Shoreline variability and coastal vulnerability: Mossel Bay, South Africa

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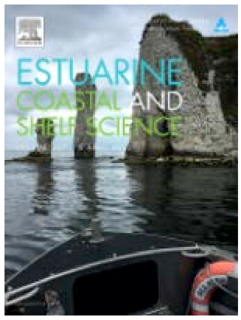

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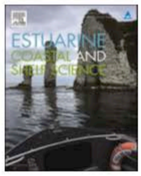

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ABSTRACT

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Highlights

- Landsat 7/8 and Sentinel 2A scenes capture variability in shoreline position
- DSAS-derived shoreline change rates indicate long-term stability
- Short-term shoreline change influenced by inlets, megacusps and rocky outcrops
- Alongshore variability in wave conditions reflected in shoreline change patterns
- Coastal processes and vulnerability described in three morphodynamic sub-cells

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Abstract

Coastal erosion may cause significant damage to property and infrastructure with far reaching socio-economic consequences. Assessing the site-specific shoreline dynamics is fundamental to understand the morphodynamic behaviour of a particular coastal area, as well as the associated coastal hazards. However, changes in shoreline position, even when significant, are not necessarily associated with increased coastal hazards. In this contribution we investigate the impact of short-term changes in shoreline position within a crenulated embayment of Mossel Bay. The 30 km-long embayment, located in the Western Cape region of South Africa, lies in a high-energy wave-dominated, micro-tidal setting. Mossel Bay is heavily populated and experiences an influx of tourists year-round. Much of the coastal community and infrastructure lies within 25 – 40 m of the foredune toe.

Georeferenced Landsat 7/8 and Sentinel 2A scenes are used to manually digitise shoreline position in ArcMap, using the "wet/dry" line as a shoreline position proxy. The Digital Shoreline Analysis System was then used to generate shoreline change statistical metrics. Wave conditions were modelled using SWAN wave model, implemented using a nested grid approach with a high-resolution (10 m) inshore grid, and a lower resolution (50 m) offshore regional grid. The nearshore wave field during mean and storm conditions was obtained along the 15 m isobaths along the entire embayment.

The embayment's orientation in relation to the prevailing swell direction results in significant alongshore variability in nearshore wave conditions; wave heights increase towards the east along the embayment. This variability in wave forcing is reflected by the changes in shoreline position in both long and short-term, computed using the end-point rate method. However, the areas of higher shoreline change are not those experiencing the worst detrimental effects.

Over the long-term, the present-day Mossel Bay embayment is relatively stable, with no significant signs of extensive accretion or erosion. However, rapid migration the shoreline is documented on a seasonal scale (short-term) with significant change proximal to river mouths, areas influenced by megacusps, and regions where the highly dynamic shoreline behaviour is constrained by rocky platforms and unable to freely adjust to variations in forcing. Thus, Mossel Bay is divided into three sub-cells in terms of coastal processes and coastal vulnerability with hazards associated with the location of such infrastructure rather than the specific patterns of shoreline change.

1. Introduction

Located at the interface between marine and terrestrial settings coastal zones are complex systems, yet understanding their dynamics is fundamental to sustainable coastal zone management. Coastal and shoreline change occurs over diverse temporal and spatial scales as a result of morphodynamic interaction between the coastal sediments, geology and geomorphology, wave and wind climate, tidal and ocean currents, anthropic influences and infrastructures (Carter and Woodroffe, 1994; Del Rio and Benavente, 2013; Hapke et al., 2016). Understanding coastal change is a challenging task with multiple influential factors exerting non-linear and often site-specific influences (Cooper et al., 2004). In exposed, wave-dominated environments, coastal change is primarily driven by variation in wave conditions, but nearshore waves are significantly controlled by the geomorphology of the coast and the bathymetry of the shoreface and continental shelf, affecting the patterns of sediment transport, erosion and deposition (McNinch, 2004). In any given coastal location, the bathymetry itself is determined by the availability and distribution of shoreface sediments and the geological sub/outcrops relative to mean sea level. Hence, the geological framework exerts a significant control in unconsolidated shoreface dynamics and coastal processes in response to wave climate (Thieler et al., 1995; McNinch, 2004; Del Rio and Benavente, 2013; Cooper et al., 2018).

The product of these interactions is the shoreline position; an important geoindicator for sandy coastal environments (Carapuço et al., 2016; Cawthra et al., 2020) that changes its shape and position over multiple spatial and temporal scales (Burningham and Fernandez-Nunez, 2020). Although there are a multitude of coastal features that may be used to define the shoreline position, from the wet-dry line to the vegetation line (Boak and Turner, 2005), the relative seaward or landward migration of the shoreline reflects the alongshore and cross-shore variability in coastal processes which force the addition or loss of material from the coast. Thus, variation in shoreline position marks the logical starting point when assessing coastal change as it provides a reference framework against which other influences may be compared, and coastal dynamics better understood.

Sandy beaches, extending from the nearshore zone to the foredune, represent one of the most dynamic and responsive sedimentary and morphological environments on Earth (Jackson and Short, 2020). Phases of accretion and erosion are natural, often associated with periods of high and low relative wave energy and/or changes in wave direction (Harley et al., 2015). Alternation between phases are typically linked to seasonal cycles; erosional phases in winter, and accretional phases during summer, (Senechal et al., 2015; Velegrakis et al., 2016; Umeda et al., 2018). However, variability in beach morphology can be considered at a range of timescales (Senechal and Alegria-Arzaburu, 2020), particularly short-term or event-based change driven by extreme single storms or storm groups (Ferreira, 2005), or at the timescale of years and decades, often linked to climate variability or changes in sediment supply (Smith et al. 2014; Senechal and Alegria-Arzaburu, 2020). Geologically-controlled sandy beaches add further complexity to seasonal sediment transport and deposition by introducing hard, non-erodible surfaces that limit the variability of unconsolidated beach profiles (Larson and Kraus, 2000; Vousdoukas et al., 2007; Gallop et al., 2020) while altering nearshore hydrodynamics (Cleary et al., 1996; Larson and Kraus, 2000; Vousdoukas et al., 2007; Storlazzi et al., 2010; Velegrakis et al., 2016), increasing erosion rates through scouring and reduced water infiltration (Walton and Sensabough, 1979; Larson and Kraus, 2000; Vousdoukas et al., 2009) and potentially limiting cross and along-shore sediment transport

(Vousdoukas et al., 2007; Gallop et al., 2020). In naturally functioning systems, undisturbed by anthropogenic interference and where direct human pressure is low to non-existent, phases of accretion and erosion and associated shoreline change pose no immediate risk as the coastal system is naturally dynamic. However, when infrastructure is placed within the beach or immediately landward, the interaction of a naturally dynamic system with human occupation and uses can have far-reaching consequences (Thom, 2020), including: loss of property, infrastructure, public access and amenity value (Brew et al., 2011). Hence, understanding the dynamics of the coastal zone and the impact on coastal erosion, as well as the implications for coastal hazards and associated risks to human occupation is a long-lived concern for coastal managers (Philips and Jones, 2006). Increased coastal erosion can also increase risk associated with potential loss of economically valuable land/infrastructure, sense of place and ecological services (Alexandrakis et al., 2015).

Assessing coastal vulnerability through various means is a necessary next step in management practice, highlighting areas of most concern and allowing coastal management focus to be directed effectively and efficiently. Typically, coastal vulnerability assessments fall into one of four categories: index-based methods, indicator-based approach, GIS-based decision support systems, and methods based on dynamic computer models (ETC CCA, 2011). While each particular approach is meaningful, adding value to policy and management, integrated approaches yield more comprehensive results to analyse and interrogate, thus allowing more robust evaluation of vulnerability at complementary spatial and temporal scales (McLaughlin and Cooper, 2010).

The embayment of Mossel Bay, located in the Western Cape, is heavily populated with significant infrastructure located within a densely vegetated primary coastal dune, in places less than 10 m from the high-water line. In Mossel Bay, as in many locations worldwide, there is significant potential for interaction between the natural beach system and coastal infrastructure. It is this interaction, and the associated coastal hazards that are the focus of this research. The aim of this paper is to analyse shoreline change in Mossel Bay at different time-scales and evaluate its relation to coastal hazards and vulnerability. To achieve this, we investigate: 1) long and short-term shoreline change using satellite imagery, 2) alongshore variability in the wave conditions, 3) presence and characteristics of erosional hotspots and, finally, 4) the evolution of the shoreline and forcing in the context of coastal hazards and coastal development along Mossel Bay.

