



Evaluating coastal dune vulnerability to tropical cyclone forcing using numerical modeling in a data-scarce region

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Abstract

Sandy coastlines are becoming increasingly susceptible to cyclone-induced flooding and erosion as a result of global change. The assessment of these processes, however, is particularly challenging in data-scarce regions such as Mozambique, where limited topographic and hydrodynamic data restrict robust model calibration and validation. This study evaluates the protective capacity of dunes against a range of storm and scenarios of Mean Water Level (MWL) variation, using Cyclone Eloise in Mozambique as a case study. An XBeach 1DV model in surfbeat mode was employed to simulate the hydrodynamic and morphological response of two distinct beach profiles, one reflective and one more dissipative, under different scenarios that combined varying dune heights, storms with different return periods, and MWL variations, resulting in 400 combinations. The results revealed non-linear threshold relations of dune stability, identifying a critical dune height of approximately 3 m, below which dune failure is likely under most MWL-increase conditions. The capacity of dunes to withstand storm impacts is largely determined by their height. However, higher water levels dramatically increase the risk of failure, transforming a medium-sized (3 m) dune from collision regime to inundation. Although dissipative beach profiles possess a greater intrinsic ability to resist erosion and maintain their form, this advantage weakens during extreme cyclone events. The findings in the study area provide critical thresholds for nature-based coastal protection, underscoring the necessity of maintaining dune heights above 3 m to ensure long-term defence in a changing climate.

Keywords Dune vulnerability · Overwash · Erosion · Cyclone Eloise · XBeach · Mozambique

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Introduction

Coastal dunes act as critical natural buffers against storm surge, wave action, and flooding (Kosmalla et al. 2025), since they are the first line of defense against the impact of storms (Roelvink and Costas 2019). However, projected increases in storm intensity and Sea-Level Rise (SLR) raise concerns regarding their long-term resilience, with recent projections indicating a significant increase in extreme storm surge levels under future climate scenarios (Vousdoukas et al. 2016). Understanding how dunes respond to varying hydrodynamic and morphological conditions is essential for risk assessments and the design of coastal protection strategies (Vandenhove et al. 2025). Storm impacts on beach–dune systems are commonly interpreted within the Storm Impact Scale proposed by Sallenger (2000), which defines four distinct hydrodynamic–morphodynamic regimes (swash, collision, overwash, and inundation) based on the relative elevation of wave run-up and dune morphology. This conceptual framework provides a physically based basis for interpreting thresholds in dune response, ranging from minor foreshore erosion to dune overtopping, breaching, and complete inundation. This challenge is particularly prevalent in low-lying areas of developing countries (Doorga et al. 2024), where rapid coastal development and limited adaptive capacity converge to heighten disaster risk (Neumann et al. 2015). This is evident in Mozambique (Fig. 1), whose coastline is situated in the South-West Indian Ocean basin, and is particularly exposed to these high-intensity events (Cabral et al. 2017), as tragically demonstrated by Cyclones Idai and Kenneth in 2019 (Phiri et al. 2020). The associated hazards of storm surge, extreme waves, and coastal flooding pose severe risks to communities (Bathi and Das 2016), infrastructure (Anarde et al. 2018), and economies (Fang et al. 2014).

Tropical cyclones are a major driver of coastal flooding, erosion, and dune degradation in tropical regions, particularly where vulnerable coastal communities and infrastructure are concentrated (Feehan et al. 2024; Thomas et al. 2025). In Mozambique, cyclone-induced storm surge and extreme wave conditions can severely impact beach–dune systems through erosion, overwash, and breaching, reducing their capacity to protect inland areas from flooding (Phiri et al. 2020; Cabral et al. 2017).

Mozambique represents a typical example of a data-scarce coastal region, characterized by limited availability and continuity of high-resolution topographic and bathymetric surveys, sparse hydrodynamic observations, and short time series for model calibration and validation. These constraints introduce substantial uncertainty in the representation of nearshore processes, boundary conditions, and extreme-event forcing, directly affecting the

robustness of risk assessments and the reliability of model predictions (Simmons et al. 2017). At the same time, many of these regions are exposed to high-impact cyclones, storm surge, and rapid coastal change, amplifying societal vulnerability and the consequences of modeling errors (Carrion-Bertran et al. 2024). Data limitations also impede systematic model calibration and validation, constrain the evaluation of alternative adaptation measures, and complicate long-term planning under climate change (Garlan et al. 2025).

Process-based numerical models provide a powerful means to quantify these complex coastal processes (Sánchez-Artús et al. 2023), especially in data-sparse regions like Southeast Africa, where simulations can overcome monitoring lacks. Among these, the XBeach model (Roelvink et al. 2009) has been widely used for simulating the hydrodynamic and morphodynamic response of sandy coastlines to storm conditions. Its integrated approach to compute wave, sediment transport, and morphological change makes it particularly suited for assessing cyclone-induced impacts such as flooding and erosion. Beyond traditional process-based modelling, XBeach simulations have increasingly been used to generate synthetic datasets for training surrogate models and Bayesian networks for rapid coastal hazard prediction, leveraging the computationally intensive morphodynamic outputs of XBeach as input to machine-learning frameworks (Sanuy et al. 2017; Garzon et al. 2023). However, while XBeach has been extensively validated for beach dynamics in many regions (Roelvink et al. 2009; McCall et al. 2010; Vousdoukas et al. 2012; Abanades et al. 2015; Zimmermann et al. 2015; Van Rooijen et al. 2016; Ruffini et al. 2020), its application to the complex coastal systems of Southeast Africa remains limited. As a result, existing assessments of cyclone impacts in Mozambican coastal areas have often relied on regional-scale storm surge models (Neumann et al. 2013), which provide valuable broad-scale inundation data but lack the resolution to resolve critical nearshore wave processes and localized erosion patterns. This gap limits the ability to predict site-specific impacts, such as dune breaching and infrastructure damage, which are essential for coastal risk analysis and the subsequent effective disaster risk reduction measures and policies (Cumiskey et al. 2018).

In this context, there is a need to assess the applicability of process-based models for site-specific coastal vulnerability analysis in data-scarce regions. This study applies the XBeach model to evaluate dune vulnerability under cyclone forcing in a Mozambican beach, using Cyclone Eloise (Category 2) as a realistic extreme-event scenario. The objective is to identify critical dune height failure thresholds and to examine how dune response varies across contrasting beach profile characteristics and water-level conditions.

