.5 (IPCC, 2021)

Numerical Wave Modeling

Waves parameters are modelled over the period 1970-2020 using MIKE 21 SW (DHI,2019) model, forced by offshore wave parameters from the European Centre for Medium-Range Weather Forecasts-Reanalysis v5 (ECMWF-ERA5). The module is based on the wave action conservation equation (young et al., 1994) and Young (1999). The model domain employs an unstructured mesh extending from 79.8° E to 81° E and 11° N to 14° N, with varying resolutions from offshore to nearshore. The bathymetric data obtained from Jeppesen C-Map charts were used for the wave model (Fig. 2).

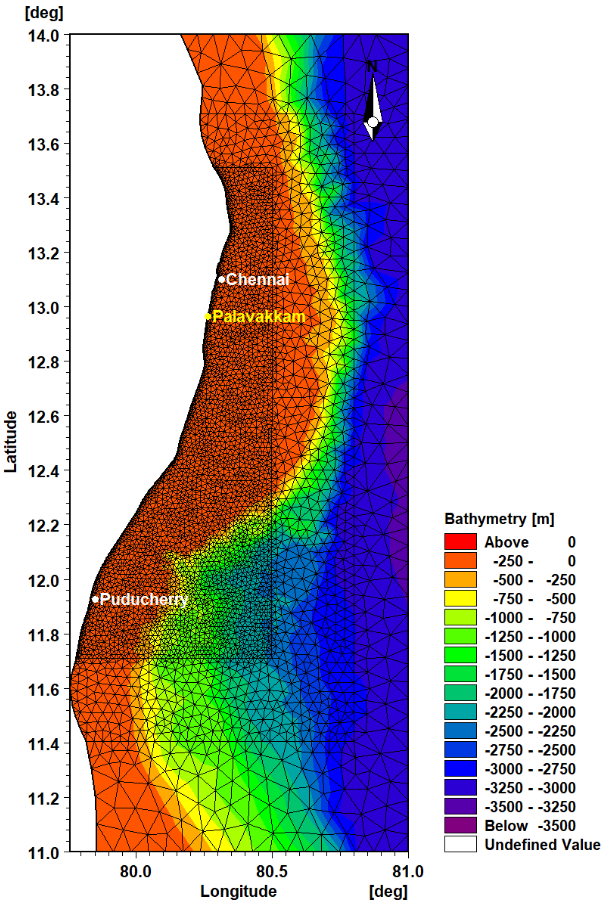

Figure 2: Model Mesh and Bathymetry (Source: Umamaheswari et al. (2023))

The point measurements from INCOIS wave rider buoys at Puducherry and Chennai were used for validation. The validated wave model from Umamaheswari et al. (2023) were used for the present study. Data covering the period from 1 January 2019 to 31 December 2019 were used for model validation. The model-simulated significant wave height (Hs) show, good agreement with the observed measurements. with r =0.83, BIAS= 0.07m, and RMSE=0.32m (Chennai), r =0.70, BIAS= -0.04m, and RMSE=0.59m (Puducherry).

Shoreline retreat due to SLR

The estimation of the equilibrium shoreline retreat R of sandy coasts due to SLR is based on the Bruun rule (Bruun, P.,1962). While the Bruun rule offers a first-order estimation, it assumes equilibrium profile adjustment and neglects alongshore sediment transport. This approach is based on the concept that beach morphology adapts to the prevailing wave climate and is given by:

$$R = E\frac{1}{tan\beta}SLR$$

Where tanβ is the active beach profile slope. And a correction factor E of 0.75 was used (Vousdoukas et al.,2020).

Beach profiles are generated by combining measured bathymetric and topographic data. The offshore boundary of the active profile is defined as a depth equal to the depth of closure, d_c, calculated using an adaptation of the original Hallermeier (1978) formula by Nicholls et al (1998) for applications on longer time scales, given by:

$$d_c = 2.28\, H_{e,t} - 68.5 \left(\frac{{H_{e,t}}^2}{g{T_{e,t}}^2}\right)$$

Where He,t is the significant wave height that is exceeded only 12 h per t years, Te,t is the associated wave period, and g is the gravitational acceleration. In this case, t is equivalent to the 1970-2020 period. The landward active profile boundary is defined as the crest of the berm height B or dune. The cross-shore distance between these two points is considered the length of the active profile L_b, of which the slope is defined as tanβ = $\frac{d_c}{L_b}$.

Results and Discussion

Wave Climate Analysis (1970-2020)

The modelled 50-year wave data (1970-2020) extracted at 30 m water depth were used to assess the seasonal and annual wave climate. The directional occurrence of significant wave height for different seasons is shown in Fig. 3. It is observed that the H_s varies up to 4.14 m with a mean of 0.96 m. The peak wave period varies from 3 – 14 s, and the mean wave direction is 14 °- 154 °. The means of T_m and D_m were 6.24 s and 112 ° (E-SE), respectively (Table 1).

