Received: 2 February 2025 | Revised: 9 August 2025 | Accepted: 18 August 2025

DOI: 10.1002/esp.70152

RESEARCH ARTICLE

ESPL WILEY

Reef island morphological change over the past two decades: Spermonde Archipelago, Indonesia

Meghna Sengupta[1] | Thomas Mann[2] | Marleen Stuhr[1] | Hildegard Westphal[1,3]

[1]Leibniz Centre for Tropical Marine Research (ZMT), Bremen, Germany

[2]Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany

[3]Department of Geosciences, University of Bremen, Bremen, Germany

Correspondence
Meghna Sengupta, Leibniz Centre for Tropical Marine Research (ZMT), Bremen, Germany.
Email: meghna.sengupta@leibniz-zmt.de

Funding information
Alexander von Humboldt Foundation

Abstract

Low-lying coral reef islands are presumed to be highly vulnerable landforms to the effects of climate change. Rising sea levels, changes in wave regimes and reef degradation are all considered key threats to their future persistence and habitability. While a number of studies have examined morphological changes on islands over multidecadal timescales, there is a paucity of high-frequency data from recent years that discern variability in shoreline change trends at the local scale. In this study, we used frequently sampled high-resolution satellite imagery covering the past two decades and analysed the morphological evolution and dynamics of 22 reef islands of the Spermonde Archipelago at the southwest coast of Sulawesi, Indonesia - a location deemed as a climate change hotspot with sea-level rise rates higher than the global average, and anthropogenically affected reef ecosystems. Analysis of 4,329 transects cast across 192 recorded shorelines revealed a balance in erosional and accretionary response. Specifically, 32% of transects were characterized by statistically significant accretion, 29% by erosion and the remaining exhibited no significant change. The magnitude of shoreline changes showed high spatial variability across the archipelago, with marked differences between islands perched on patch reefs on the outer shelf and those in the mid-shelf and nearshore. Archipelago-wide, irrespective of a net gain or loss in land area on islands, accretion was predominant on the western margins, while the eastern margins experienced relatively high degrees of erosion, leading to a westward migration of 55% of the islands on their reef platforms. Collectively, this study provides the first high-resolution shoreline change record for the archipelago, explores contemporary patterns of island morphological change and highlights the importance of high-frequency sampling in reef island studies for understanding projections of island change and efforts towards developing robust adaptation strategies and decision-making.

KEYWORDS
climate change, Coral Triangle, Indonesia, island evolution, reef islands, remote sensing, satellite imagery, sea-level rise, shoreline dynamics, Spermonde Archipelago, Strait of Makassar

1 | INTRODUCTION

Across the tropical and sub-tropical oceans, reef islands occur as small, low-lying landforms, built predominantly from the deposition of biogenic carbonate sediments derived from coral reefs and related ecosystems, rarely reaching elevations > 2–3 m above mean sea-level (Stoddart & Steers, 1977; Woodroffe et al., 1999). Impacts of climate change, particularly rising sea levels and profound changes in wave regime, have raised a global concern on the physical stability and continued habitability of such islands, with some studies suggesting complete destabilization and loss of the islands by the end of this century (Dickinson, 2009; Storlazzi, Elias, & Berkowitz, 2015). Additionally, degradation of coral reef ecosystems, linked to both global climate (e.g., increase in ocean temperature, changes in ocean chemistry, high energy events), and local anthropogenic stressors, are expected to affect sediment supply that is critical for the physical maintenance of these landforms (Eyre et al., 2018; Perry et al., 2011, 2015), as well as reduce the structural complexity that provides natural coastal protection from wave-driven coastal erosion and inundation (Ferrario et al., 2014; Harris et al., 2018; Quataert et al., 2015).

A growing number of studies in recent decades, largely spanning the Indian and Pacific Oceans, have taken an empirical approach to document and analyse multidecadal planform island changes and have concluded that reef islands are extremely dynamic and have physically persisted and predominantly maintained their stability over periods of sea-level rise (Duvat, 2018; Ford, 2013; Ford & Kench, 2015; Kench et al., 2024; Mann & Westphal, 2016; Mann, Bayliss-Smith, & Westphal, 2016; McLean & Kench, 2015; Sengupta et al., 2023; Webb & Kench, 2010; Wu, Duvat, & Purkis, 2021). These studies have provided valuable insights into the inherent physical adaptability of reef islands to changing boundary conditions and have identified a range of styles and trajectories of morphological adjustments (Kench et al., 2024). However, there remains a paucity of high-frequency analysis of shoreline change from recent decades that coincide with instrumental records of accelerated sea-level rise (Ablain et al., 2017; Legeais et al., 2018) and conceivably an increased anthropogenic influence on shorelines as well as surrounding reef ecosystems (Gilmour, 2022; Perry et al., 2018; Pratchett, Hoey, & Wilson, 2014; Roth et al., 2018). With the availability of high-resolution satellite imagery, such an approach offers the ability to examine nuanced patterns of island morphological change over the past two decades, that can be particularly valuable in regions with permanent human settlements, catering to the need of highly resolved empirical data of shoreline change to inform adaptation strategies and potential intervention decisions (Westphal et al., 2022).

Indonesia, being the largest archipelagic nation in the world, is considered to be at the forefront of climate change impacts, with a large proportion of its population living in low-lying coastal areas, including reef islands that provide habitable land and support the livelihood of island communities (Cruz et al., 2007; Hijioka et al., 2014; Muis et al., 2020; Zikra, 2015). Despite the high socio-economic importance of these islands, and projections of accelerating rates of sea-level rise in the region (IPCC, 2021), geomorphological studies on reef island shoreline dynamics are extremely sparse (Hamylton et al., 2020; Kench & Mann, 2017). In this study, we generate a high-frequency (annual to bi-annual) record of shoreline change from the past two decades for islands of the Spermonde Archipelago, Southwest Sulawesi, Indonesia. By analysing the first high-resolution shoreline change dataset for the archipelago, we address a significant geographical gap and contribute to the efforts in generating global empirical reef island change data. We examine the islands at three spatial scales: (1) aggregated shoreline change within the archipelago; (2) intra-archipelagic variability: island groups of the outer-rim, mid-shelf and nearshore; and (3) individual island-scale variability, including a comparison between the largest erosional and accretionary islands. Finally, using a fine-scale analysis of shorelines, we provide (4) a comparative analysis of rates of shoreline change across sections of shorelines in direct proximity to anthropogenic modifications versus those that are predominantly natural. Collectively, our results provide insights into the nuanced patterns of morphological change observed on reef islands within the past two decades and offer robust empirical records that aim to inform trajectories of island physical change in the context of a changing climate and local stressors, and the formulation of adaptation and management strategies for island communities.

2 | STUDY AREA

The Spermonde Archipelago (4°00′S – 6°00′S and 119°00′E–119°30′E) comprises about 120 coral reef islands and lies within the Coral Triangle, between the southern arc of Sulawesi and the Makassar Strait. Approximately half of these islands are permanently inhabited, and the majority of them have undergone varying levels of anthropogenic modifications, collectively supporting a population of approximately 50,000 (Glaser et al., 2015). Unlike most examined islands of the Pacific and Indian Oceans (Duvat, 2018; Mann & Westphal, 2016; McLean & Kench, 2015; Sengupta et al., 2023; Wu, Duvat, & Purkis, 2021) where islands primarily occur on rims of isolated atolls with a distinct lagoon, islands of the Spermonde Archipelago are perched on isolated patch reefs across a shallow carbonate platform (Umbgrove, 1929, 1930; Kuenen, 1934; Figure 1a) near a highly urbanized coastline, characterized by terrestrial input from the mainland as well as localized anthropogenic impacts around densely populated islands (Girard et al., 2025; Janßen et al., 2017; Pol'onia et al., 2015). The city of Makassar has expanded rapidly since the 1950s and driven urbanization along the Sulawesi coastline, prompting land-use changes and land expansions (Surya et al., 2021). The impacts of the development of Makassar and its satellite cities have substantially increased nutrient run-off, sedimentation, turbidity, eutrophication and coastal pollution in nearshore areas, impacting the archipelago's coral reef ecosystems and their functioning (e.g., Cleary et al., 2005; Estradivari et al., 2025; Nurdin et al., 2023; Teichberg et al., 2018).