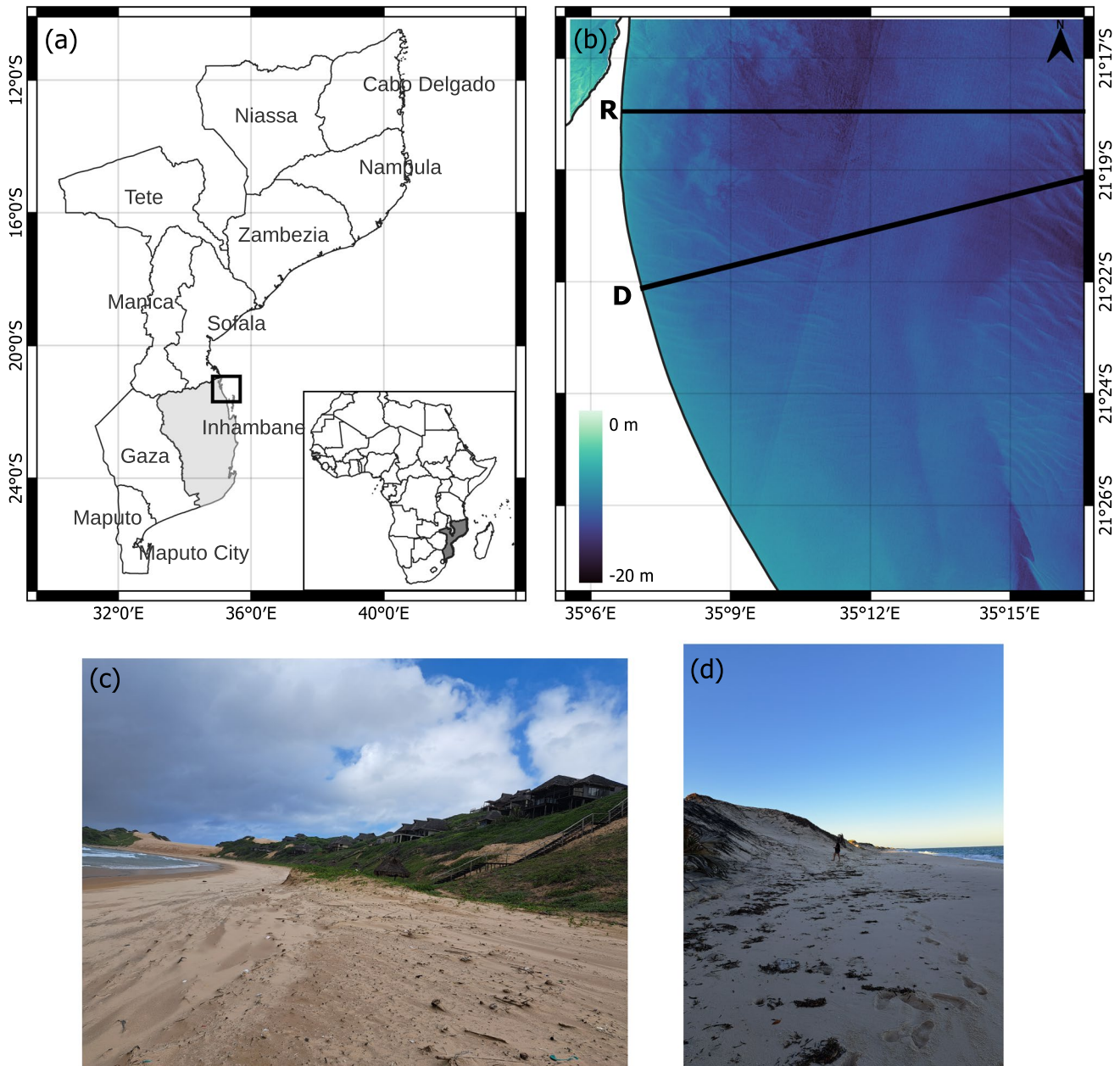


Fig. 1 Location map of the study area. **(a)** Map of Mozambique showing provincial boundaries and the location of Inhambane Province (shaded area). **(b)** Detailed map of the Inhassoro coastal region high-

lighting the study transects (R for reflective, and D for dissipative profiles) with satellite-derived bathymetry of the area. **(c, d)** Representative examples of beach morphology in the Inhambane region

Methods

Study area

Inhassoro Beach, located in Inhambane Province on the central Mozambican coast, is a microtidal, fine sandy beach situated 25 km north of the village center. The aeolian dune systems occur extensively along Mozambique's coastline and are typical of fine sandy beaches in the region (Freitas et al. 2023). The shoreline is characterized

by a relatively narrow foreshore backed by sand dunes ranging from 6 to 9 m in height (Moreira 2005) (Figs. 1C, 1D). The tidal regime is semidiurnal, with amplitudes varying from 0.9 m during neap tides to 2.8 m during spring tides (Sete et al. 2002). The coastline is largely unmodified, with few anthropogenic structures, and the predominant local activity is artisanal fishing. The area has suffered the impact of cyclones over time, some of which have been categorised as Category 2 cyclones on the Saffir-Simpson scale (Saffir 1973; Simpson 1974).

This is the case of Cyclone Eloise, which occurred in January 2021. Tropical cyclogenesis was first described by Frank (1987) as the strengthening of a tropical disturbance into a tropical depression (Tran et al. 2025). In Mozambique, for the 1926–2021 period, 33 cyclones were highly destructive (Nganhane et al. 2025). For the analysis, two transects were considered with significant differences in the bathymetry (Fig. 1). These transects were selected to represent the most common beach profile dynamics observed along the study area. The northern transect features a steeper, more reflective profile (hereinafter, R). The depth decreases from 0 m to -10 m over a cross-shore distance of 771 m (average slope ≈ 0.013), and from -10 m to -20 m over 6173 m (average slope ≈ 0.002). In contrast, the southern transect exhibits a gentler, more dissipative profile (hereinafter, D), with the 0 m to -10 m depth contour spanning 2963 m (average slope ≈ 0.003) and the -10 m to -20 m contour spanning 3852 m (average slope ≈ 0.004).

Data description

This study was conducted in a data-scarce coastal environment, where the absence of long-term *in-situ* observations required the integration of multiple open-access and remotely sensed datasets (Fig. 2). The datasets used include bathymetry, wave climate, tidal levels, and sediment characteristics, and were selected based on their availability and spatial coverage. A summary table is included in Table 1.

Regional bathymetric information was obtained from the GEBCO 2023 global bathymetry dataset, using Delft-Dashboard open-source program (van Ormondt et al. 2020), which provides a consistent large-scale representation of seabed morphology and was used to define the offshore bathymetric context. To improve nearshore resolution, Satellite-Derived Bathymetry (SDB) was generated from Sentinel-2 Level-1C imagery acquired before

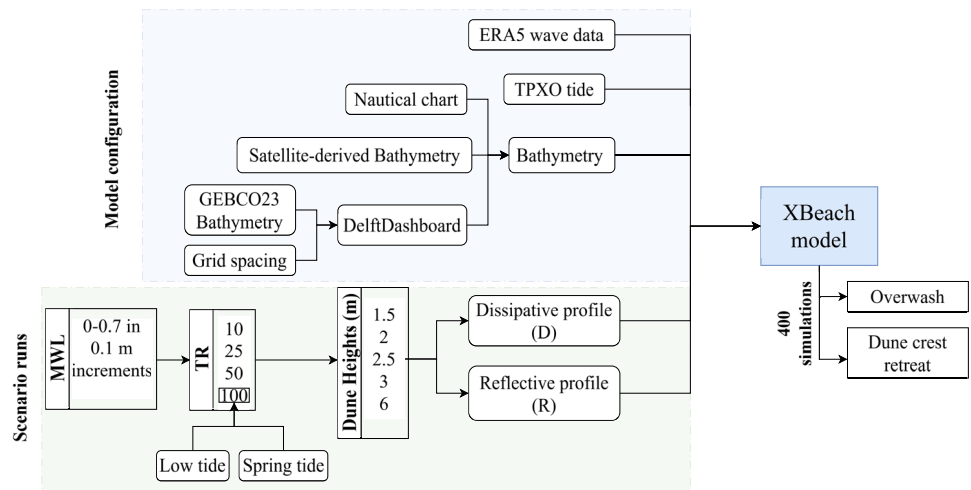
Cyclone Eloise. Atmospheric correction was performed using the ACOLITE software (Vanhellemont and Ruddick 2016) to derive Remote Sensing Reflectance, and bathymetry was derived using the log-ratio algorithm of Stumpf et al. (2003), calibrated and validated with ICE-Sat-2 photon-derived bathymetric points (RMSE=0.33m), accessed via the SlideRule Python library (Shean et al. 2023), with a refraction correction applied to account for water penetration. Nautical chart data from the US National Geospatial-Intelligence Agency (NGA) were additionally used to constrain bathymetric contours in shallow and nearshore areas.

Wave forcing was characterized using a combination of ERA5 reanalysis data and synthetic storm scenarios. ERA5 hourly wave parameters were used to represent extreme conditions associated with Cyclone Eloise (100-year return period scenario, see Table 3 for further information). For lower return periods (10, 25, and 50 years), synthetic storm time series were constructed based on storm evolution patterns in the region (see Fig. 8). Tidal water levels were obtained from the TPXO global tidal model (Egbert and Erofeeva 2002), providing predicted tidal elevations for both low-tide (tidal range = 0.6 m) and spring-tide (tidal range = 2 m) conditions relevant to the simulated events.

Sediment characteristics were defined based on granulometric analysis of a field-collected sample, from which a representative median grain size ($D_{50} = 0.25$ mm) was obtained and assumed spatially uniform across the model domain.

All datasets were integrated to construct representative cross-shore profiles and hydrodynamic forcing conditions suitable for process-based numerical modeling. While uncertainties are inherent due to the combination of several data sources, the joint use of independent datasets allows for the representation of coastal processes in the absence of detailed *in-situ* measurements.

Fig. 2 Flowchart of the methodology followed in the study



XBeach model setup

The methodological framework of this study combines process-based numerical modeling with representative bathymetric profiles and hydrodynamic forcing derived from multiple open-access datasets (Subsection 2.2). The XBeach model was used to simulate nearshore hydrodynamics and storm-driven morphological changes, with a particular focus on dune erosion and overwash processes under extreme events (Roelvink et al. 2009).

