Modelling shoreline dynamics and management of Adelaide's beaches at seasonal to decadal timescales

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SUMMARY

Sandy beaches around the world are under pressure from increased urban development and challenges posed by a changing climate. A common result of these pressures is coastal erosion which can pose a hazard to coastal communities and jeopardise the values of the coastal environment. These values vary significantly, ranging from ecological functions to social benefits such as recreation, and economic contributions like tourism. Considering this high value of beaches, it is essential that coastal practitioners develop coastal adaptation strategies founded on a thorough understanding of coastline dynamics and their drivers. Coastal practitioners typically use a number of strategies to understand the dynamics of coastlines including, measured data, observations and physical modelling. These strategies often provide a direct indication of the state of coastlines, however in many cases lack the ability to provide insight into the complexities and drivers of change which explain why a coastline is in its current state and importantly, how it may change in the future. To provide these critical insights, numerical models can be used to understand aspects of coastlines which are not superficially clear. This thesis will delve into this topic and explore how numerical models can be used to inform coastal management.

Similarly to other developed coastlines around the world, Adelaide's managed beaches require coastal management to mitigate risks posed by coastal erosion. In this thesis it is found that this is caused particularly by the net northerly longshore transport in the absence of sufficient southerly sand supply, which was analysed using a combination of coastline position data and numerical models to compute sediment transports. A coastal management strategy has been evaluated and detailed for Adelaide's managed beaches comprised of seawalls, training walls, offshore breakwaters, beach nourishment from sand recycling within the system and beach nourishment from sand outside the system. This study's original contribution to knowledge lies in the development of techniques utilising numerical models to better understand the efficacy and long term viability of coastal management strategies and exploring the sensitivities of Adelaide's beaches to environmental drivers of change in the wider region.

The thesis consists of four main chapters which contribute to the understanding of long term shoreline change on Adelaide’s managed beaches, all of which involve a new model application. The first part of this study investigates the wave climate of Gulf St Vincent in which Adelaide’s managed beaches are situated. A 40-year modelled wave hindcast developed using ‘Delft3D-WAVE’ is used to investigate the climatic drivers of the bimodal wave climate within Gulf St Vincent. Fluctuations of the Southern Annular Mode (SAM), ENSO and the Indian Ocean Dipole were all found to correlate with anomalies in the bimodal wave climate with nuanced seasonal interactions.

The second part of the study investigates the efficacy of shoreline management techniques on Adelaide’s Managed Beaches using a one-line shoreline model driven by the wave climate developed in part one of the study. The 32-year hindcast model developed using the ‘ShorelineS’ one-line shore model is a novel application of the software, building upon its capabilities to model a long but narrow beach with a varying active profile height and array of shoreline management techniques. The analysis highlights the importance of the beach nourishment regime on Adelaide’s Managed Beaches, where due to a significant sediment transport gradient and the influence of impeding structures the recreational beach width is under significant risk of erosion.

The third part of the study links the climate drivers investigated in part one to the longshore transport rates derived from part two. The analysis found that there is a significant relationship between longshore transport on Adelaide’s Managed Beaches and the Southern Annular Mode (SAM). This relationship is nuanced with directional and seasonal dependencies, however the conclusion is that less erosion of Adelaide’s beaches occurs during positive SAM phases. In this case the relationship between the Southern Annular Mode and longshore transport can assist coastal managers in understanding the seasonal fluctuations which are a primary driver for beach nourishment requirements. Moreover, the projected changes to the Southern Annual Mode with climate change can be related to management requirements on the shoreline.

The fourth part of the study investigates the future viability of beach nourishment as a coastal management strategy for Adelaide’s managed beaches. Through the development of an automatic nourishment capability, ‘ShorelineS’ is used to simulate future nourishment requirements to test the sensitivities of sea level rise, wave height and wave direction. The study found that annual anomalies in wave height (±20%) and direction (±10) degrees can cause significant (>80%) impacts to the required beach nourishment to maintain recreational beach widths. This year-to-year variance is expected to play a significant role in beach nourishment, compounded by sea level rise, where nourishment requirements will increase by ~50% over a 10-year period if not offset by external sand sources.

DECLARATION

I certify that this thesis:

1. does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university

2. and the research within will not be submitted for any other future degree or diploma without the permission of Flinders University; and

3. to the best of my knowledge and belief, does not contain any material previously published or written by another person except where due reference is made in the text.

Signed:

Date: 29/08/2024

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Undertaking a PhD is a significant personal journey, however it wouldn’t be possible without the support, guidance and motivation from a range of people.