Due to its location, the Spermonde Archipelago experiences a complex climatic and oceanographic regime influenced by monsoonal wind patterns, reversing between winds from the northwest during the boreal winter or the wet season (December to February) and from the southeast during summer or the dry season (June–August). Generally, the region is characterized by low to moderate wave energy, which varies seasonally, with mean significant wave height averaging annually around ~0.4–0.5 m, peaking at ~0.8 m and ~1.0 m during the peak of wet and dry seasons, respectively (Durrant et al., 2014). Rates of sea-level rise in this region have been recorded to be higher than the global average, with a rate of ~5.2 mm/year based on altimetry observations between 1993 - present (Ablain et al., 2017; Legeais et al., 2018). The formation of reef islands and their morphological characteristics have been linked to the wind-wave regime and transformation of wave energy on their near-circular reef platforms, which dictate sediment transport pathways and nodal positions for the accumulation of sediments (Kench & Mann, 2017; Figure 1b). A distinct difference in sediment texture and composition has been identified between islands of the outer shelf, close to the Makassar Strait where islands are largely composed of coarser sediments (sandy-gravels) and are coral-dominated, with a relatively higher abundance of *Halimeda*, benthic foraminifera and gastropods, in contrast to the inner shelf, where island sediments are mainly

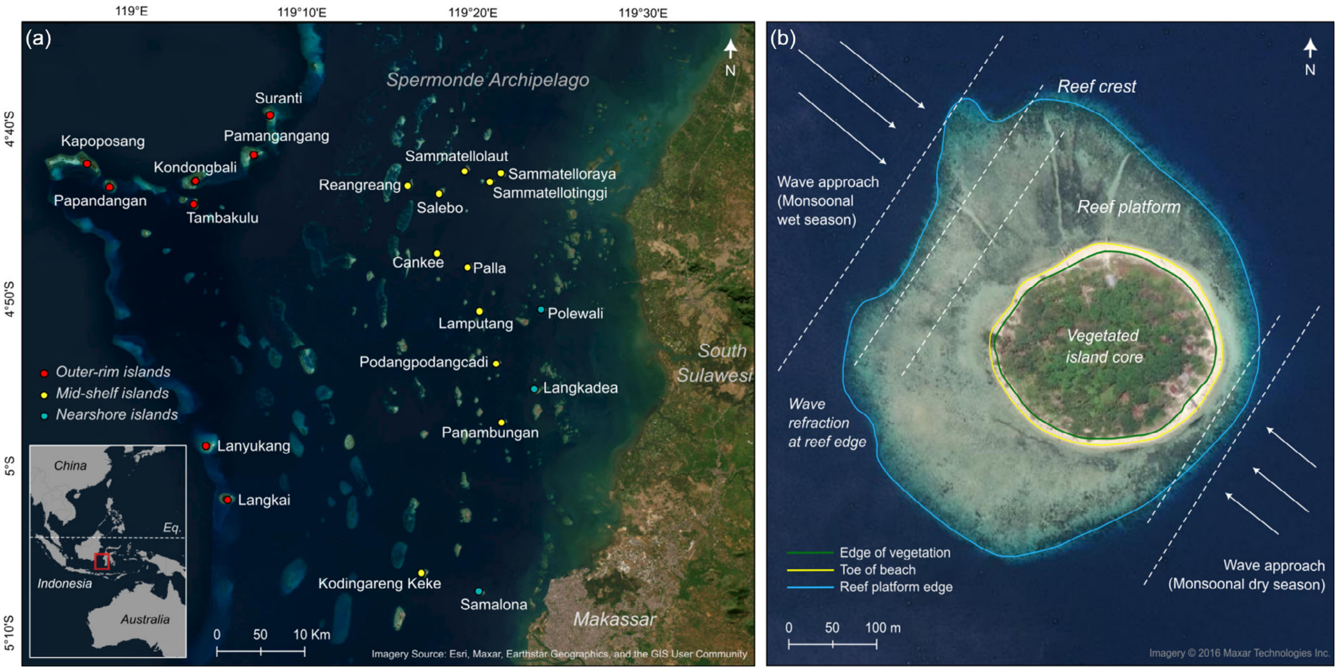

FIGURE 1 (a) Location of the 22 study islands in the Spermonde Archipelago, Indonesia. (b) Typical planform characteristics of a reef island in the Spermonde and monsoonal wind-wave directions: example of Sammatelloraya. Note the location of the island aligned eastward on the reef platform.

coralline algae-dominated (Janßen et al., 2017). The planform size of islands within our sample ranges between 0.52 ha (Kodingareng Keke) and 37.68 ha (Kapoposang), with the average size being 6.48 ha. Their underlying reef platforms are similarly diverse in size, ranging from 16.64 ha to 667.80 ha. Islands are predominantly circular in shape, with 50% of islands ($n = 11$) with a circularity ratio greater than 0.8. All elongate islands with a circularity ratio less than 0.3 ($n = 3$) occur on the outer rim (see Suppl. Table 1 for details).

3 | METHODS

3.1 | Selection of study islands, data sources and processing

The selection of islands across the Spermonde Archipelago analysed within this study is based largely on the availability of high-resolution imagery on a multi-temporal basis within the past two decades. Anthropogenic modifications on islands across the Spermonde Archipelago are highly variable, and a number of islands are highly modified to the degree where shorelines consist predominantly of reclaimed land, as observed on the satellite images. These islands were excluded from analysis, given the absence of a clear shoreline proxy for changes that may reflect any natural signal. The sample of islands was selected to ensure a maximal spatial coverage of the archipelago, in particular the three zones: the near-shore (3 islands), the mid-shelf (11 islands) and the outer-rim (8 islands).

The high-resolution imagery used in this study was obtained from a range of multispectral optical sensors, including WorldView2/3 (spatial resolution of 0.3–0.5 m), GeoEye (0.4 m), Pléiades (0.5 m), SPOT (1.5 m) and PlanetScope (3 m). All images were georeferenced using the respective highest resolution imagery (WorldView2/3) as the source of reference and ground control, and were transformed using a second-order polynomial transformation. Permanent features such as buildings, causeways and/or temporally stable natural features within the study period, such as beachrocks were used as ground control points. The maximum root mean square error of rectification was 0.5 m. Sampling of images was done to enable annual to bi-annual frequency of shorelines, with the period of analysis ranging between 8 and 22 years and a minimum of 6 to a maximum of 13 images analysed per island (Suppl. Table 1).

3.2 | Shoreline proxy and shoreline change statistics

The choice of shoreline proxy is an important element of consideration when quantifying shoreline change statistics. While the wet/dry line is widely used as a proxy of beach periphery, it is highly affected by tidal fluctuations and short-term, seasonal fluctuations in wind-wave regimes. In reef island systems, particularly when tracking changes at annual to multidecadal scales, edge of vegetation provides a robust proxy for island shorelines (Duvat, 2018; Ford, 2013). To avoid short-term noise from changing hydrodynamic regime owing to reversing monsoonal winds, we used the edge of vegetation as the shoreline proxy and, consequently, the vegetated island core for shoreline change and island area calculations. Shorelines were digitized at a uniform scale of 1:1000 by a single operator as polyline features in ArcMap 10.8.2. To provide a context for the area of beach that envelopes the vegetated island core, we digitized the toe-of-beach in each image for each island (Figure 1b) and subtracted the respective areas of the vegetated island core. We used the Digital Shoreline Analysis System (DSAS), available as an extension within the ArcGIS suite, which is a widely used tool for calculating shoreline change statistics from multi-temporal shoreline data (Thieler et al., 2009). Onshore baselines were created manually across the study islands, transects were cast at equal intervals of 5 m across the recorded shorelines, and classified as showing statistically significant erosion, accretion or no significant change using a confidence interval of 95% within DSAS (Thieler et al., 2009). From the range of statistical metrics provided by DSAS, we used End Point Rate (EPR) as well as Linear Regression Rate (LRR) to analyse the rates of shoreline change in this study. EPR was calculated by normalizing the distance between the oldest to the most recent shoreline position by elapsed time, whereas LRR was obtained by fitting a least-squares regression line across all the recorded shoreline positions. While both have been used by previous studies, the LRR is indicative of the trend in the shoreline response and filters out short-term fluctuations in shoreline position (Ford, 2013). Additionally, Shoreline Change Envelope (SCE) was used to provide a measure of the net movement in shoreline positions by calculating the distance between the shoreline farthest and nearest from the baseline, therefore covering the expanse of shoreline movement within the study period, irrespective of time.