Representative cross-shore beach and dune profiles were constructed by integrating the bathymetric datasets, capturing the distinct slope characteristics of reflective and dissipative beach profiles observed in the study area.

Hydrodynamic forcing associated with Cyclone Eloise and a range of synthetic storm scenarios were applied at the offshore boundary. A total of 400 scenarios were simulated, spanning combinations of dune crest elevations, MWL, storm return periods, and beach profile types. This ensemble approach allowed for a systematic assessment of dune vulnerability across a wide parameter space.

Model outputs were analysed using quantitative metrics describing overwash occurrence and dune crest retreat. These metrics enabled the identification of critical thresholds for dune failure and facilitated comparison between reflective and dissipative beach responses under increasing storm intensity and water level conditions.

Model description

Nearshore hydrodynamics and morphological changes were simulated using the open-source XBeach model (Roelvink et al. 2009, 2018). XBeach is a process-based, depth-averaged (2DH) numerical model designed to simulate wave propagation, sediment transport, and morphological changes on beaches (Roelvink et al. 2009; Sánchez-Artús et al. 2024, 2025). This model started as a short-wave averaged group-resolving model to simulate the impact of extreme storms and hurricanes on sandy barrier island systems (Roelvink et al. 2018). The model was run in surfbeat mode, which resolves the time-varying wave group structure by solving the wave action balance equation. This mode is particularly suitable for simulating infragravity waves and effectively computes both coastal flooding and morphological changes. The inclusion of infragravity-wave processes is relevant because these long-period waves can contribute substantially to extreme run-up, overwash, and dune erosion during energetic storm conditions, thereby influencing the hydrodynamic forcing experienced at the dune toe and crest. Avalanching is introduced via the use of a critical bed slope for both the dry and wet area (keyword: *wetslp* and *dryslp*). It is considered that inundated areas are much more prone to

slumping and therefore two separate critical slopes for dry and wet points are used. The default values are 1 and 0.15, respectively. When this critical slope is exceeded, material is exchanged between the adjacent cells to the amount needed to bring the slope back to the critical slope (Roelvink et al. 2009). The groundwater/infiltration module was not activated in the present simulations. Therefore, infiltration and exfiltration processes were not explicitly represented.

Model domain, grid and scenarios

For computational efficiency, the model was set up in 1DV profile grid. The cross-shore domain extended 7 km (1916 cells) from the offshore boundary to the dune crest. A variable grid resolution was employed to balance computational cost and nearshore accuracy, with the offshore cell size set to 15 m, which gradually refined to 1 m in the swash and surf zones and extended landward to the dune crest. The same spatial discretization was applied to both the reflective and dissipative profiles.

A series of scenarios, as illustrated in Fig. 2, were simulated for both profiles (Fig. 3) to analyze the beach response under varying wave and water level conditions. These scenarios were established based on the dune heights found along the Inhambane region, with the highest dunes corresponding to those found in Inhassoro Beach (see Subsection 2.1). Although natural dune heights in the study area typically range from 6 to 9 m, lower dune elevations were also considered to evaluate the sensitivity of coastal vulnerability to progressive dune degradation. This approach allowed the protective role of dunes to be quantified by assessing how reductions in dune height influence overwash and erosion processes. Overall, 400 scenarios were evaluated to test dune vulnerability against overwash and erosion under different Mean Water Level (MWL) scenarios, storm return periods (RP), dune heights, and beach profiles (Fig. 2). The RP100-LT scenario with MWL = 0 m and an initial dune height of 6 m corresponds to the Cyclone Eloise reference case. All other simulations were generated by systematically modifying dune height, MWL, tidal conditions, and storm characteristics to evaluate dune vulnerability under a broader range of present and future conditions.

Physical parameters and model inputs

Wave conditions were forced at the offshore boundary using a default JONSWAP spectrum ($\gamma = 3.3$). Wave breaking was parametrized using the Roelvink-Daly formulation (*break* = *roelvink-daly*) (Daly et al. 2012) with a breaker parameter (*gamma*) of 0.36. Sediment transport was simulated using the default transport relation, assuming a uniform sediment size with a median grain diameter (D_{50}) of 0.25 mm,

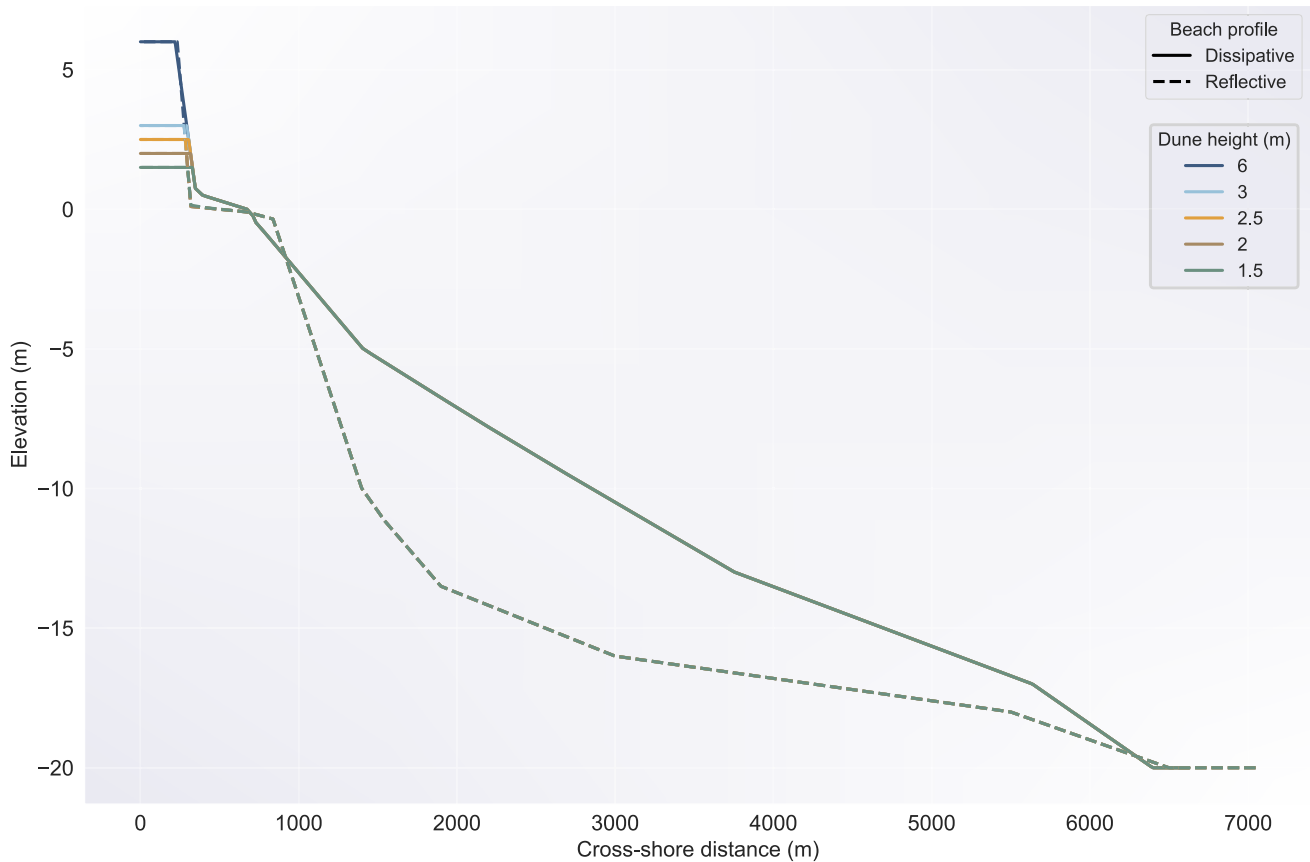


Fig. 3 Cross-shore elevation profiles for five dune-crest scenarios with heights of 6 m, 3 m, 2.5 m, 2 m, and 1.5 m

obtained from the granulometry of a sample collected in the field. The model configuration was primarily based on the parametrization proposed by Garzon et al. (2023). Because no site-specific hydrodynamic or morphodynamic observations are available for calibration or validation in the study area, this parametrization was adopted as the baseline configuration. Nevertheless, selected parameters were adjusted to improve numerical stability, particularly the breaker parameter (γ), while others ($facAs$ and $facSk$) were maintained at their default values. A morphological acceleration factor of $morfac = 6$ was adopted as a compromise between computational efficiency and the accuracy of the simulated morphodynamic response. A summary of the key model parameters is provided in Table 2. Parameters not explicitly discussed were left at their default XBeach values, following standard model practice and to avoid introducing additional uncertainty in the absence of site-specific calibration data. Consequently, the simulations should be interpreted as process-based scenario analyses aimed at identifying relative morphodynamic behaviour and threshold responses rather than as fully calibrated site-specific predictions.