2. Regional setting

South Africa's Cape South Coast (hereafter: South Coast) extends semi-continuously from Cape Hangklip in the west to Plettenberg Bay in the east (Fig. 1a) and is characterised by a seaward-dipping, low-relief coastal plain incising the base of the Cape Fold Belt. Extension, deformation associated with the Gondwana break-up (Watkeys, 2006), led to the formation of a series of rift basins along the southern margin of Africa that are characterised by graben and half-graben structural styles and infilled with Mesozoic sedimentary deposits (McMillan *et al*. 1997; Broad *et al*. 2006, 2012; Paton *et al*. 2006). The South Coast has served as a significant sediment sink, particularly with respect to the deposition and accumulation of marine, aeolian and lacustrine sediment during the Neogene and Quaternary Periods (Dingle et al. 1983, Flemming and Martin, 2017). The continuity of this coastline is fragmented into a series of variable sized coastal embayments that correspond morphologically to log-spiral embayed beaches. Offshore, the Agulhas Bank has been extensively planed by sea-level fluctuations in Neogene and, in particular, Pleistocene times (cf. Cleghorn, et al., 2020). Inshore, more recent deposits are preserved as low-relief ridges, shoals and shelf sands along the now submerged course of the Great Brak River (Cawthra et al., 2015). Onshore, upper Cenozoic shallow marine deposits of the Klein Brak Formation and aeolian sediments of the Waenhuiskrans Formation belong to the Bredasdorp Group and overlie older Neogene Wankoe Formation deposits in places (Malan, 1990). The younger unconsolidated Strandveld Formation constitutes the modern beaches and dunes. Palaeo shorelines have been extensively investigated in this bay (e.g., Carr et al., 2010; Jacobs et al., 2011; Roberts et al., 2012; Cawthra et al., 2015; 2018) as the Mossel Bay coastline was always a valuable resource to humans (Marean et al., 2007; Marean et al., 2015).

Regarding the wider oceanographic and climatic setting, the southwestward-flowing Agulhas Current closely follows the continental shelf break southward along South Africa's east coast and the Agulhas Falkland Fracture Zone moving offshore south of Port Elizabeth (350 km east of Mossel Bay) where the Agulhas Bank shelf broadens from ca. 50 km to ca 130 km (Martin and Flemming, 1986). The offset in continental shelf and interaction with the Agulhas Current results in an eastward-flowing Agulhas counter current and localised eddies (Rogers, 1971). Thus, Mossel Bay is not directly influenced by the Agulhas Current core, but rather a dynamic eddy and counter-current system. The South Coast receives precipitation derived from westerly driven frontal systems that bring winter rainfall and the Intertropical Convergence Zone bringing summer rain from the east, resulting in a year-round rainfall regime (South African Weather Bureau 1986; Taljaard 1996). Spring and autumn rainfall, associated with coastal cut-off low-pressure systems, may result in flooding in the region (Taljaard 1996).

The Mossel Bay embayment represents a micro-tidal coastline, with spring tides exhibiting a vertical range of less than 2 m (Davies, 1980; South African Navy, 2017). The spring tidal range for much of the coastline lies between 1.8 and 2.0 m with neap tidal ranges between 0.6 and 0.8 m (Cooper, 2001). The coastline is swell dominated with prevailing wave direction originating from the southwest, resulting in a net eastward longshore drift, with average conditions characterised by a significant wave height of 2.7 m and mean wave period of 6.6 s, while storm conditions (95% exceedance) are associated to significant wave heights of 4.6 m and mean wave periods of 8.1 s. The rate of contemporary sea-level rise along the southern Cape coast is estimated at 1.57 mm/year (Mather et al., 2009).

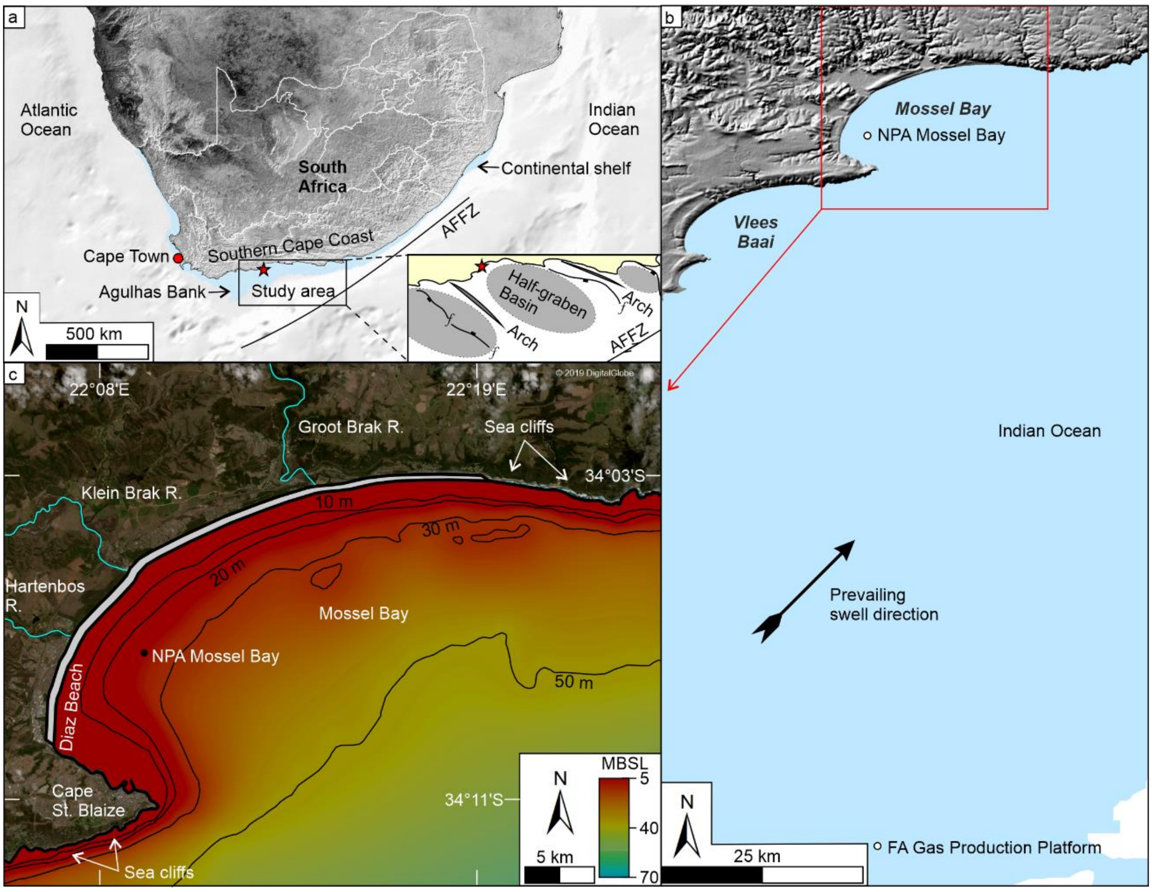

Fig. 1. a) Southern Africa; the Agulhas Bank hosts several structural basins (inset) bound offshore by the Agulhas Falkland Fracture Zone (AFFZ). Note: location of the study area (red star) mid-way along the southern Cape coast. b) Mossel Bay is a log-spiral bay in the Western Cape, South Africa. The Transnet National Port Authority (NPA) wave buoy lies within Mossel Bay, while the FA Gas Production Platform wave buoy is located directly south of the embayment. c) General bathymetry of Mossel Bay as digitised from South African Navy (SAN) Chart 123. (Base map from Google Earth, © 2018 AfriGIS (Pty) Ltd; © 2019 DigitalGlobe).

3. Data and Methods

3.1. Satellite imagery

Satellite images, derived from Landsat 7/8 (2000 to 2015), and Sentinel 2 (Jan to Dec 2016), were selected based on acquisition date and cloud cover such that the most meaningful scenes were identified for the period of time considered in this study (Table 1). Scenes with minimum cloud cover were chosen for optimum assessment of the shoreline position and also as ground control points (GCP). The spatial resolution of Landsat 7/8 scenes is 20 m, while Sentinel 2 scenes offer 10 m resolution. While Landsat and Sentinel imagery are provided as georeferenced products, to independently evaluate the positional accuracy of each scene for shoreline change analysis, a total of five carefully considered GCPs proximal to the shoreline across the study area and visible in each scene were identified and compared to the most recent imagery (the control scene). This allowed to determine the relative positional error in the satellite images used in this study, with RMSE ranging from 6.0 to 33.6 m, with a mean RMSE for all images of 15.99 m. (Table 1).

Table 1: Date, RMSE, source and resolution of scenes used in this study.