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To my supervisors Graziela, Patrick, Bas and Dano, I can’t thank you enough for the support and mentorship you have provided throughout my study. Graziela and Patrick, you welcomed me with open arms into the Flinders community, always encouraged me to take on opportunities and opened doors that would have otherwise remained closed. Bas and Dano, your generosity to offer your time and unparalleled expertise to my project has lifted my study beyond what I thought possible.

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I’d also like to thank the folks at Hatch and Tonkin + Taylor who have supported my development, provided exceptional mentorship and given me opportunities to grow my coastal engineering skillset in the consulting environment while completing my studies.

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COAUTHORSHIP

This thesis includes 4 chapters in manuscript format. All manuscripts were developed with the intention of publication and at the time of submission, 2 have been accepted (Perry et al., 2024a, Perry et al., 2024b), 1 is under revision with a journal (Perry et al., Under Review) and 1 is yet to be submitted (awaiting acceptance of 2 manuscripts under revision).

Though coauthors of these manuscripts contributed to the conceptual research design and editing of manuscripts, I am the lead of all research outputs with decisions regarding these manuscripts ultimately being my own. This includes independently performing all analysis, creating all figures, developing the first draft of each manuscript and leading the review process.

I am grateful for these contributions from supervisors, co-authors and journal reviewers of these manuscripts which have greatly improved the quality of the research in this thesis.

CHAPTER 1.

1.1 Context

This thesis explores and develops novel numerical modelling techniques to help understand shoreline dynamics and the efficacy of coastal management strategies. It also provides the first detailed examination of the Adelaide coast (see Figure 1-1 for location) and inner Gulf St Vincent wave climate. The study includes innovative analysis of the climate modes affecting the regional wave climate and longshore sediment transport, and a novel exploration into the efficacy of Adelaide beach management and investigation into the future requirements of beach nourishment to maintain recreational beach widths.

Understanding the medium to long term change (defined in this study as seasonal to decadal change) of sandy beaches is a complex yet necessary exercise for coastal managers around the world. These changes have been studied at a variety of spatial scales, from global analysis to analysis of individual cross shore profiles. Global studies which have analysed satellite derived shoreline positions suggest that sandy beaches around the world are facing threats from coastal erosion driven by sea level rise (Luijendijk et al., 2018, Mentaschi et al., 2018). These studies offer high level insight into the fragility of sandy beaches, however it is also accepted that the dynamics of sandy beaches are complex with nuanced responses to sea level rise (Cooper et al., 2020). In addition to environmental complexities, the added impact on anthropogenic interventions on the coast leads to challenges in understanding long term shoreline change (McCarroll et al., 2021). Numerical models set out to capture these influences with varying success, often dependent on the complexity and understanding of physical process, computational ability and availability of appropriate measured data to calibrate and validate the model results. Given the wide variability that exists in sandy beaches around the world, it is important to continue to apply models in a variety of locations, not only to better understand sandy beaches in different environmental settings, but also to build upon the capability of numerical models. This thesis contributes to this by applying both a wave model and shoreline change model for Adelaide’s managed beaches.

Figure 1-1 Location of Adelaide's managed beaches - (A) continental scale, (B) regional scale and (C) local scale with focus on the Adelaide Managed Beaches.

1.1.1 Drivers of coastline change

Understanding the basic drivers of morphodynamic change is a critical first step for studies of geomorphological processes (McLachlan et al., 2018, Hardisty, 1990). McLachlan and Defeo (2017) suggest the defining physical elements of a sandy beach are sand, waves and tides with unique combinations of these factors appearing around the world. These factors are interrelated with varying impact on a beach's morphology. From a morphodynamics standpoint, the most important sand characteristic is its particle size, which along with its density, define the critical bed shear stress by which sediment entrainment occurs (Amoudry and Souza, 2011). For submerged sediment, this entrainment occurs when the bed shear stress imposed by water movement exceeds the critical bed shear stress (NiÑo et al., 2003). The drivers of this water movement are largely waves and currents, influenced by tides, wind, waves, density variations or river outflows (Soulsby et al., 1993, Kamphuis, 2020, Komar, 1977, Nielsen, 2009). Variations of these drivers result in a diverse array of sandy beaches around the world, broadly classified as dissipative, intermediate and reflective, with further classification of intermediate beach types as longshore bar-trough, rhythmic bar and beach, transverse bar and rip, and ridge-runnel or low tide terrace Wright and Short (1984). This beach state model was developed further by Masselink and Short (1993), where tidal range combined with breaker wave height is used to inform which beach type prevails at any given location. The beach type of the study site in this thesis is an intermediate low tide terrace as described by Short (2020). This beach type, combined with the predominant south-westerly wave direction causes a northerly movement of sand which is discussed in detail later in this thesis.