For the RP100 low-tide (RP100-LT) and RP100 spring-tide (RP100-ST) scenarios, offshore wave forcing was applied using hourly ERA5 wave conditions, with peak

significant wave heights (H_s) reaching 9 m and peak wave period (T_p) reaching 11.4 s (Fig. 4A). For the RP10, RP25, and RP50 scenarios, synthetic storms were constructed following a triangular temporal evolution. This storm shape was selected based on observations of three historical tropical cyclones that affected the Mozambican coast (Idai 2019, Kenneth 2019, and Eloise 2021), whose temporal evolution exhibited a similar pattern characterized by a gradual increase in intensity, a well-defined peak, and a subsequent decrease. Consequently, a triangular profile was adopted as a simplified but representative approximation of storm evolution in the region, allowing the main characteristics of cyclone-induced forcing to be incorporated into the synthetic storm scenarios (Figs. 4, 8). Selected H_s increased from 2 m to peak values of 6 m, 7 m, and 8 m, respectively, based on return period estimates derived from extreme value analysis. T_p increased from 7.5 s to 8.5 s, 8.75 s, 9.5 s, respectively, with observed wave periods for the corresponding wave heights.

Tidal water levels were applied using predicted tidal elevations extracted for Inhassoro Beach, considering both low-tide and spring-tide conditions. Water level time series were defined over 40-hour simulation periods representative of cyclone and spring-tide conditions (Fig. 4B).

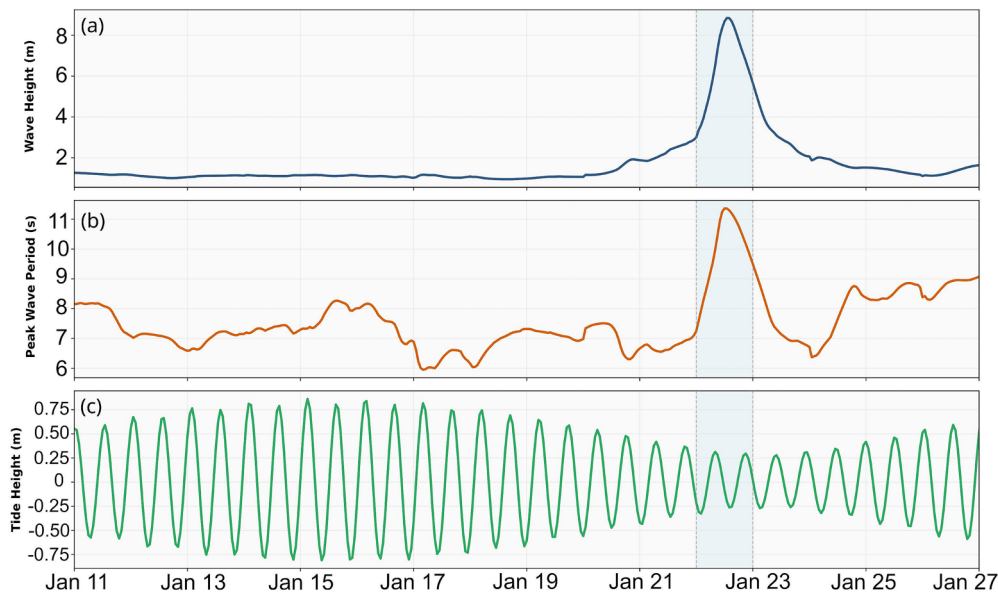


Fig. 4 Time series of (a) H_s (m), (b) peak wave period (s) during Cyclone Eloise (11–28 January 2021). A pronounced peak in wave height and period around 22–23 January corresponds to the cyclone's

closest approach. (c) TPXO tide prediction timeseries for January 2021. The highlighted blue region marks the period during which cyclone Eloise made landfall at the coast (Low tide conditions)

Metric description

Dune overwash was quantified using the elevation (z_b) of the most landward wet cell in the final profile (z_{bf}). The location of this cell, denoted by (x_{wd}), corresponds to the transition point where the model output parameter (*wetz*) changes from 1 (wet) to 0 (dry). The overwash metric was then computed as the ratio between the bed elevation at this location in the final profile and the maximum initial dune elevation (z_{bi}) (Eq. 1; Fig. 5). As a simplification, Eq. 1 is the percentage of the maximum run-up height relative to the initial dune height. Because the metric is normalized by the initial dune crest elevation, it approaches 100% once the wet-dry transition reaches the dune crest. Consequently, it is designed to quantify the onset and degree of dune overtopping rather than the inland extent of inundation after overtopping has occurred.

$$\text{overwash} = \frac{z_{bf}(x_{wd})}{\max(z_{bi})} \times 100 \quad (1)$$

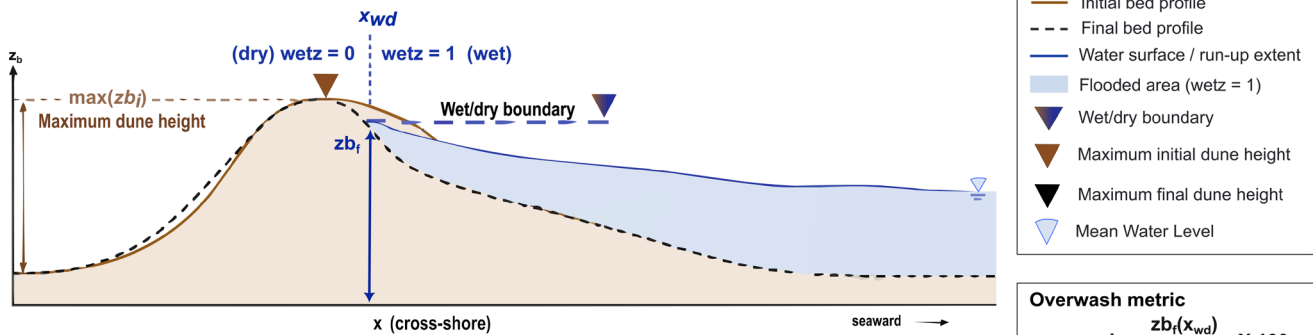
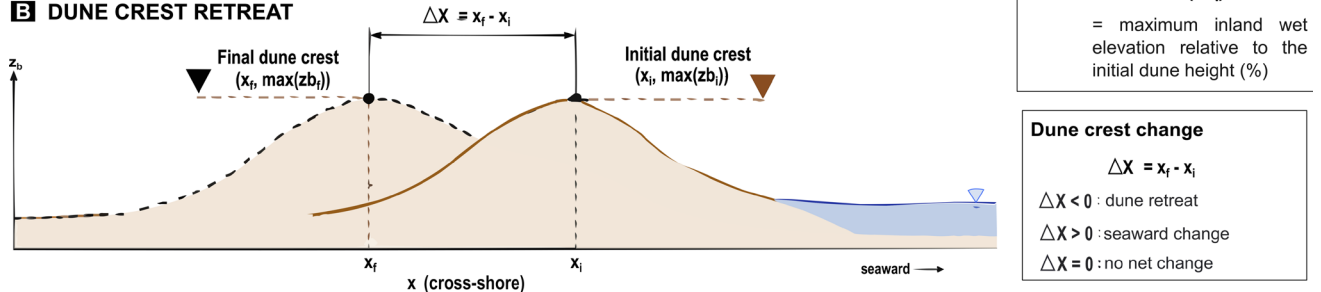
The dune crest position was defined as the cross-shore location of the maximum bed elevation (z_b). For each simulation, the bed profile was analyzed at every time step to track the crest's movement. Consequently, the initial and final crest positions were determined by the maximum z_b at the start and end of the simulation, respectively. Dune crest change (ΔX) was quantified as the difference between the final (x_f) and initial (x_i) dune crest positions along the cross-shore axis (Eq. 2):

$$\Delta X = x_f - x_i \quad (2)$$

Negative values of ΔX indicate landward retreat driven by erosion, scarping, or overwash. Conversely, positive values are generally not expected, as significant dune accretion is an aeolian process. However, small positive shifts may occur in low-elevation dunes during minor storm events, caused by overwash redistribution.