There exists marked variability in shoreline modifications and the presence of anthropogenic activities on the study islands. We categorized transects as *'distal'* or *'proximal'*, defining whether these transects (or sections of shorelines) were in direct spatial proximity to anthropogenic structures and in the vicinity of settlements. Transects that intersected shoreline modifications, such as causeways, seawalls and other artificial protection structures, or were directly in front of settlements, were classified as *'proximal'*, otherwise *'distal'*. This classification serves two purposes for investigation: (1) identifying and comparing the response of shorelines armoured with direct artificial structures, (2) identifying potential hotspots of erosion close to anthropogenic settlements; both of direct interest for coastal management and possible adaptation measures.

4 | RESULTS

4.1 | Archipelagic-scale analysis of island change

A total of 4,329 transects were cast across the shorelines of the 22 study islands. Within these, 32% (n = 1,394) of transects were characterized by significant accretion, 29% (n = 1,257) were characterized by erosion, and the remaining 39% (n = 1,678) showed no significant change. This balance of erosional and accretionary responses across the shorelines resulted in no significant gain or loss in land area recorded at the archipelagic-scale. Analysis of the magnitude of shoreline movement reflects an average shoreline change envelope of 11.98 m, highlighting the considerable morphological changes occurring at the local scale (Figure 2).

4.2 | Intra-archipelagic variability

Within the subsets of nearshore, mid-shelf and outer islands, the average rate of change was accretionary for the outer islands

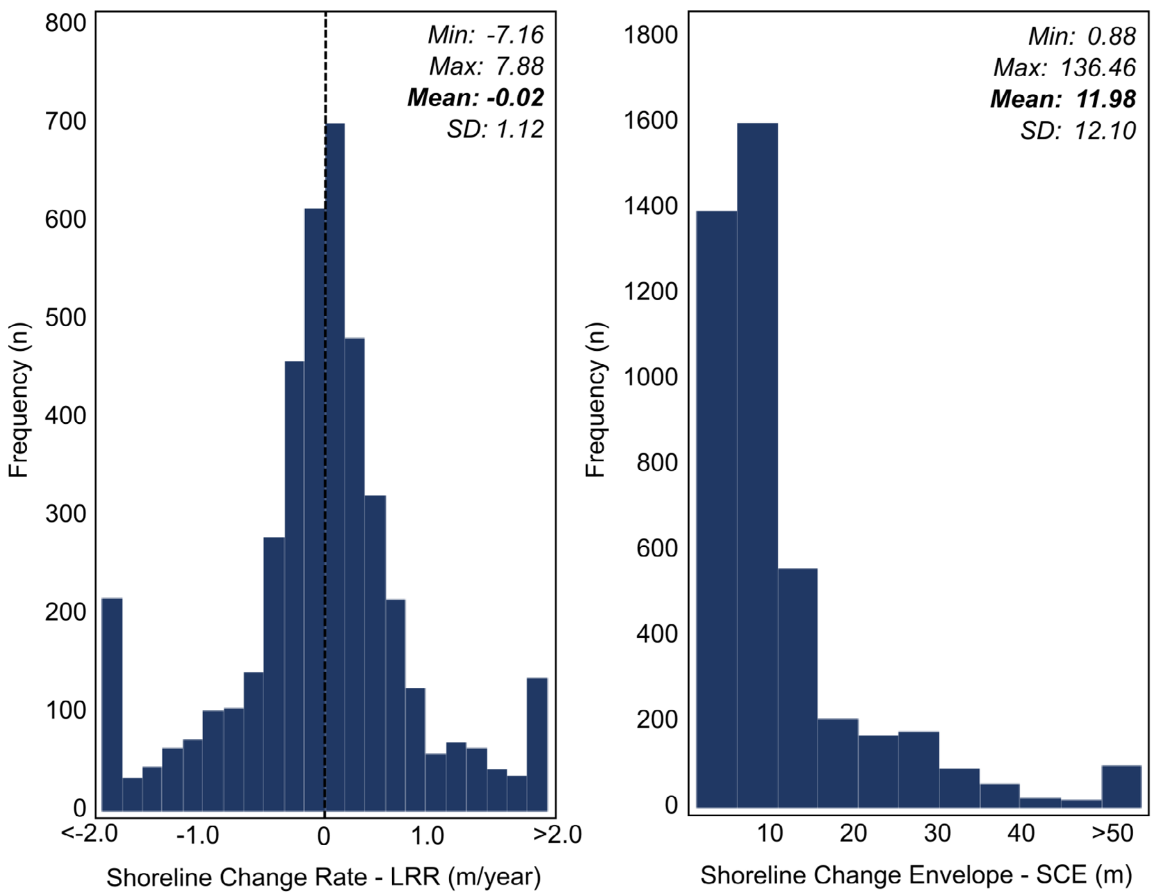

FIGURE 2 Archipelagic-scale shoreline change statistics – Linear Regression Rates (LRR) and Shoreline Change Envelope (SCE) across the 4,329 transects cast across the 22 study islands.

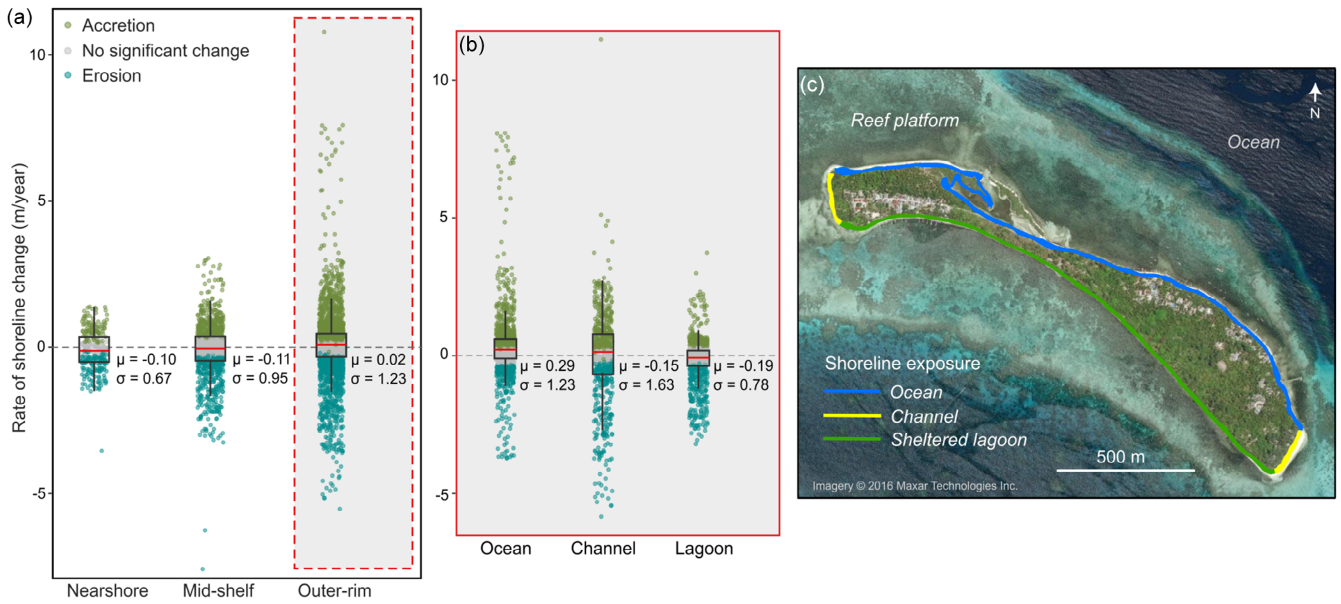

FIGURE 3 Distribution of shoreline change rates across all transects of islands (a) of the three zones (b) subset of the outer-rim islands with varying exposure types. Points (jittered) represent rates across all transects. (c) Example of shoreline sections categorized as ocean, channel and lagoon-facing on the outer island of Kapoposang.