The higher wave heights were observed during the NE monsoon seasons. During pre-monsoon and SW monsoon, mean H_s generally varies in a range of 0.85 m and 0.96 m, and during NE monsoon, 1.07 m.

Table 1: Long-term mean annual wave characteristics (1970-2020)

Wave parameters	Annual average minimum	Annual average maximum	Annual average mean
H_s (m)	0.1	4.41	0.96
T_p (s)	3.2	14.4	6.24
D_m(deg)	14	154	112

During the study period, about 48% of waves from the southeast (SE) (112.5°–135°), 20 % from south-south-east (SSE) (135°–157.5°), 10% from the East (E) (67.5°–90°),8 % from the East-south-east (ESE) (90°–112.5°), and about 5 % from east-north-east (ENE) (45°–67.5°) direction respectively.

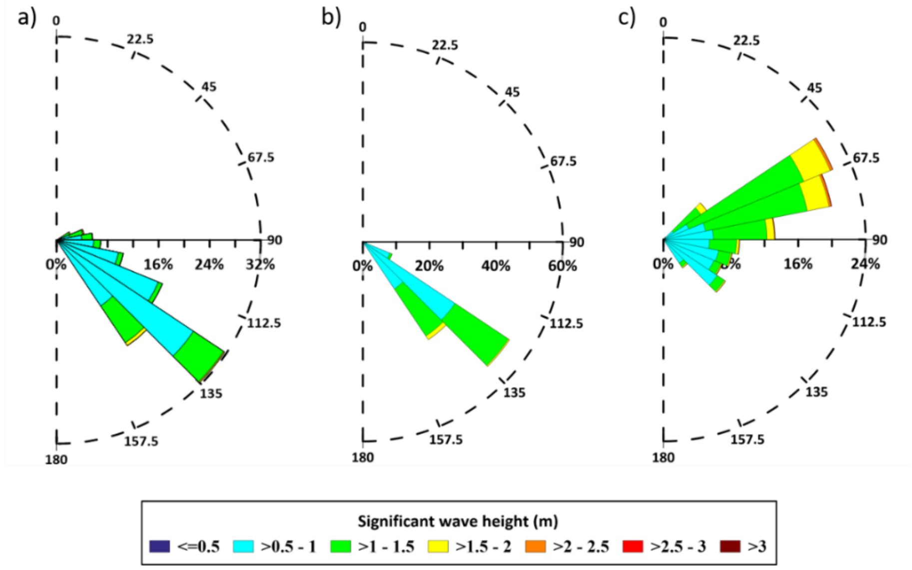

Figure 3: Wave rose plot of wave height and mean wave direction at 30 m depth (1970-2020) a) Pre monsoon, b) SW monsoon, and c) NE monsoon

Modelled wave conditions were analyzed based on 12-hour representative data for each year from 1970 to 2020 (Fig. 4). Changes in regional wind patterns and an increase in cyclone frequency in the Bay of Bengal are altering nearshore wave dynamics and directly influencing sediment transport and shoreline dynamics.

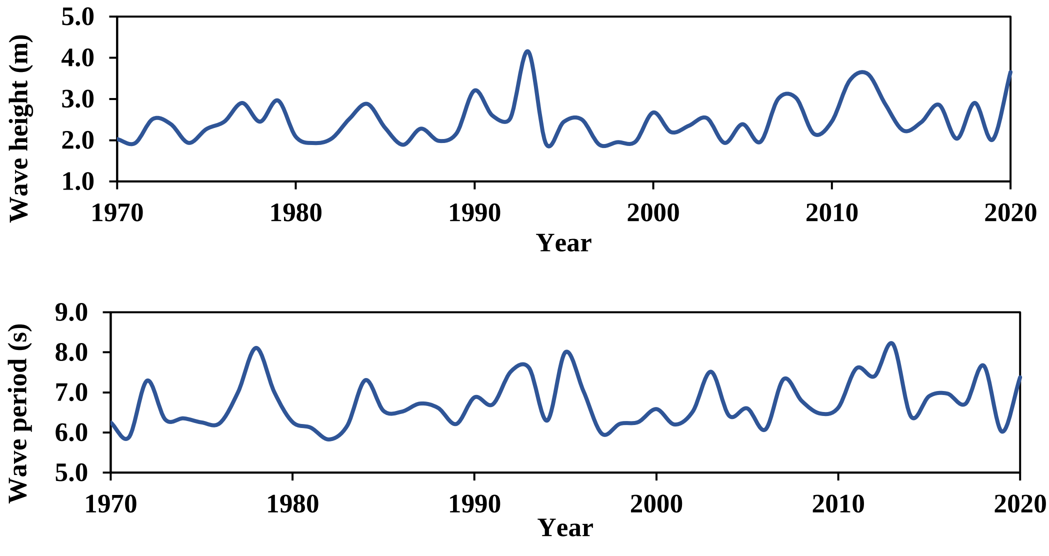

Figure 4: Modelled wave height and period (12 hours per year) for the period 1970-2020

SLR-induced retreat

The estimate of coastal recession at Palavakkam Beach, the Chennai coast was carried out using the Brunn rule and is shown in Fig.5. With the above approach, the DoC was estimated to be approximately 5 m, and the beach slope varied at 1:51.