Scene date	RMSE	Source	Resolution
20160104	7.7	Sentinal 2	10 m
20160314	11.14	Sentinal 2	10 m
20160403	7.82	Sentinal 2	10 m
20160503	12.78	Sentinal 2	10 m
20160622	7.65	Sentinal 2	10 m
20160801	6.67	Sentinal 2	10 m
20160811	6.01	Sentinal 2	10 m
20161030	9.44	Sentinal 2	10 m
20151218	33.64	Landsat 7/8	20 m
20151116	19.92	Landsat 7/8	20 m
20150727	17.21	Landsat 7/8	20 m
20150524	20.95	Landsat 7/8	20 m
20150217	17.45	Landsat 7/8	20 m
20100424	14.01	Landsat 7/8	20 m
20100118	21.14	Landsat 7/8	20 m
20101017	21.59	Landsat 7/8	20 m
20100203	26.78	Landsat 7/8	20 m
20051222	19.69	Landsat 7/8	20 m
20050731	20.06	Landsat 7/8	20 m
20050816	12.82	Landsat 7/8	20 m
20050715	19.26	Landsat 7/8	20 m
20050309	19.43	Landsat 7/8	20 m
20001122	14.47	Landsat 7/8	20 m
20000717	16.17	Landsat 7/8	20 m
Mean RSME	15.99		

3.2. Shoreline change analysis

Shorelines were manually digitized in ESRI ArcMap using the wet/dry line as the proxy for shoreline position. The wet/dry line is accepted as an indicator of the high-water line position (Boak and Turner, 2005); and this is the most conspicuous and reliable shoreline proxy that can be obtained from the medium-resolution satellite imagery used in this study. Discontinuities in the shoreline (i.e. river mouths) were not considered in the analysis. Some scenes suffer from data gaps as a result of technical problems with the scan line corrector in the Landsat 7 multispectral sensor (Fig. 2). When encountered, these data gaps were filled using a subsequent scene because the gap location is different for each scene (Storey et al., 2005).

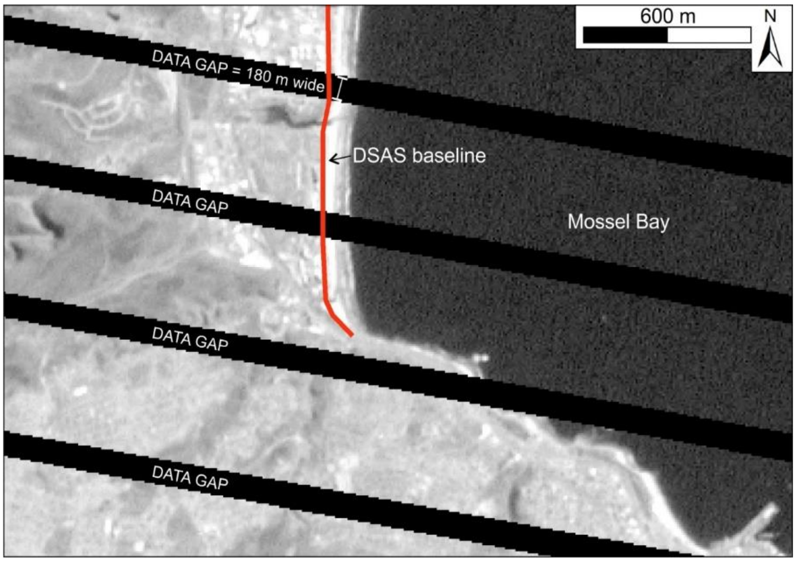

Fig. 2. Example of data gaps due to the Scan Line Corrector malfunction in the Landsat 7 imagery.

The Digital Shoreline Analysis System (DSAS) version 4.3 developed by the United States Geological Survey (USGS) was used for the analysis of shoreline changes over time (Thieler, et al., 2009). The DSAS is embedded in ESRI ArcMap and allows analysis of shoreline change using the End Point Rate (EPR) method, as well as by calculating Shoreline Change Envelope (SCE), Net Shoreline Movement (NSM), Weighted Linear Regression (WLR), and the uncertainty associated with the EPR (cf. Thieler, et al., 2009) (Table 2).

Table 2: Shoreline change statistics generated by the DSAS

	Statistic	Comment
EPR	End Point Rate	Quotient of shoreline movement over time elapsed between the oldest and the youngest shoreline
SCE	Shoreline Change Envelope	A measure of horizontal distance between the proximal and distal shorelines, relative to the baseline, irrespective of age
NSM	Net Shoreline Movement	time sensitive; NSM determines the horizontal distance between the oldest and youngest shoreline
WLR	Weighted Linear Regression Rate	More reliable data are given greater emphasis when determining a best-fit line

Changes in shoreline position are related to a *baseline*, which corresponds to a reference line inshore of the landward-most shoreline. Perpendicular transects spaced every 50 m and extending 200 m seaward of the baseline where generated by DSAS, intersecting all the digitised shorelines; each representing a time-specific shoreline position (Fig. 3). Shoreline change statistics computed by DSAS use the information retrieved from the intersections in relation to the baseline position. In DSAS 4.3 the computations are performed trough MATLAB executables bundled with DSAS.

In this study, the analysis was performed to investigate two temporal shoreline change scenarios: the first scenario is a multiannual, lower temporal resolution analysis of shoreline position change from 2000 to 2015; while the second scenario focused on a shorter-term, higher temporal resolution analysis of seasonal shoreline change in 2016.

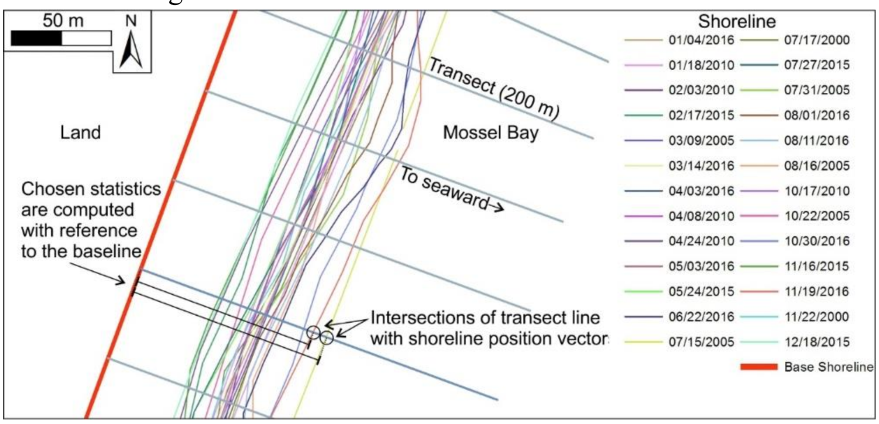

Fig. 3. Example of DSAS analysis. Shoreline position over time is compared to the base shoreline.

3.3. Bathymetric data

Regional bathymetry data were digitized in ESRI ArcMap, using soundings and isobaths of South African Navy Chart 123 and gridded to a 50 m spatial resolution. High-resolution multibeam bathymetry data within the embayment were collected from April – May 2011 using the survey vessel S/V 'GeoManzi'. During this survey, the continental shelf was mapped between depths of 10 m and 55 m below Mean Sea Level (MSL) using a 400 kHz Reson Seabat 7125 multibeam echosounder. Vessel motion was corrected using an Applanix POS MV 320 motion reference unit and positions were constrained within sub-decimeter resolution by a C-Nav Differential GPS. The survey navigation was done using QPS Qinsy software. Sound velocity profiles were collected daily within the survey area to correct the multibeam echosounder data for changes in the velocity of sound through the water column. As soundings inshore of 10 m were not available along the entire study area a depth of 15 m was chosen as the inshore data limit to ensure the model used recent high-resolution data. These survey data were gridded at a final resolution of 10 x 10 m for integration with the regional bathymetry for use in the wave modelling analysis.

3.4. Wave modelling

Wave data from two locations proximal to Mossel Bay coastline were made available by the South African WaveNet service operated by the CSIR, specifically the FA Gas Platform and Mossel Bay buoy (Fig 1). Deepwater wave conditions were obtained from the FA Gas Platform, located ca. 72 km offshore Mossel Bay in water depth of 113 m, while inshore waves, used for modelling validation, were obtained from a Waverider buoy located in the eastern section of the embayment in water depth of 24 m (Fig. 1). Wave direction was retrieved from the GOW2.0 global wave reanalysis (Perez et al., 2017). To determine nearshore wave parameters along the entire embayment, the spectral wave model SWAN (Simulating WAves Nearshore; Booij et al., 1999) was implemented using a nested modelling scheme. In the coarser regional grid (50 m resolution) SWAN was forced using the mean and 90th percentile wave height and period determined from the FA Gas Platform and wave direction from the GOW2.0 dataset. The model runs for the regional grid allowed to determine the boundary conditions for the finer inshore grid (10 m resolution), which was used to characterize the nearshore wave field along the 15 m isobath. Following Matias et al., (2019) and Anfuso et al. (2020), SWAN was run in 2D stationary mode, i.e. time is removed from the simulations and the waves are propagated instantaneously across the modelling domain, using a JONSWAP spectral shape to represent the wave field and including default parameterizations for bottom friction dissipation, non-linear wave interactions, diffraction and depth-induced breaking. The model runs were forced in the offshore boundary with the parametric wave information for mean wave conditions (wave height of 2.7 m, mean wave period of 6.6 s, wave direction 201˚) and storm wave conditions corresponding to the 90^{th} percentile of the wave distribution (wave height of 4 m, mean wave period of 7.8 s, wave direction 218˚)

3.5 Grain size analysis

Sediment samples were collected from the active beach at 21 sites in Mossel Bay, approximately 1 km apart along the embayment, during winter (24^{th} – 27^{th} June, 2015). Samples were analysed using a Malvern Instrument Mastersizer 2000 particle size analyser. Replicate sample results were output from the Mastersizer 2000 to Microsoft Excel and averaged for interpretation.