(0.02 m/year), while both mid-shelf and nearshore islands were observed to have eroded on average with rates of −0.11 m/year and −0.10 m/year, respectively (Figure 3a). The standard deviation of LRR was least in the nearshore islands, and highest in the outer islands. Of note, results from a one-way ANOVA showed a statistically significant difference in mean rates of change (LRR) between islands of the nearshore, mid-shelf and outer-rim ($df = 2$, $f.\ value = 3.44$, $p\text{-}value = 0.032$).

Unlike the inner islands, where the islands are perched on isolated patch reefs and their shorelines are entirely sheltered from the open-ocean, the outer island shorelines observe variable exposure with the western and northern shorelines fronted by larger water depth and exposure to open-ocean swell. Average rate of change within these settings shows considerable variability with both channel and shallow-shelf lagoon-facing shorelines characterized by erosion with average rate of change at −0.15 m/year and −0.19 m/year, respectively. In contrast, accretion is observed on the ocean-facing shorelines with an average rate of 0.29 m/year (Figure 3b).

4.3 | Island-scale analysis: largest erosional and accretionary islands

Island-averaged rates of change showed large variabilities with LRR ranging between −0.61 m/year and 0.48 m/year (Suppl. Table 2). The largest accretionary rate was observed in the outer island of Pamangangang where 58% of transects showed significant accretion (Figure 4a). In contrast, the largest erosional rate was observed on Podangpodangcadi with 56% of transects showing significant erosion (Figure 4b). It is noteworthy that while the aggregated rates of change of the two islands were highly contrasting, similarities can be observed in the spatial patterns of erosional and accretionary hotspots around the island periphery (Figure 4). Both islands showed accretion on their western and south-western margins and erosion on their eastern margins, leading to a shift of the island footprint on the reef platform, towards the west. The northern edges of the islands showed no significant change and highlight the similarity in patterns and pathways of sediment transport and deposition across reefs within the Spermonde. Of note, the observation of a westward migration is prevalent across the archipelago, with 55% of the study islands showing a westward shift of the entire island footprint on the reef platforms.

4.4 | Shoreline change with respect to anthropogenic modifications on islands

To investigate the rates of change in sections of shoreline in direct proximity to settlements and/or artificial modifications, we categorized transects as *distal* or *proximal*, as detailed in Methods. Based on this classification, 43% of the transects (n = 1873) were categorized as *proximal* and the remaining 57% (n = 2,456) as *distal*. Results show that there is a statistically significant difference in the mean rates of change across *proximal* and *distal* shorelines from anthropogenic modifications ($t = 2.812$; $p\text{-}value = 0.005$). Of note, the average rate of change (LRR) across the *distal* group was accretionary (0.02 m/year) while the average rate of change across the *proximal* group was erosional (−0.07 m/year) (Figure 5).

4.5 | Active sediment reworking on outer islands: Island coalescence

Active sediment reworking can lead to islands splitting or merging as observed across various atoll settings in the Pacific (Sengupta, Ford, & Kench, 2021; Webb & Kench, 2010). Two cases of such island coalescence were observed within the Spermonde over the last two decades. Both of these cases occurred on the outer reef rim.

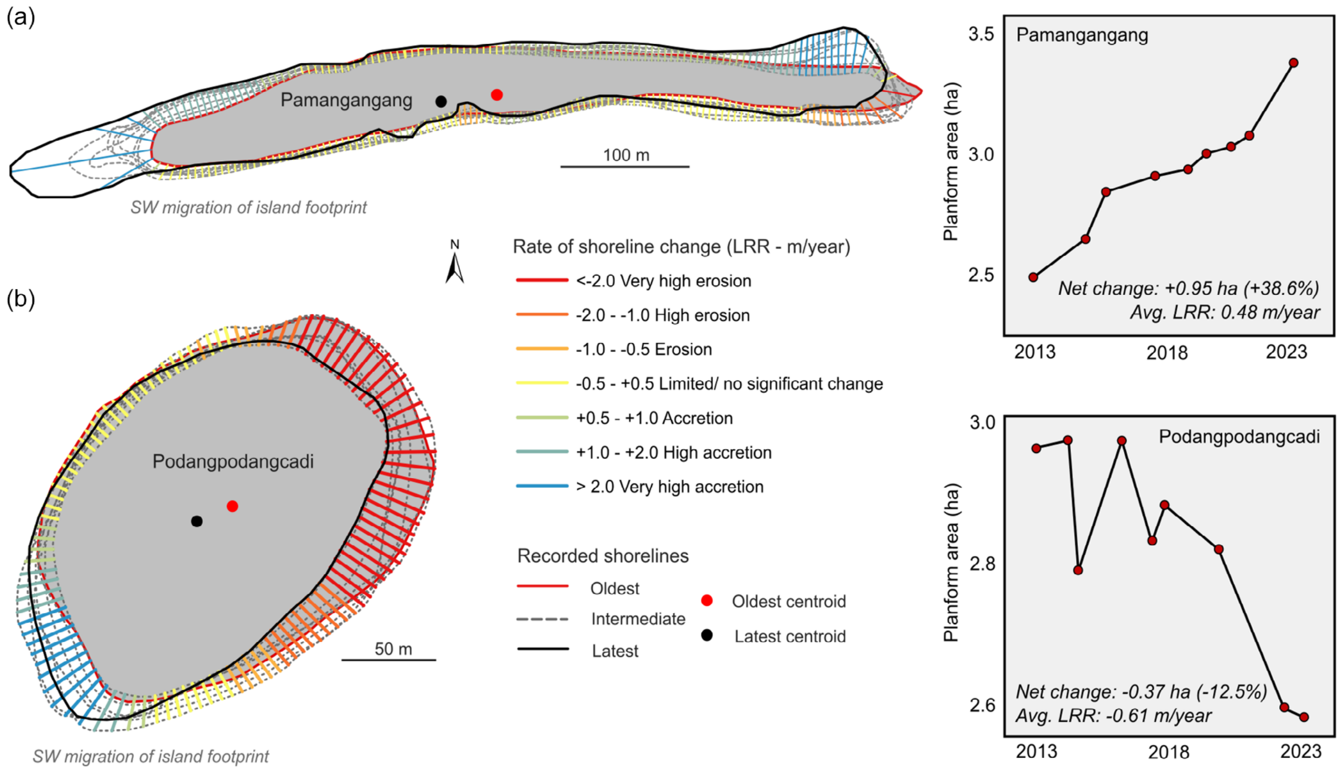

FIGURE 4 Largest erosional and accretionary rates of shoreline change. Note the comparable spatial pattern of accretion, erosion and migration of islands towards SW in both cases.