Results

The output of the 400 simulations was analysed to extract the overwash and dune crest change. The analysis indicated a consistent, nonlinear response to overwash across the range of MWL variations and return-period storm scenarios (RP10–RP100) (i.e., the magnitude of the dune response did not scale linearly with increasing MWL) (Fig. 6). For all scenarios, overwash remains limited under low MWL variations (0–0.2 m), with values generally < 40% regardless of dune height. As MWL variations increased, overwash exhibited an abrupt rise, reflecting the transition from the swash and collision regimes to the overwash regime (Sallenger 2000), once run-up elevations exceeded the original dune crest. This threshold is typically crossed between MWL values of approximately 0.4–0.5 m, beyond which overwash frequently exceeds 50%. This MWL variations would correspond to the projections from the SSP5-8.5 scenario presented in the IPCC Sixth Assessment Report (Calvin et al. 2023).

A OVERWASH METRIC**B DUNE CREST RETREAT****Overwash metric**

$$\text{overwash} = \frac{z_{b_i}(x_{wd})}{\max(z_{b_i})} \times 100$$

= maximum inland wet elevation relative to the initial dune crest height (%)

Dune crest change

$$\Delta X = x_f - x_i$$

$\Delta X < 0$: dune retreat

$\Delta X > 0$: seaward change

$\Delta X = 0$: no net change

Fig. 5 Schematic illustration of the overwash metric and dune crest migration on a reflective beach profile. **(A)** The beige area represents the initial cross-shore bed profile, while the dashed black line shows the final bed profile after wave action. The dark blue line indicates the maximum water surface (wave run-up extent), and the light blue shaded region denotes the inundated area. The orange triangle marks the maximum initial dune crest elevation, and the wet–dry transition

defines the overwash limit (x_{wd}). The overwash metric is calculated as the maximum inland wet elevation relative to the initial dune crest height. **(B)** Dune crest migration is quantified by the horizontal displacement (Δx) between the initial and final dune crest positions, where $\Delta x < 0$ indicates dune retreat, $\Delta x > 0$ indicates seaward migration, and $\Delta x = 0$ indicates no net change

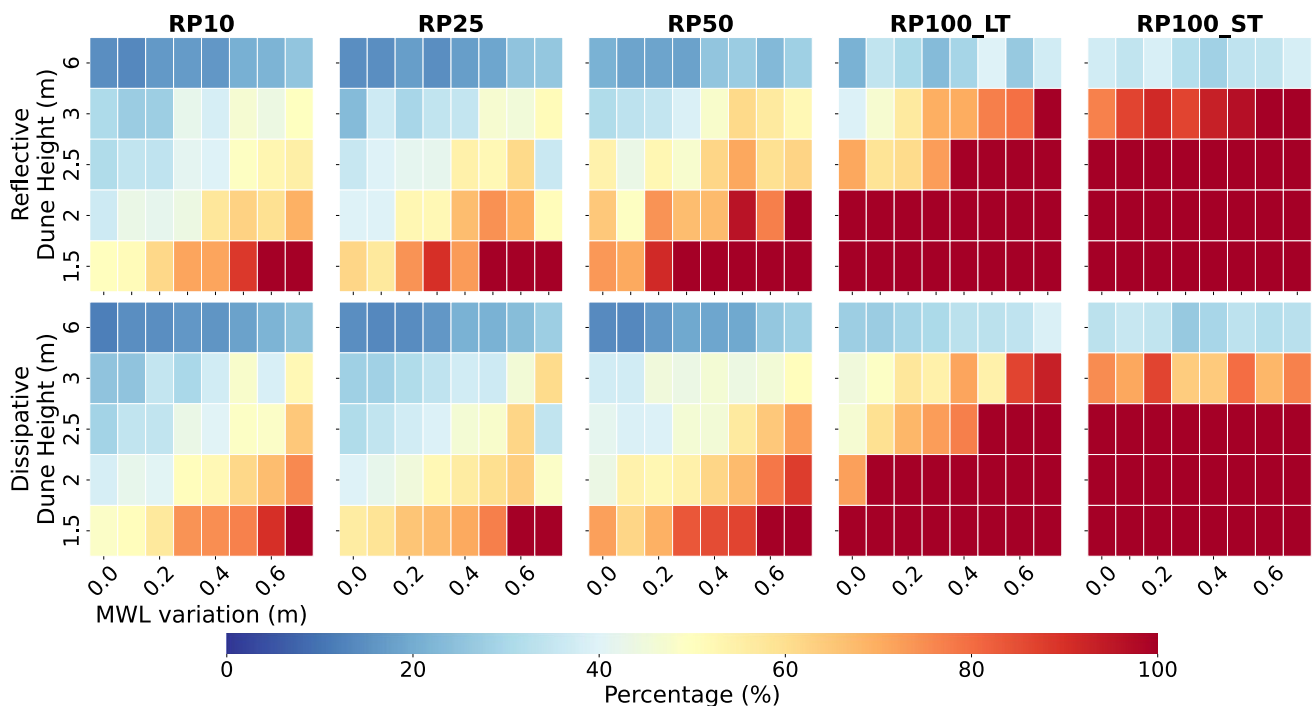


Fig. 6 Overwash percentages (% of dune height flooded) for different dune configurations under various MWL variation scenarios at R (top row) and D profiles (bottom row). The color gradient represents overwash severity from blue (low overwash) to red (complete overwash)

At low MWL variations, dunes ≥ 3.0 m remained largely intact, confirming their current protective capacity. Meanwhile, at moderate MWL variations (0.3–0.5 m), the zone of vulnerability expanded significantly, with dunes up to 2.5–3 m showing rapid increases in overwash percentage. This indicates that moderate MWL variation scenarios may destabilize dunes that are currently capable of resisting overwash. At high MWL variations (0.6–0.7 m), the failure threshold shifted upward. All low and intermediate dunes (≤ 3.0 m) underwent complete overwash, regardless of the storm return period. Under these conditions, overwash approached or reached 100% for most dune heights, while the highest dunes (6 m) still exhibited some degree of residual protection, although significantly reduced. This suggests that, at the higher MWL variations, dune height becomes a less effective control on overwash extent, but does not fully eliminate its influence.

Increasing storm intensity (larger RP values) consistently amplified overwash across the MWL gradient. Relative to RP10 and RP25 conditions, RP50 and RP100 storms induced substantially higher overwash at moderate MWL levels (0.2–0.4 m), effectively shifting the overwash–MWL relationship toward lower thresholds. Under RP100 scenarios, particularly the spring tide condition, overwash reaches 100% at MWL values as low as 0.5 m for almost all dune elevations, demonstrating the susceptibility of dunes to extreme events.

Dune height modulated the magnitude and onset of overwash, with taller dunes exhibiting reduced overwash under lower MWL conditions, with a pronounced morphological stability threshold observed at approximately 3.0 m (Fig. 6). However, medium-high dune classes (2.5–3 m) experienced 80–100% overwash under elevated MWLs or high-intensity RP events, indicating that morphological resistance is ultimately constrained under extreme hydrodynamic forcing.

Differences between the two profiles (R and D) are also observed, as the reflective profile generally reached complete overwash at lower MWL values under RP50 and RP100 scenarios, suggesting a lower capacity for structural resistance to overwash compared with the dissipative profile. Overwash transitioned from moderate ($>40\%$) at low MWL to near-total overwash ($>90\%$) at MWL ≥ 0.3 –0.4 m, indicating a precarious state where small increases in water level can trigger regime shift in dunes near the threshold (2.5–3 m). For both profiles, significant overwash became increasingly pronounced ($>40\%$) under RP50 and RP100 storms, particularly at moderate MWL variations (0.2–0.4 m), where substantial inundation was already observed. However, near-total overwash conditions were predominantly reached only under the most extreme combined forcing scenarios, namely RP100 events coupled with the highest MWL variations, which led to widespread

inundation across most dune classes. Consequently, the two representative beach profiles exhibited markedly different overwash responses, governed by their distinct energy dissipation mechanisms. Reflective profiles concentrated wave energy at the dune toe, leading to more severe overwash. The system was characterized by a rapid, non-linear transition from partial to total (100%) overwash as MWL increased. However, dissipative profiles (D) favoured off-shore wave breaking, dissipating energy across the surf zone and resulting in lower overall overwash. This innate ability to withstand overwash and maintain dune integrity was most evident under RP25 and RP50 scenarios. However, this buffering capacity was diminished under RP100 events, where erosion rates for dunes ≥ 2.5 m became comparable to those observed on the reflective profile.