4. Results

4.1. Long-term shoreline change

Changes in shoreline position in Mossel Bay over the 15-year period from 2000 to 2015 are characterized by an overall erosion pattern reflected in negative shoreline change rates, as indicated by the EPR and WLR statistics, and a generally negative NSM (Fig. 4). However, there is considerable alongshore variability in shoreline change, which is evident in all shoreline change metrics presented. In terms of the envelope of change, significantly higher shoreline variability is observed in the eastern part of the embayment (transects 350 to 570 in Fig.4), with shorelines ranging in position in excess of 80 m over the fifteen-year period (2000 – 2015). Lower shoreline variability was measured along the central and western sections of the Mossel Bay embayment (approximately in the range of 20 to 30 m for SCE), with more dynamic locations associated with the three prominent river mouths. However, when considering the results from the other variables (EPR, NSM and WLR) it becomes evident that there is relatively moderate shoreline erosion along the entire embayment over the 2000 – 2015 period, with more significant shoreline retreat in the eastern section and at a few localised hotspots (Fig. 4). This can be observed through the End Point Rate, expressed as metres per year (m/yr), which varies from - 2.5 to -3.5 m/yr in the vicinity of the Hartenbos River mouth (transects X to Y) to more than 4 m/yr at the Klein- and Groot Brak River mouths as well as at Glentana in the eastern part of the areas of the study area. Based on the NSM results, there is consistent higher variability eastward from transect

310 to the eastern end of the embayment. Although the net shoreline change displays a generally negative trend, a few accretional hotspots are also evident. The central region of the embayment, from transect 224 to 320, exhibits reduced variability despite a small net negative trend. Over the entire period of analysis, when accounting for the uncertainty in the data, the overall shoreline behaviour in Mossel Bay based on the WLR results is characterized by an average retreat of 0.8 m/yr, with a maximum shoreline retreat of 5 m/yr. Shoreline retreat is more pronounced in the western and eastern sections, with the shoreline in the centre of the embayment (transect 200 to 320) displaying very low annual rates of change.

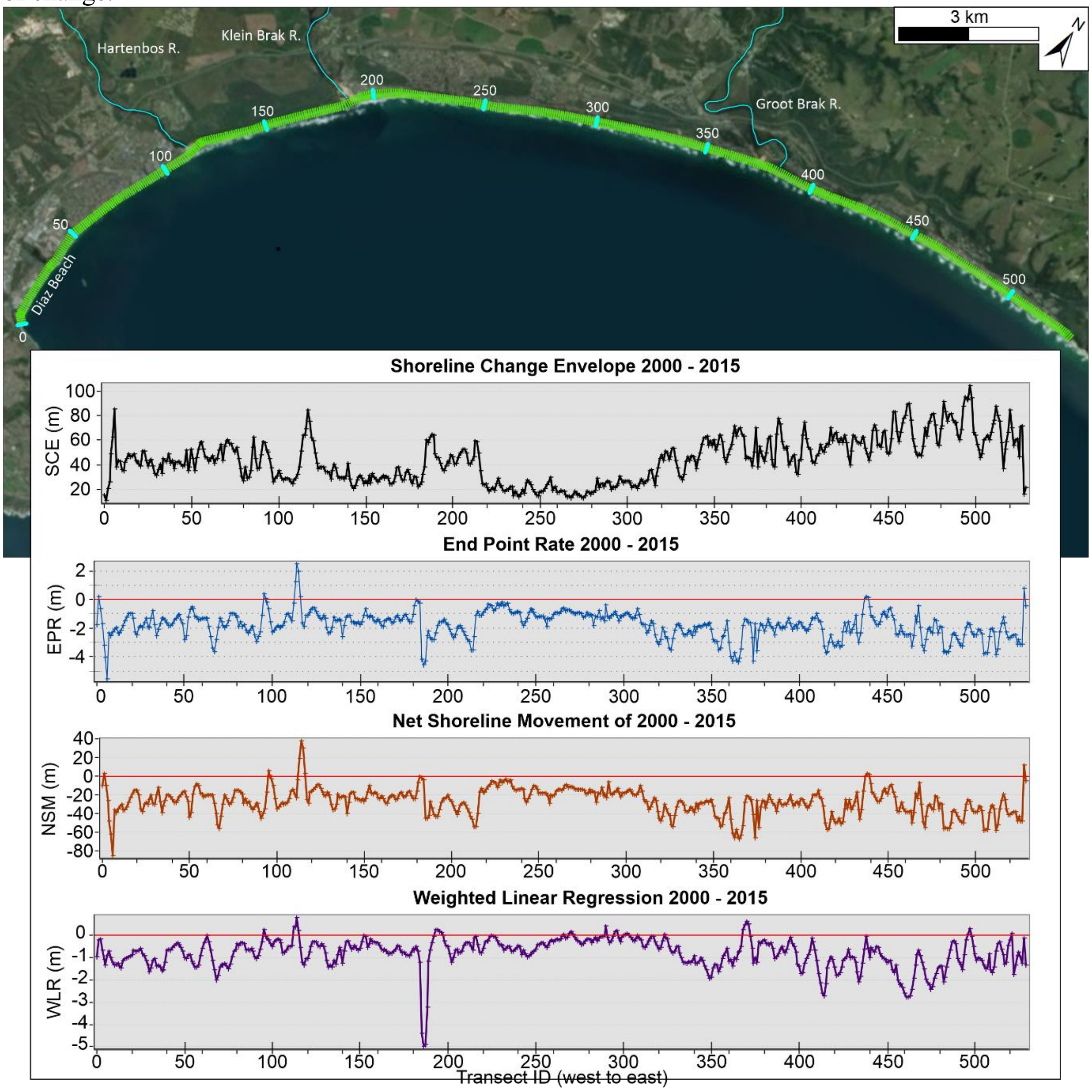

Fig. 4. Long-term shoreline change statistics in Mossel Bay, representing the period from 2000 to 2015.

4.2. Short-term analysis

The short-term shoreline variability along Mossel Bay, as demonstrated by the envelope of change or SCE for the period between January and December 2016 (Fig. 5), is higher in the eastern section of the embayment (transects 360 to 550) with values in excess of 20 m of shoreline change in this 12-month period. Shoreline change is substantially less pronounced in the western to middle parts of Mossel Bay, with no apparent increase in shoreline variability linked to the location of the three river mouths.

According to the results for the EPR, NSM and WLR, an alternating or rhythmic pattern of erosion and accretion is evident in the eastern section of the embayment (eastward of transect 320). Overall, short-term accretion is observed along the central and western sections of Mossel Bay, with a localised hotspot of erosion in proximity to the Groot Brak river mouth. An 8 km stretch of coast that extends from Diaz Beach in the southwest (transect 1 to 20) to the Hartenbos and Klein Brak Rivers towards the northeast (transect 170) is dominated by overall accretion. Because shoreline change rates are computed for yearly periods, the EPR and WLR mirror closely the NSM; overall there is a largely positive (seaward) migration of the shoreline over the short-term. The WLR average along the embayment is 16.3 m/yr, ranging from maximum erosion of -42.29 m/yr and maximum accretion of 82.05 m/yr.