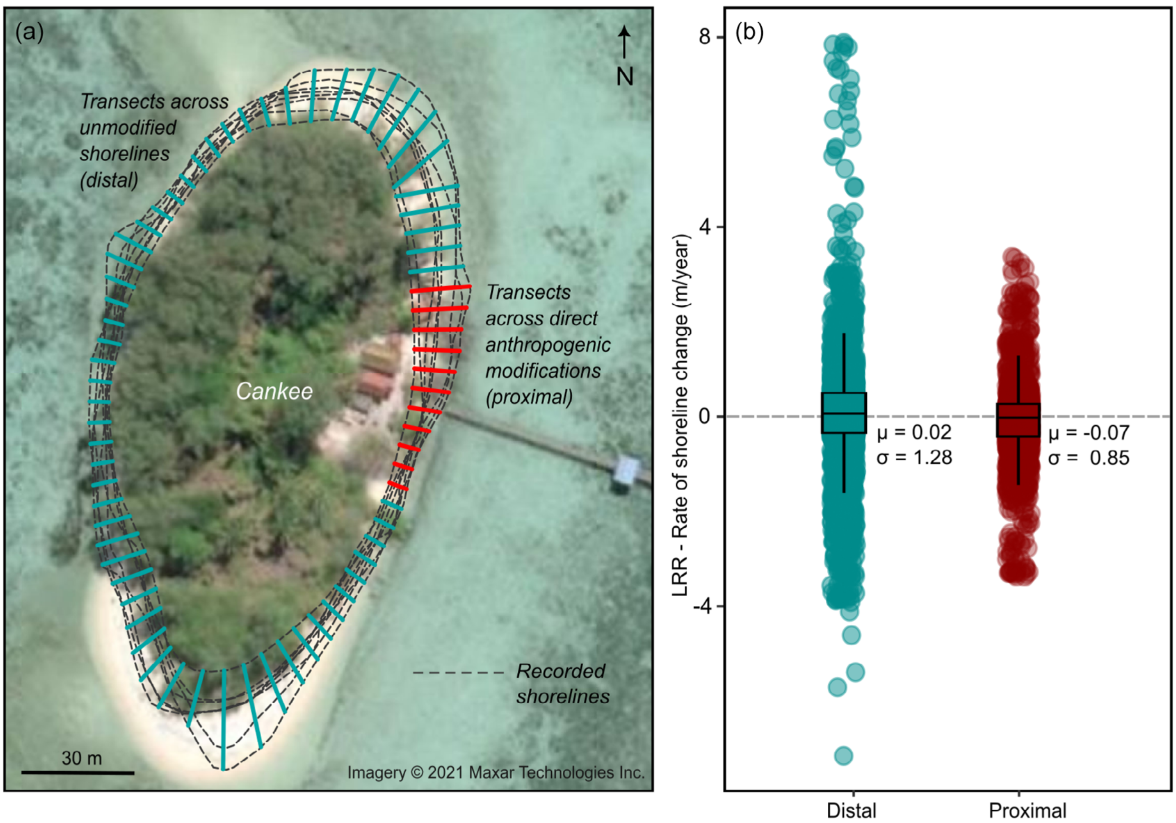

FIGURE 5 Variability in shoreline change rates across the study island shorelines with respect to anthropogenic modifications on islands: (a) example of classification of transects across shorelines of Cankee island, (b) variability of rates of change across shorelines at the local-scale (transects across all study islands).

Relatively smaller islands on reef platforms of Kapoposang and Suranti, located northwest and north in the archipelago, were observed to have undergone substantive changes and merging and splitting with the main islands. In Kapoposang, the smaller island of size 0.58 ha split from the main island as observed in 2016. This small island remained separated from the main island in subsequent years; however, its north-western spit eroded, and the island migrated southeast, eventually merging again with the main island, as observed in 2022. A net gain in land area of 0.35 ha (~1%) was recorded in Kapoposang between 2013 and 2022 (Figure 6a). On the contrary, at

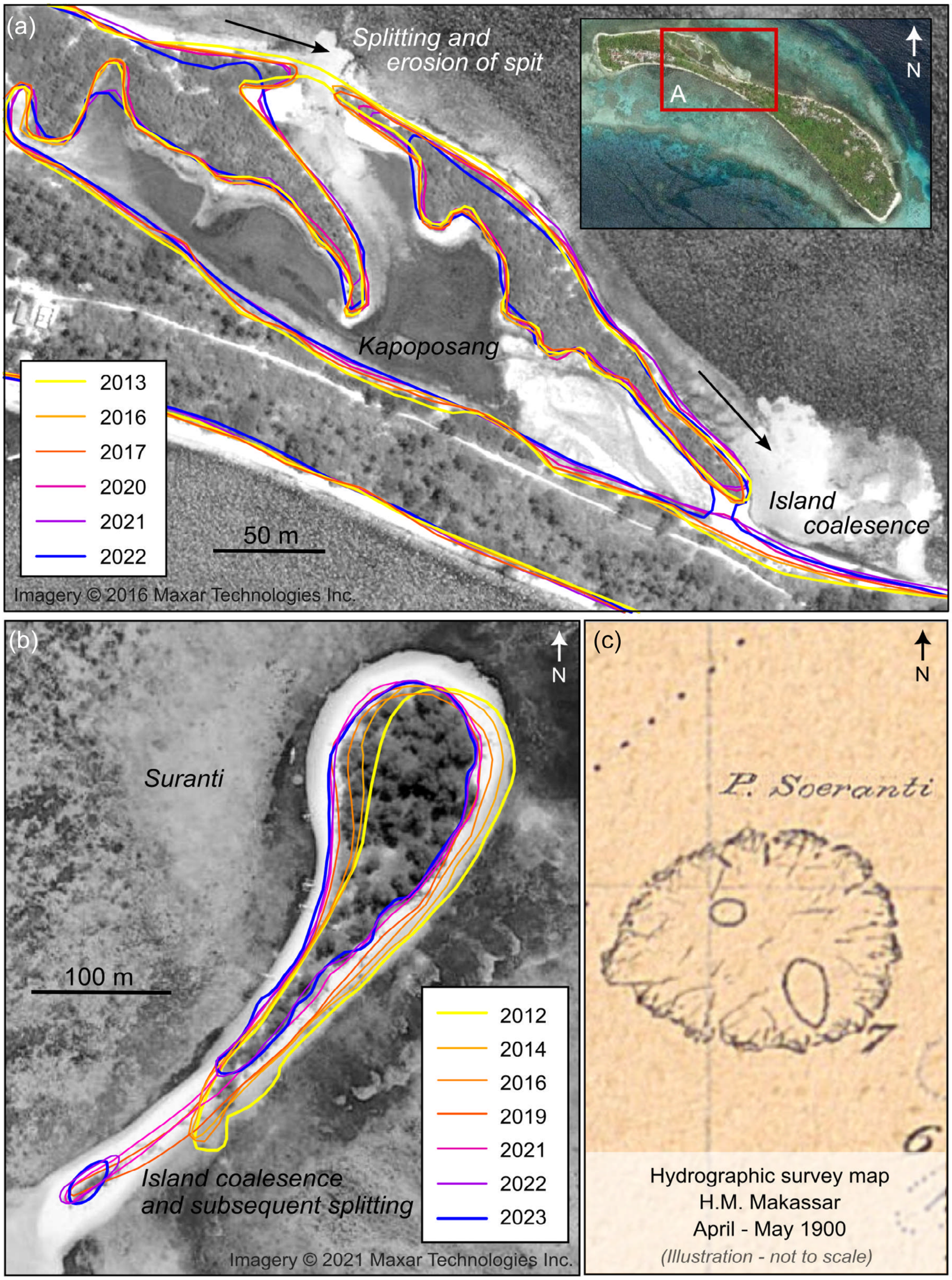

FIGURE 6 Island coalescence: (a) splitting and subsequent coalescing of a small island with the main island of Kapoposang; (b) Suranti in recent decades showing coalescing and subsequent splitting of a small island at its southern margin; (c) Hydrographic survey map illustrating island footprints of Suranti – two distinct islands mapped on the reef platform (Source: National Archives, The Hague).