Storm characteristics, while secondary to dune height and MWL variations, exerted a critical influence on the spatial extent and pattern of overwash. Under RP10, RP25, and RP50 storms, high overwash percentage was largely confined to the lowest dunes (≤ 2.0 m), with higher dunes experiencing minimal impact. However, the RP100-LT storm expanded the range of severe overwash to include dunes up to 3.5 m across most MWLs. RP100-ST produced the most spatially extensive overwash, resulting in the complete flooding of low and mid-height dunes (1.5–3.0 m) across nearly all water level variation scenarios. The extreme wave energy proved catastrophic even for dunes near the identified stability threshold (≥ 3 m).

The modeled dune crest displacement revealed a clear threshold-type morphological response across storm return periods, MWL variations, and dune heights (Fig. 7). In all scenarios, crest migration was exclusively landward, with no positive displacement observed during the simulated events.

At RP50, the dune crest retreat became evident, though erosion remained limited in both magnitude and spatial extent. Landward displacement was primarily observed for lower dune heights (≤ 2.0 –2.5 m) and was most pronounced under moderate to high MWL variations (≥ 0.3 –0.4 m). In contrast, dunes with heights ≥ 3.0 m exhibited little to no crest displacement under RP50 forcing. Overall, erosion at this return period was localized.

A marked increase in erosion occurred under RP100 conditions. Crest displacement increased systematically with increasing MWL variation and decreasing dune height. For MWL variations exceeding 0.5–0.6 m, substantial landward retreat was observed across most dune configurations, including intermediate and higher dunes near the identified stability threshold (~ 3.0 m). The spatial footprint of erosion expanded considerably relative to lower return periods, with crest displacement occurring across a broad range of dune heights and water-level scenarios.

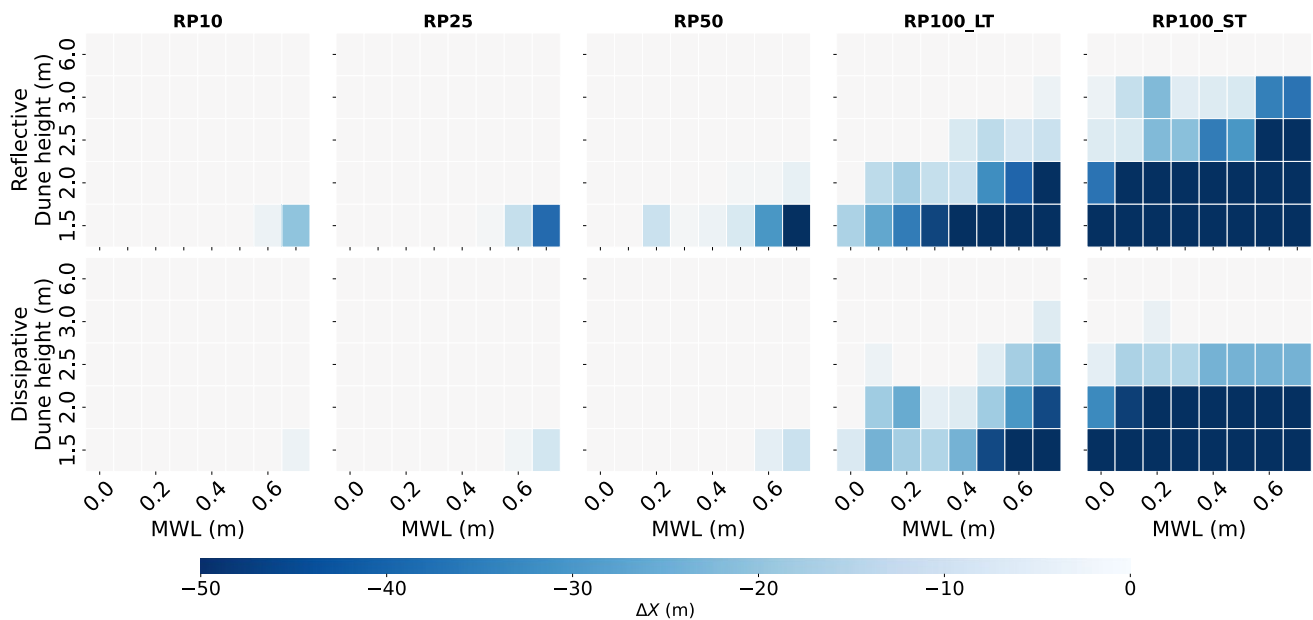


Fig. 7 Difference in dune crest position between the initial (x_0) and final (x_f) states as a function of MWL and initial dune height for multiple storm return periods (RP10–RP100). The color gradient represents erosion magnitude from white (low erosion) to dark blue (strong erosion)

Tidal phase influenced erosion magnitude during RP100 scenario. Spring tide conditions resulted in larger crest position differences and a wider range of affected dune heights compared to low tide conditions, particularly at elevated MWL variations. This amplification was most evident for lower and intermediate dunes but remained detectable across higher dune elevations.

Differences between beach profiles were also evident under extreme forcing. During RP100 events, the reflective profile consistently exhibited larger crest displacements than the dissipative profile for comparable MWL and dune height combinations. Under RP10, RP25, and RP50 conditions, crest displacement differences between profiles were negligible. The contrast between profiles became pronounced only when high storm intensity coincided with elevated MWL variations.

Overall, the largest dune crest displacements occurred when extreme hydrodynamic forcing coincided with lower initial dune crest elevations, highlighting the strong coupling between dune morphology and overwash processes. In particular, the most substantial landward migrations were observed for dunes below the identified stability threshold (~ 3.0 m) under high MWL variations (≥ 0.5 – 0.6 m) and RP100 storm conditions, where overwash percentages approached or reached 100%. These conditions correspond to inundation regimes in which the dune crest becomes fully submerged. As a result, crest retreat increased rapidly once complete overwash was reached, reinforcing the threshold-type response observed in both the flooding and crest-displacement analyses.

Discussion

In recent decades, intense development and use of coastal zones have been observed, leading to major socio-economic and environmental transformations that are likely to continue. Under these scenarios, disaster risk reduction strategies must be evaluated in a spatially efficient manner. These findings are particularly relevant for coastal areas undergoing urban development, where early planning decisions strongly influence future exposure to extreme events. Integrating knowledge of dune dynamics, storm thresholds, and morphological susceptibility into spatial planning can help preserve the protective function of dune systems and reduce long-term risk (Mehrtens et al. 2023; Brodie et al. 2025), especially in cyclone-prone regions. The analysis demonstrates that dune response to cyclone forcing is governed by nonlinear interactions between dune morphology, MWL variability, storm intensity, and beach-profile type. These factors collectively control not only the magnitude of sediment loss but also the threshold at which protective dunes transition into a system prone to overwash or structural failure.

Under RP10 and RP25 conditions, no measurable crest displacement occurred across the full range of dune heights and MWL variations. Crest position remained unchanged, indicating that these lower-intensity storm events did not induce detectable erosion even when combined with elevated mean water levels.

Results demonstrate that once hydrodynamic forcing surpasses critical threshold values (≥ 0.5 m), dunes experience

abrupt morphological adjustment, with crest displacement and overwash acting synergistically to accelerate dune degradation. These findings highlight that dune height, MWL, storm intensity, and profile type collectively determine not only overwash but also the landward displacement of the dune system, emphasizing the importance of preserving dune volume and morphology to maintain their protective function. Previous physical model studies, such as D'Alessandro and Tomasicchio (2016) and Conti et al. (2025), have demonstrated that dune response to storm forcing is controlled by hydrodynamic and morphological parameters, with clear observational evidence of collision, overwash, and breaching regimes in wave flume experiments that link wave period and water depth to the capacity of beach–dune systems to withstand and recover from storm impacts.

Erosion results obtained in this study emphasize that dune vulnerability is controlled by the interplay between height, MWL, storm intensity, and profile type. Lower dunes under elevated water levels are particularly susceptible, highlighting the importance of maintaining dune volume and morphology to preserve coastal protection (Zainuddin et al. 2024). From a management perspective, this suggests that interventions aimed at enhancing dune height or restoring dune profiles could be critical for reducing erosion during extreme storm events (Marino et al. 2025). More broadly, the findings illustrate that dune systems do not respond linearly to storm forcing; instead, abrupt changes occur once threshold conditions are exceeded, underscoring the need for adaptive management strategies that account for both typical and extreme storm scenarios.