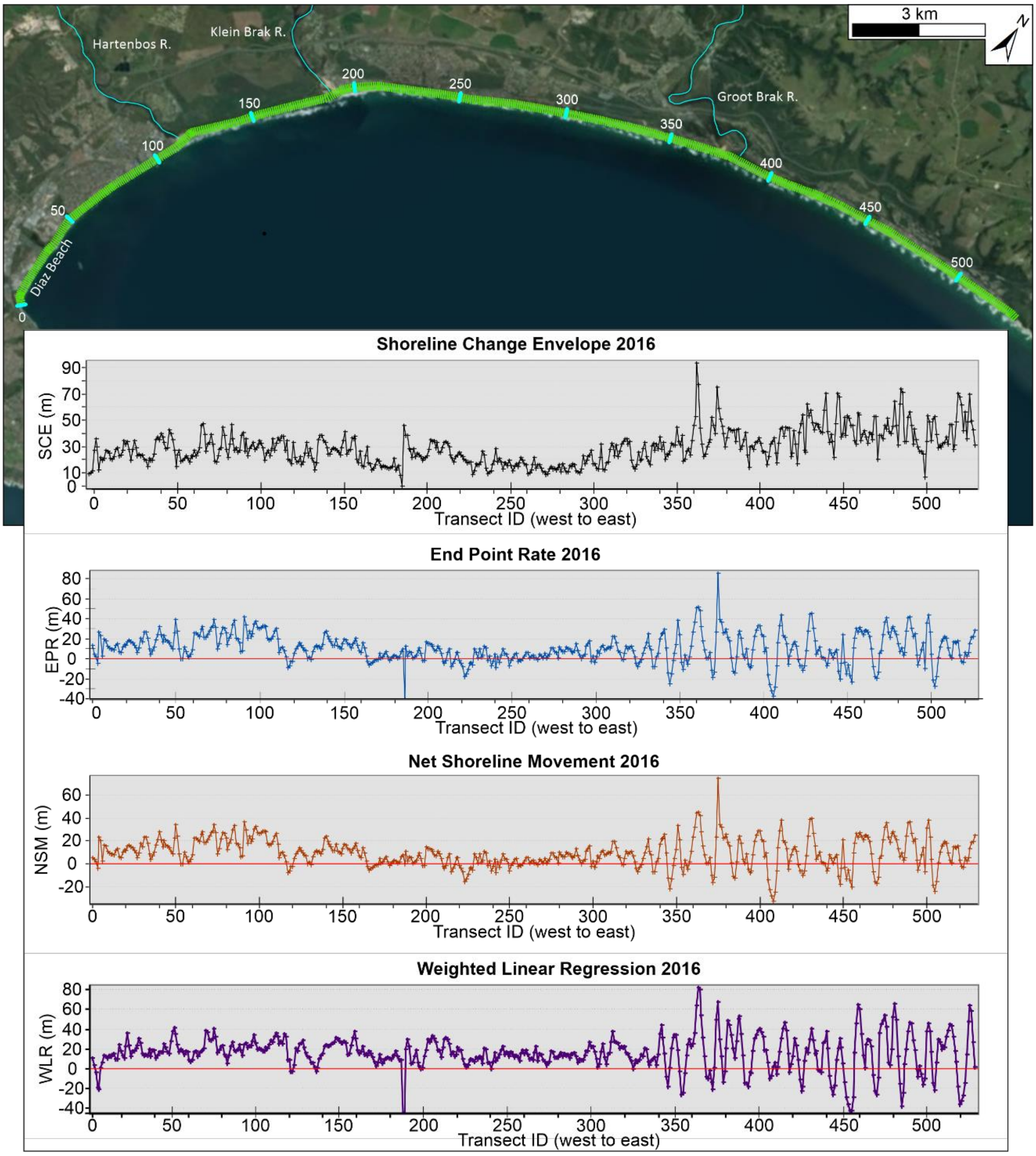

Fig. 5. Short-term shoreline change statistics in Mossel bay, representing the period from January to December 2016.

4.3. Nearshore wave conditions

Alongshore variability in nearshore wave conditions determined from wave modelling shows very similar trends for mean and storm wave conditions, characterized by a gradual increase in wave height towards the eastern section of the embayment (Fig. 6). Modelled mean and storm wave parameters are in close agreement with the data for equivalent conditions obtained from the nearshore wave buoy located in the protected western section of the bay. During both mean and storm conditions, the prominent headland of Cape St. Blaize (Fig. 1) affords a significant degree of protection to the western sector of the embayment, given that both mean and storm waves approach this coastline from a SSW to SW direction. The shadow effect of this headland leads to a significant gradient in wave height along the embayment, with wave heights in the protected western sector approximately 50% lower than in the exposed western sector for both wave conditions. Nearshore wave heights along the 15 m isobath contour reach approximately 2 (3) m for mean (storm) conditions in the more energetic western sector, gradually decreasing along the central section of the embayment, where they reach between 2.5 and 2 meters during storms (Fig. 6).

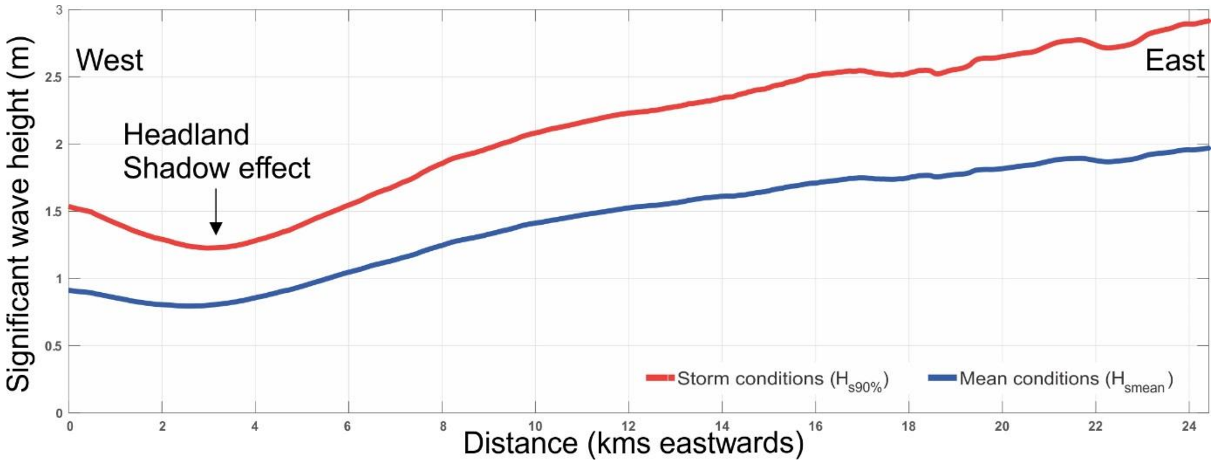

Fig. 6. Alongshore gradient in mean and storm nearshore wave heights for Mossel Bay.

4.4. Grain size

Sediment analysis in 21 locations along the embayment reveals a dominance of medium sand (250 – 500 um) in all but four sites (Fig 7). These four beaches (P10, P12, P13 and P14) are located in the central part of the embayment; three are dominated by coarse sand (500 – 1000 µm) while the fourth (P14) exhibits a higher percentage of very coarse sand (1000 – 2000 µm). Regarding the finer sediment fractions, fine sand (125 – 250 µm) is more prevalent in the western sector of the embayment, with a sharp reduction towards the the central and eastern sectors. Significant but not dominant contributions from very coarse sand (>10%) is noted at five sites; three in the coarse central region and one example in the west and east respectively. Sorting increases substantially from the central to the eastern sector of the embayment, with sediment distribution in most sites between P15 and P21 represented in over 60% by medium sand (250 to 500 µm).