Suranti, we recorded a net loss of −0.39 ha (∼ − 18%) of land area between 2012 and 2023. The island migrated northwest and lost substantial vegetated land area along its eastern and southern margins, with its shoreline retreating by ∼40 m. An elongate spit in its southern edge extended and split subsequently leaving a small piece of land separated from the main island (Figure 6b). The hydrographic survey map, although not to scale, shows two distinct land masses on the reef platform illustrating the highly dynamic nature and active sediment reworking ongoing at Suranti at least since the early 20th century (Figure 6c).

5 | DISCUSSION

Our study provides insights into the physical dynamics of reef islands at the contemporary timescale, identifies the spatial patterns of local-scale morphological change and investigates the variability of change observed across the Spermonde archipelago. Through analysis of high-frequency data, results showed great dynamism in shorelines and large magnitudes of change at intra-island scales. Variability was observed across islands of the inner shelf versus islands perched on the outer rim. Magnitude and occurrence of erosion and accretion were balanced at the archipelagic scale; however, marked variability is observed at the individual island-scale. We discuss the styles of observed changes, including spatial patterns of morphological change across the archipelago, observed changes with respect to beach area, anthropogenic modifications on islands and reef condition, and finally, we outline the broader implications of our key results for future research towards understanding projections of island morphological responses and management efforts across reef islands.

5.1 | Spatial patterns of shoreline change and links to geomorphological configuration

While net responses of island change, both in terms of land area and shoreline change rate, were highly variable across the study islands, there were marked similarities in the spatial pattern of island change across the archipelago. Notably, regardless of whether an island lost or gained land area during the period of our study (2000–2023), a clear trend of accretion was observed along the western margins, while the eastern margins were observed to have experienced erosion (Figure 7a).

The morphological setting of an island, including the reef width and local water depth across the reef platform, play a key role in defining wave energy gradients, sediment transport patterns and degrees of wave interactions with shorelines (Brander, Kench, & Hart, 2004; Kench & Brander, 2006a, 2006b). Island changes across the Spermonde have shown a distinct spatial pattern, wherein irrespective of net loss or gain in land area, the spatial pattern of island change was comparable across the shelf, where the western margins showed a tendency to accrete, and eastern margins were characterized by net erosion, though with a cyclic trend (Figure 7b). Of note, the location of islands of the Spermonde aligned eastward on the reef platforms, and a predominantly circular shape (Suppl. Table 1; Suppl. Figure 1), is a reflection of energy gradients and transport

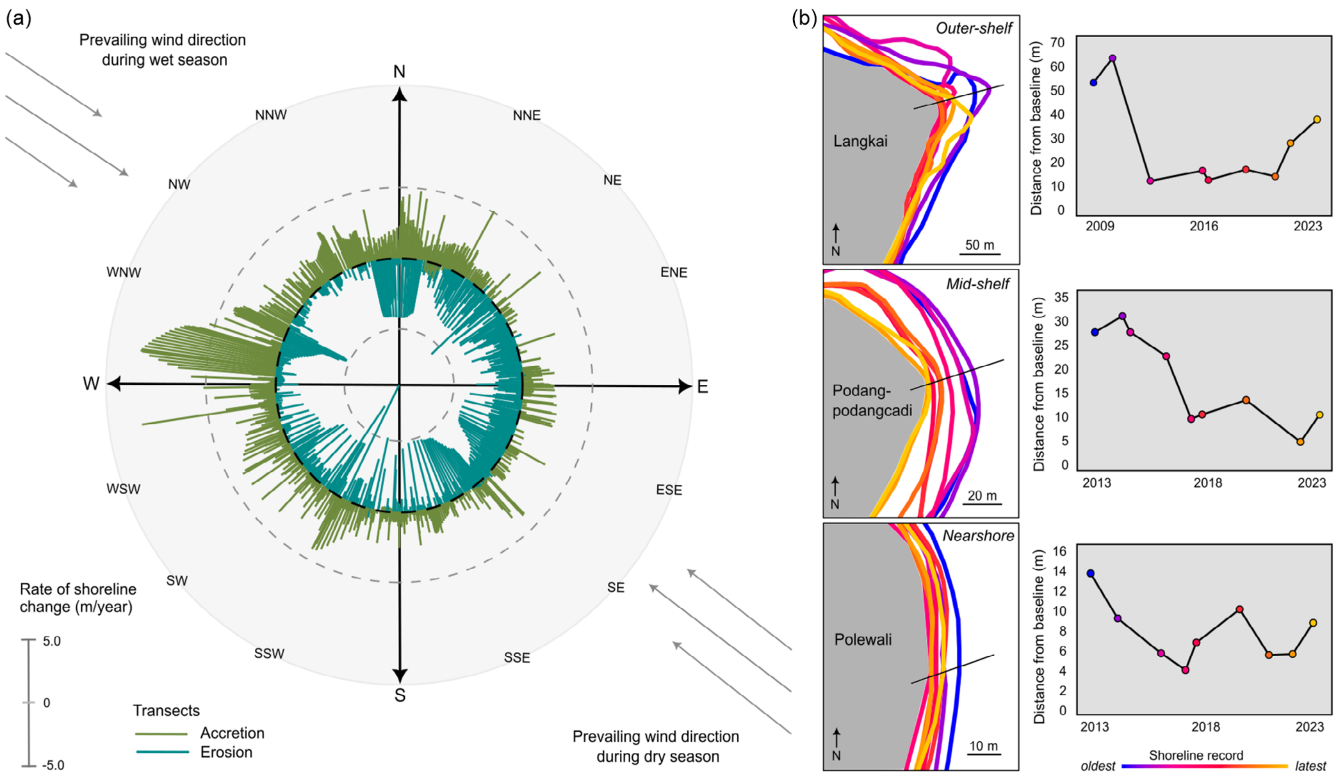

FIGURE 7 Spatial variability in shoreline change: (a) Shoreline change across all transects showing significant erosion or accretion with respect to direction: length of the transect indicates the magnitude of the rate of change. Accretion is prevalent on W-NW margins, erosion across E-SE. (b) Eastern margins of islands show a cyclic response with a net erosional trend: examples from islands of the outer-rim, mid-shelf and nearshore.

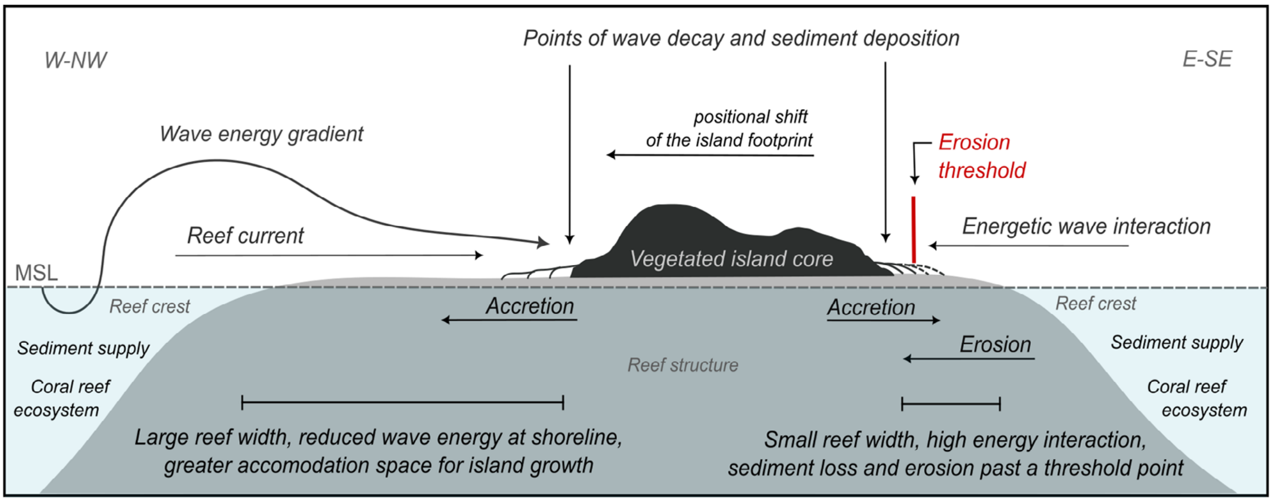

FIGURE 8 Conceptual model of island shoreline response in a typical reef island setting in the Spermonde Archipelago.