The results indicate a significant shoreline retreat by 2100, approximately 17 m and 26 m under the SSP2-4.5 (0.45 m by 2100) and SSP5-8.5 (0.69 m by 2100) scenarios, respectively. The projected shoreline retreat is consistent with previous regional assessments for the Bay of Bengal (Raghavendra

G. Patil and M. C. Deo,2020). Increasing sea levels will result in significant shoreline retreat, underscoring the risks associated with high-emission scenarios, particularly for urban and infrastructure areas along the coast. While the Brunn rule assumes uniform sediment transport and beach profile, this may not hold for all sections of the coast.

Table 2: Bruun rule estimates of coastal recession at Palavakkam beach, Chennai

S.NO	SLR (2100) (m)	DoC (m)	Recession (R) (m)
1	SSP2 - 4.5	~5	17
2	SSP5 - 8.5	~5	26

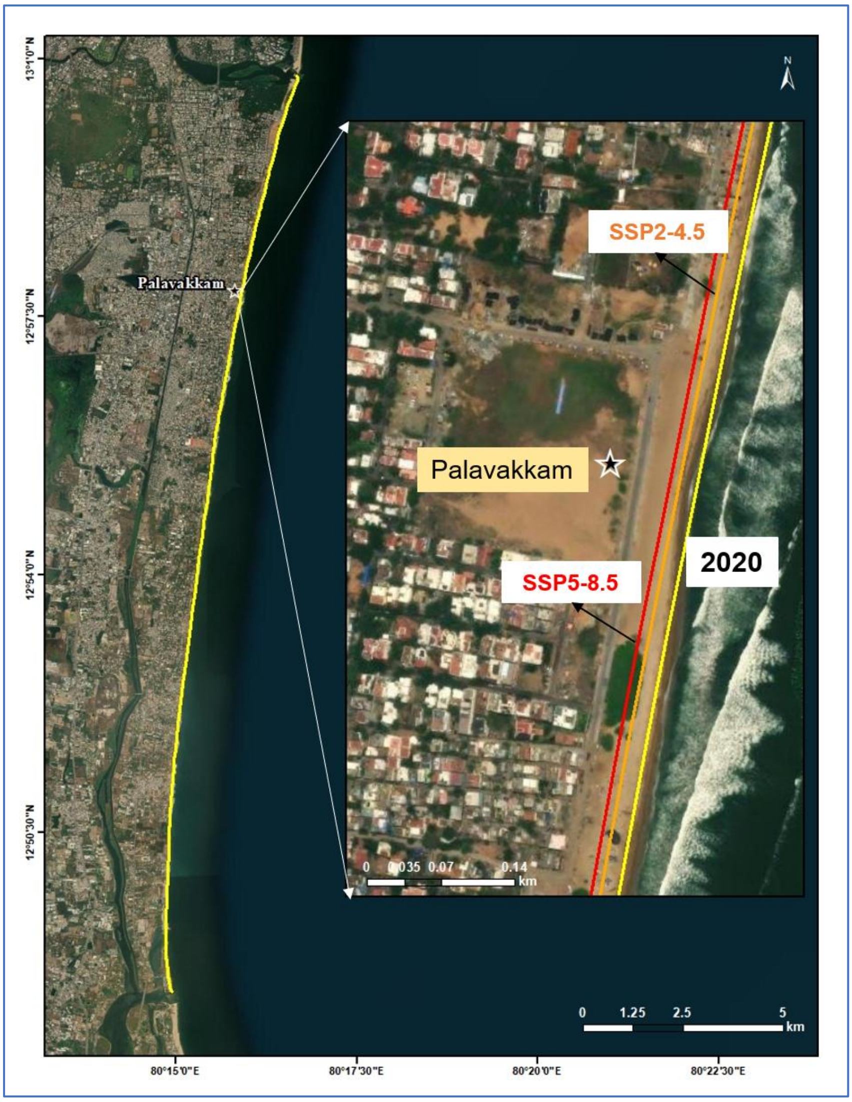

Figure 5: Estimated shoreline recession for the year 2100. Yellow line - 2020 shoreline, orange line - predicted shoreline under SSP2-4.5 scenario, and red line - predicted shoreline under SSP5-8.5 scenario

These projections highlight that, the need to incorporate future projections in adaptive coastal management planning. The present study improves reliability in using site-specific slope, local DOC, wave hindcast data to improve the prediction.