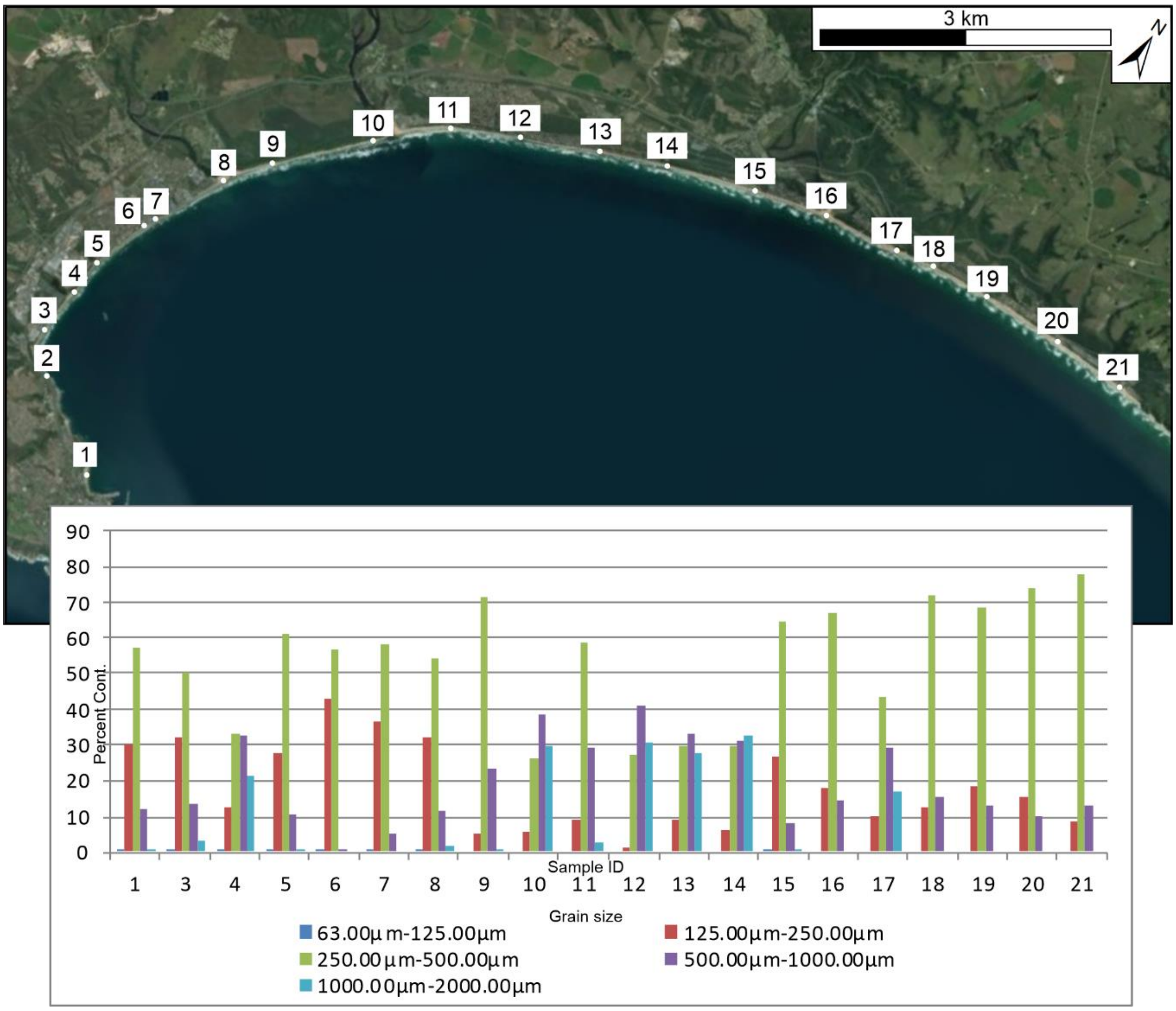

Fig 7. Distribution of grain size classes along Mossel Bay. P2 is a rock outcrop with no beach (devoid of sediment).

4.5. Beach and nearshore rock outcrops

Three well-defined areas of inter to subtidal rocky outcrop are evident along the beach and nearshore areas of Mossel Bay (Fig. 8). The western outcrop (Platform A) is the smallest, roughly half the size of the central platform (Platform B), with the eastern platform (Platform C) covering for a much wider area (Table 3). Platform A extends for approximately 430 m offshore from the shoreline, with a seaward edge characterised by a steep gradient (ca. 1.5°) between ~9.5 m and ~13 m depth. Seaward of the platform edge, the gradient is reduced to 0.3°. Platform B shares most of the same geometrical characteristics of Platform A, apart from a much steeper platform edge (ca. 3.8°). Platform C, in the east, is marginally wider that Platforms A and B, and presents substantial alongshore variability, with a steeper platform gradient in the central section. Seaward of the platform edge, the slope of the nearshore is steeper in this section of the embayment.

The surface of Platform C hosts an elongated coast parallel sandbar covering ca. 0.5 km^2 and extending 5 km across the outcrop (Fig. 8). In the west the bar merges with the nearshore sediment wedge as the outcrop relief diminishes, while to the east the sandbar attaches to the beach; the underling rock crops out 300 m offshore. Platform A is generally restricted to the subtidal area of the nearshore, while Platforms B and C extend to the upper intertidal zone. All three outcrop platforms extend seaward across the upper shoreface. Platform A is associated with distinct sand patches which overlie the consolidated rock surface. Platform B is draped by unconsolidated sands in the east, however, sediment cover thins rapidly in the middle and eastern sections of the outcrop that terminates around the Klein Brak River mouth. Outcrop of Platform C decreases in relief above the adjacent sediment wedge from ca. 8 m in the east, to 4 m off the central platform and finally merging with unconsolidated sands at the western extent.

Table 3: Rocky platform geometry and geomorphological context

ID	Area	Platform edge elevation difference	Platform edge gradient	Shoreline to platform edge	Seaward gradient	Outcrop location
A	0.8 km^2	3.5 m	1.5°	430 m	0.3°	Nearshore/Sub-tidal
B	1.5 km^2	4.5 m	3.8°	430 m	0.3°	Nearshore/Intertidal
C	3.6 km^2	8 m(Eastern) 8 m (Central)	1.9° (Eastern) 2.6° (Central)	500 m (Eastern) 530 m (Central)	0.6°	Nearshore/Intertidal

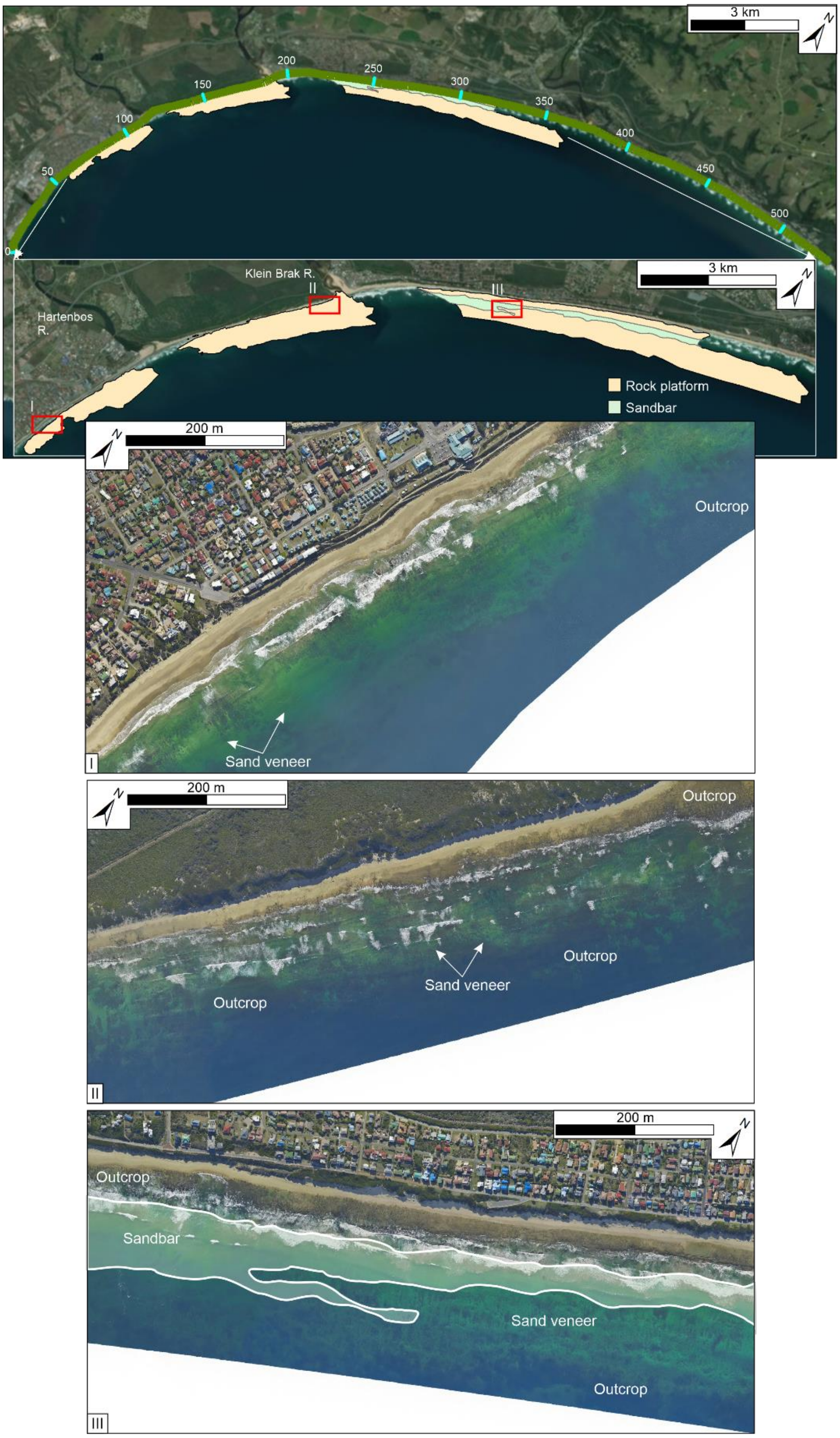

Fig. 8. Prominent beach and nearshore rocky platforms along Mossel Bay. The platforms are typically covered by a thin sand veneer, which becomes a distinctive sandbar in the easternmost platform.