1.1.2 Wave climate modelling

As noted above, it is important to understand the local wave climate which is a primary driver of morphological change on sandy beaches (Lu et al., 2015). This understanding can be developed through a range of techniques including observation, physical modelling, analytical solutions and numerical modelling. Due to the rapid improvement of powerful computers and the development of a range of numerical modelling techniques, wave climate modelling has become a reliable, cost effective and time saving tool (Thomas and Dwarakish, 2015). Ocean wave prediction models stem from the work by Gelci et al. (1957) who found that the energy balance equation for the two-dimensional wave spectrum could be used to give the basic evolution of ocean waves. The energy balance describes the evolution of the two-dimensional wave spectra as a sum of three categorised physical processes given in equation 1-1-1.

$$S = S_{in} + S_{nl} + S_{ds} = \frac{dS(f, x, t, \theta)}{dT} \qquad 1\text{-}1$$

Where the two-dimensional wave spectrum *S* is defined as frequency *f*, propagation in direction θ, defined over geographic coordinates *x* and time *t*. This spectrum can be used to define the net source function *S* as a sum of wind input waves S_{in}, the energy conservation mechanism of nonlinear wave interactions S_{ln} and the wave energy lost due to dissipation S_{ds} (SWAMP, 1985).

Numerical wave models can be broadly categorised as first, second or third generation (Thomas and Dwarakish, 2015). First generation models are predominantly based upon wind which is represented by the term S_{nl} in equation 1-1-1without the consideration of nonlinear interactions of energy within the spectrum (Janssen et al., 2000). These early models require an almost order of magnitude increase in wind forcing above theoretical estimates in order to achieve realistic wave generation (Janssen, 2008). This correction is required to account for the nonlinear interactions that were later identified by Hasselmann et al. (1973) through field observations of wave growth under distinct fetch-limited wind conditions. Second generation models use varying wind fields with the introduction of nonlinear interactions, however, due to lack of computing power their representation remains limited to simplified spectral shapes to infer physical effects. Modern, third generation models parametrise physical processes without being bound to preconceived spectral shapes to determine nonlinear interactions. Examples of widely used third generation wave models are WAVEWATCH III (WAVE-height, WATer depth, and Current Hindcasting), WAM model (from the WAve Model Development and Implementation group), DHI MIKE 21/3 (Danish Hydraulic Institute, Modelling Integrated Knowledge for Environmental Studies) and SWAN (Simulating WAves Nearshore) (Booij et al., 1996, WAMDI Group, 1988, Warren and Bach, 1992, Tolman, 2009).

1.1.3 Shoreline modelling

Modelling morphological change on a coastline requires careful consideration of the time scales and processes of interest (Hunt et al., 2023). Generally, the time scale and inclusion of processes is a trade off, governed by the computational power available (Roelvink and Reniers, 2011). Though computing power continues to improve at a rapid rate, in order to model time scales of seasons to decades there needs to be a reduction of complexity in the model. Models used for this purpose are often referred to as ‘reduced complexity’ models and a common type of these models are ‘one-line models’ where shoreline change is modelled by a single line with a fixed coastal profile (Kristensen et al., 2011). Pelnard-Considère (1956) proposed a simple relationship (equation 1-2) using the sediment continuity equation which predicts the shoreline position relative to an alongshore axis.

$$\frac{dy_{shore}}{dt} = \frac{-1}{1-n}\frac{1}{h_{act}}\frac{dQ}{dx} \qquad \text{1-2}$$

Where y_{shore} is the shoreline position perpendicular to the coastline (m), x is the distance along the coastline (m), n is the porosity, Q is the transport volume (m³/s) and h_{act} is the active profile height (m). Numerous transport formulations have been used in one-line models to calculate the Q term in the equation above, including the Coastal Engineering Research Center (1984) CERC formula (equation 1-3).

$$Q = K\left(\frac{\rho\sqrt{g}}{16\gamma^{0.5}(\rho_s-\rho)(1-n)}\right)H_b^{5/2}sin2\theta_b \qquad \text{1-3}$$

Where, *Q* is bulk transport volume (m³/s), *K* is an empirical coefficient, $H_b$is the breaking wave height (m), γ is breaker coefficient, ρ_s is sand density (kg/m³), ρ is water density (kg/m³) and θ_b is the wave crest angle at break point.