The most significant finding is the existence of a clear, MWL-dependent threshold that dictates systemic dune collapse. In the study area, under low MWLs and RPs, dunes ≥ 3.0 m maintain their protective function with overwash remaining limited across all storm intensities. However, in this particular beach, once MWL reaches a critical range of ~ 0.4 – 0.5 m, an abrupt, non-linear shift occurs, and dunes rapidly transition from partial to near-total overwash. This establishes MWL as the primary driver of overwash, with storm intensity acting to amplify this nonlinear response. Proactively revising plans based on these projected hydrodynamic thresholds is essential for long-term resilience (Grases et al. 2020). The concurrence of near-complete overwash (>80 – 100%) and substantial sediment mobilization under RP100 scenarios reveals a destructive feedback loop. Overwash acts not only as an indicator of dune degradation but also as a driver of morphological collapse (Lezcano et al. 2025). The breaching of this critical overwash threshold results in intensified wave penetration and sediment transport, ultimately triggering dune failure (Palmer and Holman 2011). This MWL-dependent threshold

represents a regime shift in the classification of Sallenger (2000), marking an abrupt transition from the collision regime to the overwash or inundation regimes as wave run-up exceeds critical dune elevations. Once this threshold is exceeded, dunes lose their ability to function as a first line of defence, and the system undergoes systemic collapse rather than incremental degradation.

Dune height strongly modulated the onset of overwash (Goldstein and Moore 2016), as dune height is an important predictor of impact during a storm event given that taller dunes have a lower likelihood of being overtopped than shorter dunes (Itzkin et al. 2021). Dunes ≥ 3.0 m consistently resisted overwash at low MWLs, affirming their current role as the primary coastal defence (Hanley et al. 2014). However, dunes in the 2.5–3.0 m range emerged as highly vulnerable transition features. For these dunes, minor MWL increases triggered shifts from $<40\%$ to $>90\%$ overwash, identifying a critical height of morphological vulnerability. This indicates that elevation alone cannot guarantee resilience under future elevated water-level scenarios.

The contrasting behaviour of reflective (R) and dissipative (D) profiles highlights the importance of nearshore energy dissipation (Eichentopf et al. 2019). Reflective profiles transitioned more rapidly from collision to overwash regimes due to concentrated wave energy at the dune toe, whereas dissipative profiles delayed regime shifts through enhanced offshore energy dissipation (Senechal et al. 2018) in the low- to moderate-intensity events (RP25–RP50). However, under extreme forcing, this buffering capacity was overwhelmed. Overwash rates on dissipative profiles converged with those on reflective profiles. The rapid onset of cyclones prevents significant morphological adaptation, leaving reflective beaches more vulnerable during high-magnitude events. This indicates that the rate and intensity of storm forcing are critical in controlling system response.

The present methodology provides a robust framework for simulating nearshore hydrodynamics and morphological change, enabling a detailed assessment of how well dunes can withstand storm impacts and resist overwash. The model was implemented in 1DV configuration, which is particularly suited to data-scarce regions, allowing for a large number of simulations and detailed cross-shore analysis. Conceptual similarities exist with Bayesian Network-based coastal hazard frameworks (Poelhekke et al. 2016; Plomaritis et al. 2018; Garzon et al. 2023). However, the adopted strategy demonstrates how meaningful process-based modeling can still be achieved under limited data availability. A uniform sediment grain size ($D_{50} = 0.25$) was used to provide a consistent baseline for sediment transport assessment, although incorporating spatial heterogeneity in future studies could improve representation of localized erosion and deposition processes (Dong et al. 2015). Similarly,

bathymetry was reconstructed from integrated datasets to ensure comprehensive spatial coverage, while future inclusion of in-situ measurements could enhance the accuracy of nearshore slope and run-up predictions (Geheran et al. 2024). The use of surfbeat mode enables effective representation of infragravity wave dynamics (Roelvink et al. 2009), and despite simplified wave–current–morphology interactions, the approach yields valuable insight into morphological responses. Finally, application of a morphological acceleration factor ($\text{morfac} = 6$) substantially reduced computational cost (Roelvink et al. 2009; Newell and Maldonado 2023). Although the use of morphological acceleration is known to potentially amplify nonlinear morphodynamic feedbacks relative to natural temporal scales (Ma et al. 2024), the sensitivity tests performed in this study showed no noticeable differences in the overall morphodynamic response or in the identified vulnerability patterns for the adopted value (0.2% difference). Consequently, the use of $\text{morfac} = 6$ does not affect the qualitative interpretation of the identified dune vulnerability thresholds.

The present framework provides a useful approach for assessing dune vulnerability in data-scarce regions. However, several limitations should be acknowledged. First, model calibration and validation were constrained by the limited availability of in-situ observations, introducing uncertainty in parameter selection and the magnitude of simulated morphodynamic response. Second, the simulations were conducted using a 1DV configuration, which captures dominant cross-shore processes but excludes alongshore processes such as Longshore Sediment Transport (LST), embayment-scale circulation, and alongshore dune variability. In a microtidal embayed system exposed to oblique cyclone waves, these processes may influence local overwash and erosion patterns. Therefore, the identified thresholds should be interpreted as representative cross-shore estimates rather than fully three-dimensional system behaviour. Additionally, a spatially uniform sediment grain size ($D_{50} = 0.25$ mm) was assumed throughout the domain, whereas natural variability in sediment characteristics may alter transport and erosion processes. Finally, the use of a morphological acceleration factor ($\text{morfac} = 6$) substantially improved computational efficiency but may moderately amplify nonlinear morphodynamic feedbacks and affect the temporal evolution of sediment redistribution.

Although a formal uncertainty analysis was beyond the scope of this study, the identified sources of uncertainty should be considered when interpreting the results. The principal findings, including the nonlinear response of dune systems and the emergence of critical thresholds, were consistently observed across the simulated scenarios. However, the exact numerical values of the identified thresholds (e.g., critical dune height and MWL ranges) may vary under

different sediment characteristics, hydrodynamic conditions, or inclusion of alongshore processes. Consequently, these thresholds should be interpreted as indicative values for the investigated system rather than universally fixed limits.

The framework provides transferable insights into dune vulnerability, overwash potential, and morphodynamic vulnerability that can inform risk screening, early-warning strategies, and adaptive coastal planning. These capabilities are especially valuable in regions experiencing rapid coastal urbanization or infrastructure expansion, where anthropogenic pressures may amplify natural erosion processes and constrain natural recovery pathways.

The results underscore the critical importance of protecting and maintaining coastal dunes in their present form, as they represent the most effective and spatially efficient natural defence against cyclone impacts in coastal regions (Harris and Ellis 2025). Unlike many highly urbanized or developed coastlines in Europe and other regions, where dunes have often been removed to make way for infrastructure, Mozambique still retains extensive and relatively intact dune systems. This contrast highlights the role of natural coastal features in mitigating storm surge and wave impacts, similar to the way mangrove forests act as protective buffers against extreme events in tropical coastlines (Alongi 2008; Nordstrom 2014). The existence of a clear, MWL-dependent threshold for systemic dune collapse highlights that dune integrity is lost abruptly once critical hydrodynamic limits are exceeded, making preventive conservation far more effective than post-storm intervention. The construction of infrastructure on dune crests or foredunes fundamentally compromises their protective function by constraining natural sediment redistribution, lowering effective dune height, and amplifying the consequences of overwash and breaching once threshold conditions are reached. Maintaining dune volume, continuity, and sediment mobility is therefore essential to delay the onset of overwash, limit sediment loss, and reduce inland hazard propagation. In the context of intensifying tropical cyclones, coastal management strategies must prioritise dune conservation and restoration (Putri et al. 2025), strictly avoid development on dune systems (Sampath et al. 2025), and incorporate projected MWL thresholds into long-term planning to prevent irreversible loss of this primary natural defence. Additionally, nature-based strategies, such as maintaining and restoring dune vegetation (e.g., by mixing seagrass leaves with sand), may enhance sediment stability, reduce wind and wave erosion, and improve overall resilience against storm impacts (Chen et al. 2022; Gracia et al. 2025). Effective implementation of these approaches requires integration into adaptation pathways under global change, ensuring that dunes are monitored, maintained, and embedded in restoration agreements to remain functional over time, with clear triggers for intervention when thresholds are approached (Dietrich et al. 2025).