5. Discussion

5.1 *Wave forcing and shoreline change*

The wave conditions in Mossel Bay are forced by south-westerly swells from the Southern Ocean for both mean and storm waves. Under both conditions a defined wave shadow zone develops in response to diffraction and refraction of waves around Cape St. Blaize, leading to a marked alongshore gradient in wave heights along the embayment (Fig. 6). When comparing the long-term shoreline change patterns with wave forcing along Mossel Bay, there isn't a clear association between rates of change for the EPR and NSM metrics and higher wave heights in the more exposed eastern sector. However, this exposed sector does exhibit a consistently higher envelope of change (SCE), indicating that in this sector of Mossel Bay, shoreline variability over the 15 period between 2000 and 2015 is higher, although such increased variability is not reflected in increased shoreline erosion (Fig. 4). When considering short-term shoreline change throughout the year of 2016, the association between higher wave forcing and increased shoreline variability becomes much more pronounced (Fig. 5), with a clear transition from relatively moderate SCE, EPR and NSM in the western and central sectors of the embayment, in contrast with a much wider envelope of change and large variability in shoreline change rates in the eastern sector (transects 330 to 550). These results are not unexpected, and association between shoreline change and hydrodynamic forcing at regional scales is well established (e.g Castelle et al., 2018; Carvalho et al., 2020). However, by exploring in more detail the alongshore changes in wave forcing as a driver of shoreline variability in medium scale coastal embayments, this work highlights the role of spatial variability in hydrodynamic forcing, which can both contrast and complement temporal variability in wave forcing in driving long to short-term shoreline change (Carvalho et al., 2020).

5.2 Geological framework and shoreline change

In addition to spatial and temporal variability in hydrodynamic forcing, spatial variability in coastal geomorphology can also exert a significant influence or indeed control to a large extent the evolution of sedimentary coasts (Cooper et al, 2018). Often termed geological control, the presence of outcropping or subcropping rocky surfaces within sandy shorelines and their influence in beach dynamics has been increasingly recognized (Gallop et al., 2020).

Along Mossel Bay there are extensive intertidal to subtidal rock out/subcrops in the form of beachrock and/or aeolianite, which are comparable to rock-platform or reef perched beaches (Gallop et al., 2011). The location of these platforms relative to mean sea level and within the embayment plays an important role in shoreline change across spatial and temporal scales. The western platform (Platform A) occupies the nearshore to sub-tidal level, seldom exposed on the active beach (intertidal). Platforms B and C, central and eastern respectively, both extend further inshore to occupy the active beach and intertidal zone. Much of Platform C is exposed during low tides as a wave-cut platform. In all three cases it is very likely that the rock platforms extend landward and underlie the unconsolidated active beach. The influence of the rock platforms in the spatial patterns of shoreline change is consistent across temporal scales, although more pronounced for platforms B and C. This is evidenced by reduced long-term variability in shoreline position (based on SCE) and minimal rates of change (according to EPR, WLR), for the section between profiles 130 to 180 for Platform B and transects 220 to 320 for Platform C (Fig. 4). In terms of short-term shoreline variability, the reduction of shoreline variability due to the presence of the rock platform is more noticeable in the reduced rates of shoreline change in the sector fronting platform B and C (transects 170 to 320 – Fig. 5).

While the precise morphodynamic mechanisms by which the rock platforms influence shoreline change are beyond the scope of this study, based on previous investigations into the influence of nearshore reefs on hydrodynamics and sediment transport in sandy beaches (e.g. Cleary et al., 1996; Larson and Kraus, 2000; Vousdoukas et al., 2007; Storlazzi et al., 2010; Velegrakis et al., 2016), it is reasonable to suggest that the three platforms enhance wave attenuation, reducing the energy of waves that reach the coastline contribution to a more stable or shoreline position. Under storm conditions the protective role of shore platforms may be less significant, as nearshore rocky outcrops also contribute to enhance the infragravity wave energy component that reaches the beach (Gallop et al., 2020). A direct association between the rock platforms and shoreline change is further complicated by the fact that platforms in Mossel Bay vary in size, morphology and position within the embayment, but also because their seaward edge is heterogenous and offshore of the platforms a reef complex is found at depths between 20 and 45 m (Cawthra et al., 2018), which interferes and modifies the propagation of nearshore waves, particularly during storm conditions.

The embayment of Mossel Bay is considered sediment starved compared to the adjacent regions owing to a combination of low siliciclastic supply and transport regimes within the regional geological control (headland and embayment framework) (Birch, 1980). Active beach sediments are dominated by quartz and carbonate clasts reflecting the geology of the hinterland catchments and Holocene sediment wedge, and biological productivity of the adjacent Ocean, rich in carbonate-producing organisms, respectively. Active beach sedimentological characteristics complement those of the modern shoreface which are described by coarse grained bioclastic sediment, fine to medium-sand dominated shelf sands, silty mud and mud (Cawthra, 2014), although lacking the finer fraction. There are notable sedimentological variations across the embayment manifest as three zones; western, central and eastern. In the west (sample localities 1 –9), encompassing Platform A, medium and fine sand offer the greatest contribution to active beach grainsizes with less contribution, if any, from coarse and very coarse clasts (Fig. 7). Some regions (i.e., between sites 1 and 2) are, however, largely devoid of sediment with bioclastic debris (shell hash to entire shells) covering the intertidal and supratidal outcrop. The central sector (10 –14), including Platforms B and C, is associated with greater contributions of coarse sediment compared to the western zone. The eastern zone (15 –21), devoid of intertidal outcrop, is dominated by medium sand with little coarse material and only one site (17) recording very coarse clasts. Platform C position relative to the beach changes spatially (Fig. 8), with no significant outcrop extending towards the active beach from 17 through 21, which suggests that coarser sediment is not being actively sourced from the platform to the beach as in the eastern and central sectors. The change in grainsize composition along Mossel Bay is therefore interpreted as driven by both rock platform characteristics and hydrodynamic forcing, with variable contribution of the platforms as source of coarse beach sediment and transport pathways that reflect the influence of platform position in relation to the beach. Samples were collected during calm sea conditions thus represent such conditions. Localised pebble and shell lags are common, though not resolved at 1 km sample spacing hence they are not included in this regional account. As the adjacent contemporary shoreface comprises coarse grained bioclastic sediment, fine to medium-sand, it is unlikely that the beach composition would change significantly during storm events. There may, however, be local winnowing of the finer fraction creating temporarily course beaches and pebble lags. Post-storm periods would allow re-introduction of the finer fraction to the system once more.

5.3 Integrated model of shoreline change

Long-term shoreline change metrics indicate that the embayment of Mossel Bay is undergoing net erosion, with WRL providing a more reliable indication compared to EPR, as the latter does not consider uncertainty (Thieler et al., 2009). While the mean relative positional error is 15.99 m, for most images it is smaller than the image resolution (20 m for Landsat and 10 m for Sentinel - Table 1). This suggests subpixel geometric mismatch between images, which is often identified in multiscale satellite data analysis (Wu et al., 2021). Error of this magnitude naturally reduce the accuracy of the shoreline change analysis, however, when considered in the context of large shoreline change envelopes and, particularly, the incorporation of uncertainty in the determination of shoreline change rates using weighted linear regression, their impact on the accuracy of the shoreline change analysis becomes less significant. Based on these metrics, shoreline erosion observed in Mossel Bay is relatively minor, averaging -0.8 m per year (based on the 2000 – 2015 WLR), compared to the average retreat of the African East coast which approximates -1.4 m per year (Mentaschi et al., 2018), but closer to the values computed automatically for Mossel Bay during the period from 1986 to 2016 by Luijendijk et al. (2018). Over the short-term timescale and considering a single year (2016), our results indicate that average accretion of 16.3 m based on the WLR. In both long and short-term analysis there is district compartmentalisation of shoreline responses described by three sub-cells; Western, Central and Eastern (Fig. 9). Transect ca. 325 to 533 describes an eastern section within the embayment (ca. 9.7 km). This eastern sub-cell manifests significant variation in the envelope and rates of change. Thus, shoreline position is very dynamic on an annual to seasonal scale. The western extent of this dynamic sub-cell coincides with the eastern limit of the intertidal to subtidal rock platform. The of absence of this intertidal rock platform continues to the limit of the embayment at the eastern sea cliffs. Westward of transect 125, through to transect 1, we identify a western sub-cell. This sub-cell evidences shoreline change rates that are lower than the eastern sub-cell, but higher than the central sub-cell that lies in between. Medium sand dominates the beach in the eastern and western sub-cells, while the central sub-cell is characterized by coarser and poorly sorted sediment.

The eastern sub-cell is associated with high variability in shoreline position over the long and short-term with changes of up to 100 m between shoreline position. This cell experiences the greatest significant wave heights across normal and storm conditions, and a normal wave approach. The irregular to rhythmic variation in shoreline position, particularly in the short-term analysis, suggests that shoreline change in this sector may be associated to the development and migration of megacusps, creating alternating hotspots or erosion and accretion (Thornton et al., 2007).