Limitations of the study

The Bruun rule offers a first-order estimation, it assumes equilibrium profile adjustment and neglects alongshore sediment transport. This study projects only SLR-driven shoreline retreat and sediment transfer within the active part of the beach profile to adjust to rising mean sea levels (MSLs). And also, the DOC calculated based on historical wave climate for 50 years (1970-2020) and projected wave climate also to be used for 2100. This study does not cover changes due to episodic erosion during extreme storms and also anthropogenic interventions may alter future shoreline response.

Conclusion

The present study provides a first-order screening assessment of potential shoreline retreat along the open sandy coast under projected sea level rise scenarios. Although the Bruun-rule framework has recognized limitations in complex, human-modified coastal environments, it remains a useful approach for preliminary regional-scale assessment in data-limited conditions. The shoreline retreat of ~17 m and ~26 m by 2100 is projected for the Chennai coast (Palavakkam beach) under SSP2-4.5 and SSP5-8.5 scenarios. The MIKE 21 SW model was used for long-term wave dynamics (1970-2020). Wave model outputs showed good agreement with observed data. The shoreline retreat affects densely developed zones, threatening infrastructure, residential areas, and the beach systems. The integration of numerical wave model and field data into empirical models, improves confidence in the projections. This study highlights the need for localised coastal planning with the impact of sea level rise projections. The study will be providing valuable insights for planners and coastal managers to implement setback lines and adaptive shoreline policies, informing climate-resilient shoreline management.

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References

Bruun, P. (1962). Sea-level rise as a cause of shore erosion. *Journal of the Waterways and Harbors Division, 88*(1), 117–130.

Nicholls, R. J., & Cazenave, A. (2010). Sea-level rise and its impact on coastal zones. *Science, 328*(5985), 1517–1520. https://doi.org/10.1126/science.1185782

Ranasinghe, R. (2016). Assessing climate change impacts on open sandy coasts: A review. *Earth-Science Reviews, 160*, 320–332. https://doi.org/10.1016/j.earscirev.2016.07.011

Intergovernmental Panel on Climate Change (IPCC). (2021). Changing state of the climate system. In V. Masson-Delmotte et al. (Eds.), *Climate change 2021: The physical science basis* (pp. 287–422). Cambridge University Press. https://doi.org/10.1017/9781009157896

Kankara, R. S., Ramana Murthy, M. V., & Rajeevan, M. (2018). *National assessment of shoreline changes along Indian coast: A status report for 1990–2016*. National Centre for Coastal Research (NCCR). http://www.nccr.gov.in

Glejin, J., Kumar, V. S., & Nair, T. M. B. (2013). Monsoon and cyclone induced wave climate over the nearshore waters off Puducherry, southwestern Bay of Bengal. *Ocean Engineering, 72*, 277–286. https://doi.org/10.1016/j.oceaneng.2013.07.019

DHI. (2019). *MIKE 21 spectral wave module: Scientific documentation*. DHI, Denmark.

Komen, G. J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S., & Janssen, P. A. E. M. (1994). *Dynamics and modelling of ocean waves*. Cambridge University Press.

Young, I. R. (1999). *Wind generated ocean waves*. Elsevier Ocean Engineering Book Series.

Umamaheswari, M., Kankara, R. S., & Alluri, S. K. R. (2023). Numerical analysis of wave climate driven variations in longshore sediment transport along Mahabalipuram coast, southeast coast of India. *Regional Studies in Marine Science, 57*, 102732. https://doi.org/10.1016/j.rsma.2022.102732

Vousdoukas, M. I., Ranasinghe, R., Mentaschi, L., Plomaritis, T. A., Athanasiou, P., Luijendijk, A., & Feyen, L. (2020). Sandy coastlines under threat of erosion. *Nature Climate Change, 10*(3), 260–263. https://doi.org/10.1038/s41558-020-0697-0

Hallermeier, R. J. (1978). Uses for a calculated limit depth to beach erosion. In *Proceedings of the 16th International Conference on Coastal Engineering* (pp. 1493–1512). American Society of Civil Engineers.

Nicholls, R. J., Birkemeier, W. A., & Lee, G. H. (1998). Evaluation of depth of closure using data from Duck, North Carolina, USA. *Marine Geology, 148*(3–4), 179–201

Patil, R. G., & Deo, M. C. (2020). Sea level rise and shoreline change under changing climate along the Indian coastline. *Journal of Waterway, Port, Coastal, and Ocean Engineering, 146*(5), 04020002.