capacities leading to nodal positions of deposition as the islands formed (Kench & Mann, 2017). Our results highlight that these patterns of deposition are still reflected in the shoreline response, and the generic morphological characteristic of the islands likely drives the contemporary patterns of erosion and accretion. The eastern margins of the islands fronted by notably smaller reef width, were largely characterized by net erosion, with a cyclic trend alternating between phases of accretion and erosion. It appears that the smaller reef width enables more energetic wave interaction, and wave overtopping likely peaks during the dry season wind-wave regime, which is directed from the east, south-east and the shorelines undergo wave-driven erosion. However, a threshold point likely exists after which there is enough accommodation space for sediment deposition and stabilization to occur for shorelines to prograde. On the contrary, across the western margins that are fronted by significantly larger reef platforms and consequently more accommodation space, a wave energy gradient dictates a more consistent deposition of sediments, promoting shoreline accretion. These locally diverse changes are translated into a westward positional shift of the island footprints (Figure 8). It is important to note that on near-circular islands such as those within our study, wave refraction and diffraction around the island margins may drive alongshore sediment transport (Beetham & Kench, 2014; Bonesso et al., 2020; Cuttler et al., 2020; Kench & Brander, 2006b), and sediments from the eastern margins may be transported and deposited on the western margins contributing to the spatial pattern of accretion and erosion of the vegetated core as observed across our study islands.

5.2 | Beach area and the vegetated island core

While beaches are highly dynamic features on reef islands, they can provide a protective buffer around the vegetated island core and can be an indicator of available sediment in the vicinity that is available to be reworked, and replenish shorelines promoting island growth (Mann & Westphal, 2014; Toimil et al., 2023; Woodroffe & Morrison, 2001). Within our study islands, beach areas and their extents fluctuate due to the influence of changing seasonal wind-wave regimes, however, an approximate indication of beach sediments available to be incorporated into the vegetated island core can be conceptualized by the average beach area over the study period. Of note, some of the largest net gains in vegetated land area occurred on islands with consistently larger beach area on average, offering avenues for the growth of the vegetated island core, while all islands that experienced erosion and a net loss of land area were enveloped by smaller beach areas ($R^2 = 0.2315$; *p-value* $= 0.027$; Figure 9). This relationship highlights that the abundance of availability of unconsolidated material around the vegetated island core was likely able to be reworked into the island system and/or provided protection from wave-driven erosion, collectively enabling a growth of the vegetated island core. A significant relationship between the availability of beach sediments and island growth even within a relatively short, contemporary timescale illustrates the importance of measures that promote continued beach nourishment from surrounding reef ecosystems, and underscores its critical role in the long-term physical maintenance of the island core. Finer temporal scale analysis (e.g. monthly to seasonal) examining beach dynamics on individual islands, along with in-situ hydrodynamic measurements, carbonate budgets, as well as morphological characteristics of underlying reef platforms, may provide important insights into sediment transport pathways and their linkages to the longer-term spatial patterns of changes of the vegetated island core (see review by Browne et al., 2021).

5.3 | Anthropogenic modifications on islands, reef health and island shoreline response

Within Spermonde, the presence of anthropogenic influences impacting both coastal areas as well as reef ecosystems has been discussed by several studies (e.g., Estradivari et al., 2025; Haya & Fujii, 2017; Muller et al., 2012; Nurdin et al., 2023; Teichberg et al., 2018). Reef islands situated in such environments are exposed to additional challenges that may affect their long-term physical stability, such as a decline in reef health, impacting the natural feedback loop that includes active sediment generation, transport and beach nourishment (Liang et al., 2016; Perry et al., 2011, 2015). Within our

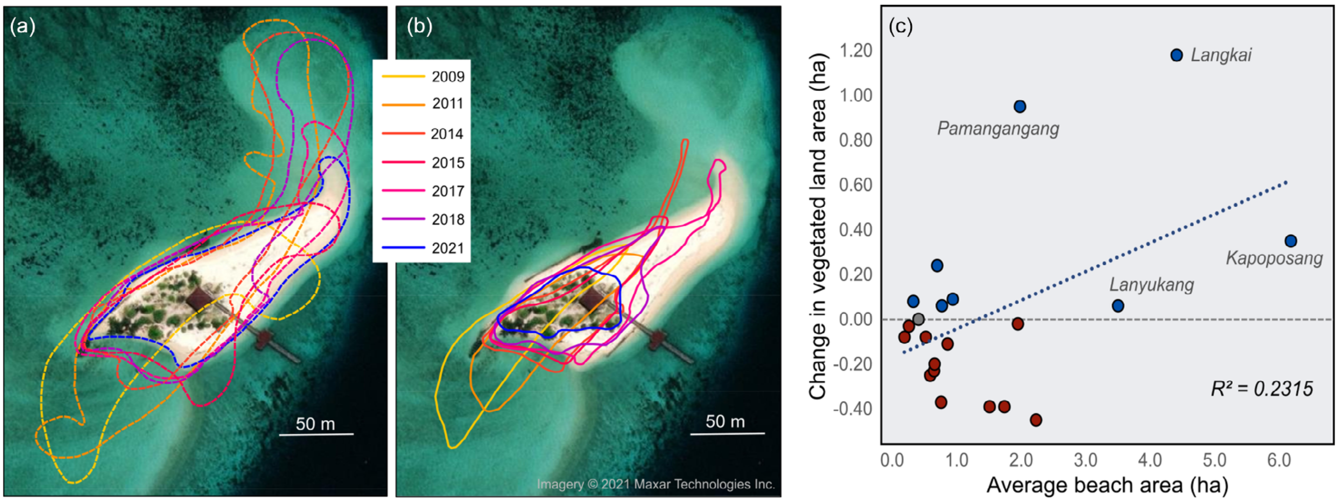

FIGURE 9 (a) Example of high dynamism in beach area and (b) respective vegetated island core as observed in the island of Kodingareng Keke. (c) Relationship between net change in vegetated land area versus average beach area across the study islands of Spermonde Archipelago. Red indicates net loss of vegetated land area, and blue indicates a net gain.

study islands, 43% of island sections were in direct proximity to artificial structures and settlements, while the remaining 57% were largely natural. The significant difference in mean rates of change between these two groups illustrates an on average accretionary trend on sections of shorelines free from visible anthropogenic modifications, where likely the natural signals of changing boundary conditions were maintained in the absence of disturbance in sediment transport pathways due to structures like seawalls or causeways (Biribo & Woodroffe, 2013; Duvat, 2013; Duvat & Magnan, 2019; Mann & Westphal, 2014; Purkis et al., 2016). On the contrary, an erosional rate dominated sections of shorelines in proximity to anthropogenic settlements and structures (e.g. causeways, seawalls). The results offer empirical insights that are likely of direct interest for decision-making for adaptation measures, particularly in areas with permanent human settlements, and highlight the importance of generating a robust knowledge base for the potential implementation of any coastal protection, restoration and/or conservation efforts and interventions such as those discussed by Westphal et al. (2022).