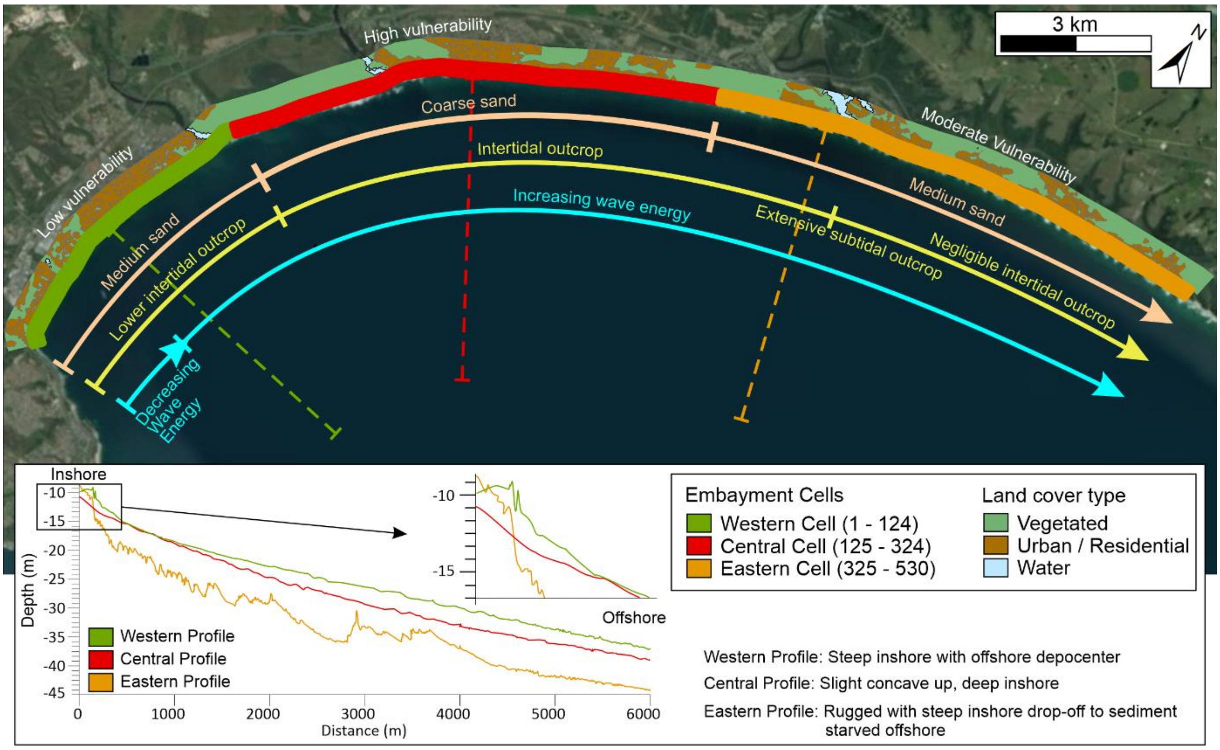

Fig 9: Conceptual model of shoreline change in Mossel Bay based on three distinct sub-cells. Coast-perpendicular profiles highlight variations in shoreface and offshore geometry.

The three sub-cells demonstrate varied coastal response to hydrodynamic forcing along the embayment, however, wave forcing is not the single control. Despite the increase of wave energy from the western to eastern across the embayment, the shoreline response is not linear. Rather, the presence or absence of rock outcrops plays a key role in modulating shoreline change. In particular, intertidal rock platforms are integral to shoreline dynamics over time, influencing the dynamics and the sediment that is found along the embayment. Coast-perpendicular bathymetry profiles show variation in geometry that may result from interactions between cells (Fig. 9). The eastern profile is rugged, relatively sediment starved and subject to increased wave exposure, hence dominated by outcrop (cf. Cawthra et al., 2015) and deeper offshore than the central and western areas The eastern shoreface is narrower and steeper (Fig.

9), shoaling rapidly towards the shoreline. Resembling the equilibrium surface of Anthony and Aagaard (2020), the central profile is concave upward, steepening across the upper shoreface. The upper shoreface of the western profile shoals more rapidly than that of the central cell, and appears to accumulate sediment across the lower shoreface to offshore acting as a depocentre within the western embayment. This western cell is subject to lower wave energy and presents lower vulnerability than the cells to the east. This likely accounts for the preferential accumulation of sediment in this region, although the mechanisms remain unknown. It is plausible that either sediment is winnowed from the central and eastern cells bypassing the eastern headland and leaving the western cell shoaler. Alternatively, sediment eroded and transported from the eastern and central regions is deposited within the sheltered western embayment, under specific conditions at least, thus increasing sediment thickness relative to the central and eastern cells.

If we consider the potential impacts of shoreline change along Mossel Bay in relation to the development of the coastal zone, as determined by the residential areas and urban infrastructure, while the western sub-cell is highly developed it experiences minor shoreline change and is exposed to less energetic forcing, making it the least vulnerable sub-cell to potential damages associated with shoreline change. The eastern sub-cell exhibits marked shoreline variability and significant coastal development, but buildings and infrastructure are located landward to the frontal dune system, making this a zone of moderate vulnerability. Compared to the eastern and western sub-cells, the beach in the central sub-cell is narrower and the frontal dune steeper, with significant coastal infrastructure (e.g. roads and parking) and buildings located on top of the frontal dune (Fig. 8). This implies that even relatively small changes in shoreline position can have potentially severe impacts, suggesting that this region may present higher coastal vulnerability than the remaining sectors of Mossel Bay. Thus, development within this zone is not recommended owing to the likelihood of infrastructural damage.

While entirely rocky coasts are typically more stable and resistant to change at annual to decadal timescales, coastal areas comprising a mix of rocky and sedimentary coastal landforms are substantially more complex, with implications for shoreline change and coastal vulnerability. In the last decade infrastructure placed along sections of the central sub-cell has been damaged extensively as a result of seasonal shoreline migration. These changes in shoreline position, although the lowest within the entire embayment, interact more closely with existing infrastructure increasing dune instability and erosion, enhancing coastal risk. This association has implications for characterizing coastal hazards and delineating high risk zones other coastal areas, as shoreline change patterns alone provide an incomplete view of coastal dynamics. Thus, regional coastal setback lines developed without a holistic approach may not adequately account for hazards associated with local scale variation in embayment characteristics. Hence, enhanced local knowledge generation must outpace the development of this dynamic zone to enable sound coastal zone management (Stive et al., 2002). Ideally, long-term trends are best described by analysis of long-term shoreline position records. Such records would encapsulate dramatic short-term, as well as persistent long-term changes along unconsolidated shorelines enabling analysis at the highest possible spatio-temporal resolution (Castelle et al., 2021).There is much debate over the fate of sandy shorelines (cf. Vousdoukas et al., 2020 and Cooper et al., 2020), this contribution highlights the need for local-scale studies to meaningfully describe local changes, risks and hazards in response to local conditions (cf. Guisado-Pintado and Jackson, 2019). While global or continental-scale contributions provide a low-resolution high-level overview of coastal issues (Vousdoukas et al., 2022), local-scale, high resolution studies are paramount to informing coastal management and policy makers.

6. Conclusion

Digital shoreline analysis has been employed to describe shoreline trends over a period of 15 years. Over the study period, the Mossel Bay embayment is relatively stable, with no significant signs of extensive accretion or erosion. The long-term end point rate does, however, suggest that there is minor shoreline erosion (average of -1.75 m/yr) along the embayment as a whole for the period between 2000 and 2015. The short-term analysis suggests that the shoreline position is susceptible to rapid migration on a seasonal scale, particularly in response to episodic changes driven by megacusp migration. Erosion and accretion hotspots are related to areas proximal to river mouths, megacusps, and areas where the highly dynamic shoreline behaviour is constrained by rocky platforms and unable to freely adjust to variation in forcing.

Alongshore variation in wave forcing is an important driver of coastal processes along Mossel Bay, however, shoreline change is not directly related to the wave conditions along the embayment. Rather, based on the integration of wave forcing, shoreline change, sediment characteristics and presence of intertidal and subtidal rock platforms, we propose that Mossel Bay is divided into three sub-cells in terms of coastal processes and coastal vulnerability (Western: Dias Beach to the eastern bank of the Hartenbos River, Central: eastern bank of the Hartenbos River to Tergniet, Eastern: Tergniet to Glentana). The shoreline in the eastern and western cells is more variable than the central cell with regards to envelopes and rates of change. Hazards to coastal development and infrastructure are associated with the location of such infrastructure rather than the specific patterns of extensive shoreline change. Small changes in shoreline positon within an energetic embayment have resulted in loss of infrastructure, but little loss of sandy beach area in the long-term. Hence, future development along comparable energetic sandy coasts must be critically analysed from a local coastal geomorphological perspective that considers seasonal, episodic and short-term variation within the geospatial context of the site, and on management timelines.

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