Conclusions

This study demonstrated that dune response to cyclonic forcing is strongly non-linear and controlled by interactions among dune morphology, storm intensity, beach profile type, and MWL variations. Dunes remained relatively stable under low to moderate forcing conditions but exhibited abrupt morphological change once critical thresholds were exceeded.

The simulations identified critical thresholds of approximately 3 m dune height and MWL variations of ~ 0.4 – 0.5 m, beyond which overwash and dune crest retreat increased rapidly. RP100 events produced the largest responses, indicating a tipping point where the system's ability to maintain its form was substantially diminished. Elevated MWL amplified storm impacts and lowered the effective dune height required for stability.

The beach profile type also influenced system behaviour. Reflective profiles exhibited greater sensitivity to overwash and crest retreat, whereas dissipative profiles showed enhanced ability to withstand storm impacts through greater wave-energy dissipation, although this buffering capacity decreased under extreme forcing.

Overall, the results highlight the importance of maintaining dune morphology and incorporating hydrodynamic thresholds into coastal planning and risk management. The framework also demonstrates the potential for process-based assessments of dune vulnerability in data-scarce regions.

Appendix A: Data description

Table 1 Summary of datasets used in the study

Data type	Source	Resolution	Purpose
Bathymetry (regional)	GEBCO 2023	~ 15 arc-sec	Offshore bathymetric context
Nearshore bathymetry	Sentinel-2 SDB	10 m	Nearshore profile refinement
Bathymetry validation	ICESat-2	Point data	SDB calibration/validation
Bathymetric contours	NGA charts	Variable	Shallow-water constraint
Wave climate	ERA5 reanalysis	Hourly	Extreme storm forcing
Tides	TPXO model	Hourly	Water level forcing
Sediment size	Field sample	Point	Sediment transport parametrization

Appendix B: Model parameters

Table 2 Main model parameters

Parameter	Value/Formula	Description
<i>wavemodel</i>	surfbeat	Stationary (0), surfbeat (1) or non-hydrostatic (2)
<i>break</i>	Roelvink-Daly	Type of breaker formulation
<i>bed friction</i>	mannings	Bed friction formulation
<i>bedfriccoef</i>	0.02	Bed friction coefficient
<i>form</i>	vanthiel-vanrijn	Equilibrium sediment concentration formulation
<i>gamma</i>	0.36	Breaker parameter in Baldock or Roelvink formulation
<i>alpha</i>	1	Wave dissipation coefficient in Roelvink formulation
<i>turb</i>	Wave averaged	Turbulence variance at the bed
<i>morfac</i>	6	Morphological acceleration
<i>h_{switch}</i>	0.01	Water depth at which is switched from wetslp to dryslp
<i>D₅₀</i>	0.00025	Grain size (m)
<i>eps</i>	0.050	Threshold water depth above which cells are considered wet
<i>dryslp</i>	1	Critical avalanching slope above water (dz/dx and dz/dy)
<i>facAs</i>	0.2	Calibration factor time averaged flows due to wave asymmetry
<i>facSk</i>	0.15	Calibration factor time averaged flows due to wave skewness

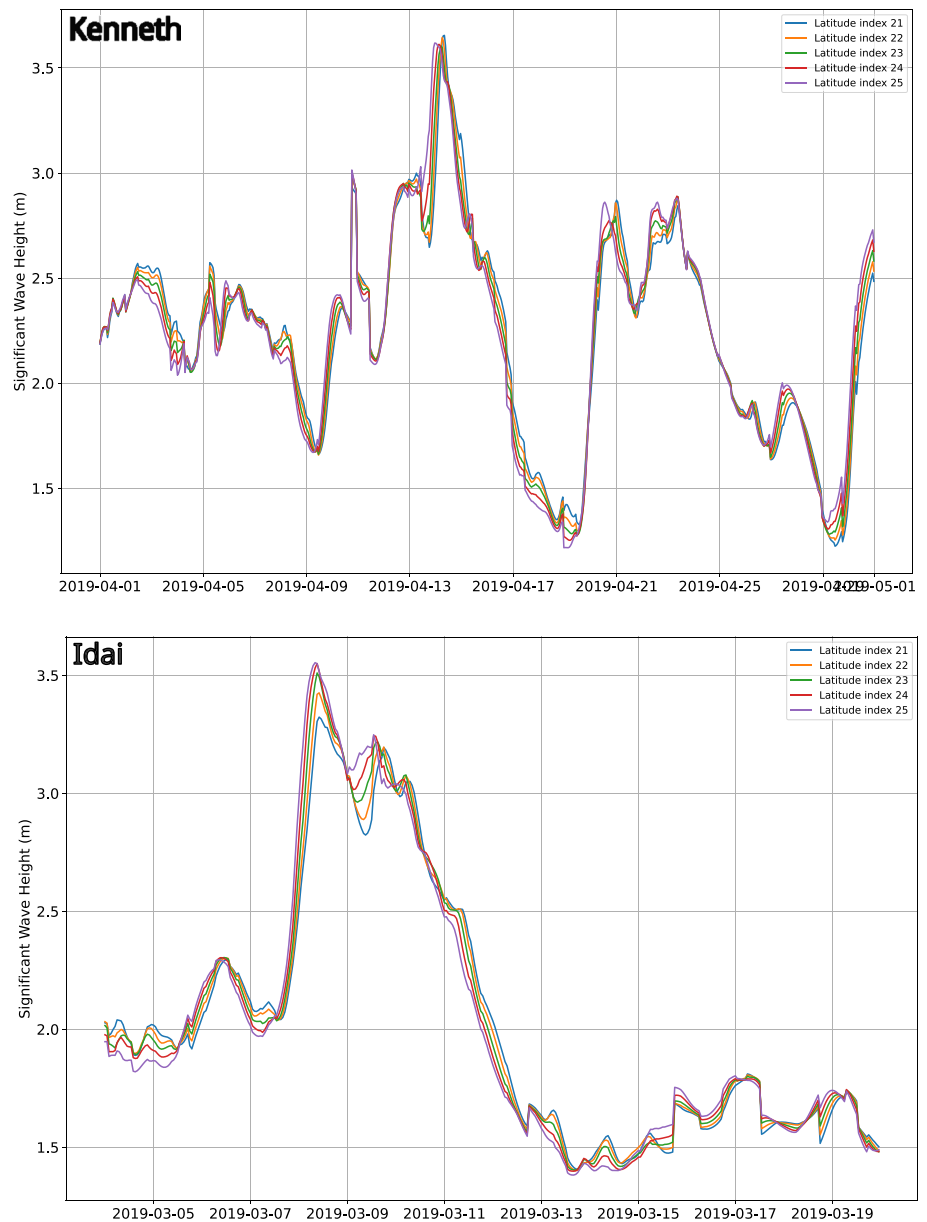
Appendix C: Return periods

The analysis of extreme waves in Mozambique was mainly performed for the ERA5 nodes using theoretical distribution functions, such as the Generalised Extreme Value (GEV) (Wang et al. 2021). For long-term wave data, we applied the Annual Maxima (AM) method (Amarouche et al. 2023). The return level and return period associated with an extreme event were calculated, to showcase the trend across different time periods at each node. To test the reliability of the results, the GEV was fitted and the 95% confidence interval was obtained. The GEV and the Cumulative Distribution Function (CDF) were plotted. The Kolmogorov-Smirnov test was performed to test the null hypothesis that both distributions, the empirical and GEV distributions, were from the same distribution. Among the analysed ERA5 nodes, node N17, which is the closest offshore node to the XBeach study site, was selected to define the wave forcing conditions used in the storm simulations presented in this study.

Table 3 H_s (m) for different return periods (in years) at different ERA5 nodes (N). Refer to the Supplementary Material to locate the nodes

Return	H_s (m)							
Period (years)	N3	N6	N10	N17	N20	N22	N26	N33
2	5.76	5.51	4.98	4.51	4.55	4.48	4.06	3.72
10	7.06	6.72	6.31	5.92	5.83	5.51	4.89	4.58
25	7.73	7.32	7.02	6.97	6.69	6.11	5.29	4.99
50	8.23	7.75	7.58	7.94	7.47	6.59	5.56	5.29
100	8.73	8.18	8.14	9.11	8.37	7.11	5.82	5.59

Appendix D: Storm shape

Fig. 8 Temporal evolution of Cyclone Kenneth (April 2019) and Cyclone Idai (March 2019)

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Data Availability Data sets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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