Beyond direct anthropogenic influence on shorelines, the coastal ecosystem of Spermonde has been under chronic stress linked to a range of activities including sand mining, intensive and destructive fishing practices, nutrient discharge, sedimentation and disposal of untreated industrial and agricultural waste (Edinger et al., 1998; Girard et al., 2025; Jompa, 1996; Pol'onia et al., 2015; Teichberg et al., 2018). Implications of such activities have been reflected in signs of reef degradation with a significant decline in coral cover and biodiversity, particularly within the nearshore and inner mid-shelf zones, as well as around densely populated islands on the outer rim (Edinger et al., 1998; Estradivari et al., 2025; Haya & Fujii, 2017; Moll, 1983; Nurdin et al., 2023). These may impact carbonate framework production as well as sediment generation, and hence alter sediment supply regimes to nearby shorelines (Browne et al., 2021; Perry, Lange, & Stuhr, 2023). A likely 'degraded reef condition signal' was observed in the shoreline response of islands of the mid-shelf and nearshore, where shorelines were notably erosional, with the largest erosional rate of −0.61 m/year observed on the island of Podangpodangcadi. Interestingly, a 'degraded' reef has been shown to have provided sufficient sediments for island growth through the increased supply by the calcifying algae *Halimeda* in one of the inhabited outer-rim islands in a recent study (Kappelmann et al., 2024), however, this observation is not mirrored in the islands of the mid and nearshore that are predominantly in an erosional state. This indicates a lack of sufficient island-building sediment supply and/or a disruption in the sediment transport pathways and connectivity between the supplying ecosystem and the islands in recent decades. Notably, the ecology and condition of the coral reef ecosystems surrounding the islands in the Spermonde Archipelago are highly variable due to the diversity and spatial variability in local pressures (Cleary et al., 2005; Faizal., 2022; Surya et al., 2021; Girard et al., 2025), e.g., locally differing protection status, fishing practices, sediment loads, nutrient and pollutant inputs, as well as coastal modifications. Human activities with greatest direct impacts on coral reefs and their functions related to carbonate production and sediment supply, such as through destructive fishing practices that turn the complex reef framework into flat patches of dead coral rubble (Figure 10a), are not necessarily highest around islands with densest populations or strong coastal modifications, because they are preferably applied at outer, remote or uninhabited islands (Suarthawan, Dirawan, & Mandra, 2022). Hence, the degree of anthropogenic modification of the island surface may not be directly correlated to the anthropogenic impacts on the surrounding ecosystems, nor may uninhabited islands be protected from human influences. Future studies should thus target the links between the condition of the coral reef ecosystems, their potential for carbonate production and sediment supply to the islands (Lange, Perry, & Alvarez-Filip, 2020; Perry, Lange, & Stuhr, 2023), to the observed shoreline changes.

5.4 | Significance for understanding trajectories of island change and adaptation decision-making

The growing number of studies in reef island change and dynamics over the past few decades have collectively provided a large and

FIGURE 10 Reef condition and anthropogenic influence: (a) Algal mats growing over fragmented corals and a bleached coral on the outer reef rim; (b, c) highly turbid reefs as observed within the mid-shelf and nearshore zones. (d, e) Unregulated waste disposal at the coast leading to pollution in the reef. (f) Fishing vessels. (g) Proximity to urbanized Makassar mainland as a cause of nutrient and sediment influx affecting the nearshore reefs (Samalona in the foreground). Photographs by M. Stuhr taken during a field visit in August 2022.

valuable dataset that serves as an empirical basis for understanding the physically dynamic nature of reef islands (Duvat, 2018; Ford, 2013; Ford & Kench, 2015; Kench et al., 2024; Mann, Bayliss-Smith, & Westphal, 2016; Mann & Westphal, 2016; McLean & Kench, 2015; Sengupta et al., 2023; Webb & Kench, 2010) and have collectively implied the necessity for high-frequency monitoring over recent decades to enable insights into the finer patterns of change, imperative for efficient adaptation planning and decision-making. While some recent studies have conducted high-frequency analysis of the wet/dry line on reef islands to understand inter-annual fluctuations (Cuttler et al., 2020; Lazarus et al., 2025), few studies to date have conducted comparable high-frequency and high-resolution sampling and analysis of the vegetation line as attempted here. In areas such as Spermonde, where most islands are inhabited, such analysis provides a unique opportunity to tease out patterns and trends in island change, and to identify reef island morphological 'behaviour' in light of contemporary climate change impacts, stressors and direct anthropogenic influences. Collectively, providing valuable insights for informing adaptation strategies and management pathways. Results showed high dynamism in shoreline responses, with outer islands showing trends of accretion while mid-shelf and nearshore islands characterized by erosion and loss of land area. However, all islands showed both hotspots of erosion and accretion, and their imbalance led to the whole island response of land gain versus loss. It is noteworthy that while all islands were characterized by variable rates of change, the spatial patterns of accretion and erosion were highly comparable across the entire archipelago. These outcomes point towards the influence of the site-specific wind-wave regime and its relationship to reef platform characteristics that underpin these islands (Kench & Mann, 2017), influencing wave energy gradients and transport processes across the reef flats (Figure 8). The whole island response can potentially be linked to the surrounding reef condition, affecting the production and delivery of island-building sediments, as well as reef-related structural complexity, resulting in a likely 'degraded reef health' signal that is beginning to emerge for the shorelines, particularly across islands of the mid-shelf and nearshore areas. Analysis of distinct responses on sections of shorelines that are free from anthropogenic modifications versus those that are armoured with artificial structures and/or are in direct proximity to settlements showed the prevalence of erosion in the latter, and has direct implications for risk assessments and management efforts across these islands. Collectively, our study provides a comprehensive record of contemporary shoreline dynamics that are critical for understanding linkages between ecological and process drivers and trajectories of island physical change within the archipelago and similar settings elsewhere. Furthermore, such records provide an empirical basis for formulating adaptation measures and assessing pathways for conservation and potential intervention decision-making.

6 | CONCLUSIONS

This study provides the first shoreline change dataset for the Spermonde Archipelago, Indonesia, closing an important geographical gap within a region of high ecological and socio-economic significance, and contributing to efforts towards generating a global record of reef island morphological change in light of climate change and sea-level rise. In addition, unlike most studied islands of the Pacific and Indian Ocean, where islands are often remote and isolated from significant anthropogenic influence, the Spermonde Archipelago lies off the densely populated coast of Makassar, South Sulawesi, and therefore islands are perched within a setting of highly stressed reef ecosystems. Our study provides a comprehensive analysis of reef island morphological change at a high spatial resolution and offers insights into patterns of erosion and accretion across the archipelago at scales that define marked styles of adjustments intra-island as well as distinctions in responses between island groups of the outer rim versus the mid-shelf and nearshore. By generating and analysing an empirical record of shoreline dynamics, this study offers avenues for further research linking carbonate production and supply to islands, reef health and shifting hydrodynamic regimes to improve our understanding of long-term trajectories of island change. Results offer evidence of the highly dynamic nature of reef islands at the contemporary, decadal to bi-decadal timescale and highlight the importance of high-frequency analysis of shoreline changes at fine spatial scales to provide insights relevant for the formulation of adaptation strategies, management and conservation across reef island settings.

AUTHOR CONTRIBUTIONS

Meghna Sengupta: Conceptualization; funding acquisition; project administration; data curation; formal analysis and interpretation; visualization; writing—original draft; review and editing. **Thomas Mann:** Conceptualization; interpretation of results; writing—review and editing. **Marleen Stuhr:** Project administration; interpretation of results; writing—review and editing. **Hildegard Westphal:** Conceptualization; project administration; interpretation of results; writing—review and editing.

ACKNOWLEDGEMENTS

Meghna Sengupta was supported by a fellowship of the Alexander von Humboldt Foundation. Open Access funding enabled and organized by Projekt DEAL.

CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

All supporting data are provided in the manuscript and the supplementary document.

ORCID

Meghna Sengupta https://orcid.org/0000-0002-3821-7235
Thomas Mann https://orcid.org/0000-0002-9182-2741

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Sengupta, M., Mann, T., Stuhr, M. & Westphal, H. (2025) Reef island morphological change over the past two decades: Spermonde Archipelago, Indonesia. *Earth Surface Processes and Landforms*, 50(11), e70152. Available from: https://doi.org/10.1002/esp.70152