A second commonly adopted transport formula (equation 1-4) was proposed by Kamphuis (1991).

$$Q = 2.33H_b^2T^{1.5}m_b^{0.75}D_{50}^{-0.25}sin^{0.6}(2\theta_b) \qquad \text{1-4}$$

Where, *Q* is bulk transport volume (m³/s), $H_b$is the breaking wave height (m), T is peak wave period (s), m_b is the mean bed slope, D_{50} is the median grain size (m) and θ_b is the wave crest angle at break point. Williams et al. (2015) suggests that the two most significant limitations of a morphological model’s ability to reproduce real-world behaviour are ‘*the dominance of short-term observations which fail to capture the full character of morphological evolution and cannot quantify fully the primary phenomena and mechanisms of change*’ and ‘*incomplete understanding of processes at all relevant scales’* (p. 1). Despite this simplification of processes such as rip currents and acute response to storms which can act in the cross-shore direction (Masselink et al., 2016), it is assumed that there is an average planform morphology of the coast that can be described by a single shoreline contour (Hurst et al., 2015). One line models were first numerically presented by

Price et al. (1972) with developments made throughout the 1970's and 1980's until the widely used model GENESIS was developed in 1989 (Hanson, 1989). This model provided a more generalised shoreline change model for coastal engineering applications to assess changes to sandy beaches in a long-term perspective from several months to several years. Since the development of GENESIS, several other one-line models have been developed including ONELINE (Dabees and Kamphuis, 1999), UNIBEST (Deltares, 2011), LITPACK (DHI, 2005), SMC (González et al., 2007) and GENCADE (Frey et al., 2012). Despite the reliance on similar fundamentals, Townsend et al. (2014) found in an assessment of GENCADE, UNIBEST and LITPACK that significantly different results were achieved between the software packages for the same problems. A common limitation in all these models is their transport curve as a function of the wave angle remained a sine curve constrained to a maximum incidence angle of approximately 45º (Roelvink et al., 2020).

More recently Roelvink et al. (2020) presented a new one-line model (ShorelineS) which uses a flexible, vector based approach that allows for unconstrained modelling of complex coastal features. This vector base approach was first presented by Kaergaard and Fredsoe (2013) who used a complex 2D coastal area model with an unstructured mesh to study a shoreline with a drastic 90 º change in orientation. Hurst et al. (2015) simplified the approach of Kaergaard and Fredsoe (2013), however both models implicitly assumed sediment rich environments. Payo et al. (2017) explored the use of a vector-based model with a variety of landform specific models in which the changes in coastal morphology are represented by dynamically linked raster geometrical objects. Unlike previous vector based one-line models, ShorelineS models the mean sea level contour as opposed to the contour on top of the active profile. This minimises the sensitivity to the required correction of the volume balance equation for strongly curved coastlines.

The governing equation for updating the coastline position used in ShorelineS (equation 1-5) is modification of the conservation of sediment equation given in equation 1-2.

$$\frac{dx}{dt} = -\frac{1}{D_c}\frac{dQ_s}{ds} - \frac{RSLR}{tan\beta} + \frac{1}{D_c}\sum q_i \tag{1-5}$$

Where x is the cross-shore coordinate, s the longshore coordinate, t is time, D_c is active profile height, Q_s is the longshore transport rate, $tan\beta$ is the average profile slope between dune or barrier crest and depth of closure, RSLR is the relative sea level rise and q_i is the source/sink term used to incorporate cross-shore transport, overwashing, nourishment, sand mining and exchanges with tidal inlets (Roelvink et al., 2020). The user is able to select the USACE (Coastal Engineering Research Center, 1984) or Kamphuis (Kamphuis, 1991) formulation for longshore transport.

Typically, one-line models have struggled to replicate the formation of spits due to high wave angle instability (Ashton et al., 2001). ShorelineS uses an ‘upwind’ treatment to represent this process in the model. When local wave angle exceeds the critical angle on one side but is less than the critical angle on the updrift side, the transport at the downdrift point is set to maximum (Roelvink et al., 2020).

The numerical implementation of the model has been discussed in detail by Roelvink et al. (2020) and Elghandour et al. (2020), Roelvink et al. (2020). The model is currently open-source and implemented in Matlab. The user inputs the initial coastline coordinates and structure locations as a column vector, transport rate boundary conditions, wave climate as a time series or characterised conditions and any additional sediment sources or sinks (i.e. nourishment or mining) with associated location. The model groups these inputs into a cell array and begins a shoreline change calculation. At each timestep, for each coastal section, a local wave transformation is calculated to find the wave angle followed by a calculation of wave shadowing based upon shoreline and structure position. The transport rate is then calculated and where applicable the high angle instability is resolved using the upwind approach to calculate coastline change. The new coastline position is then defined, and coastline sections are split or merged where appropriate. A schematic showing shoreline evolution using ShorelineS is presented in Figure 1-2.

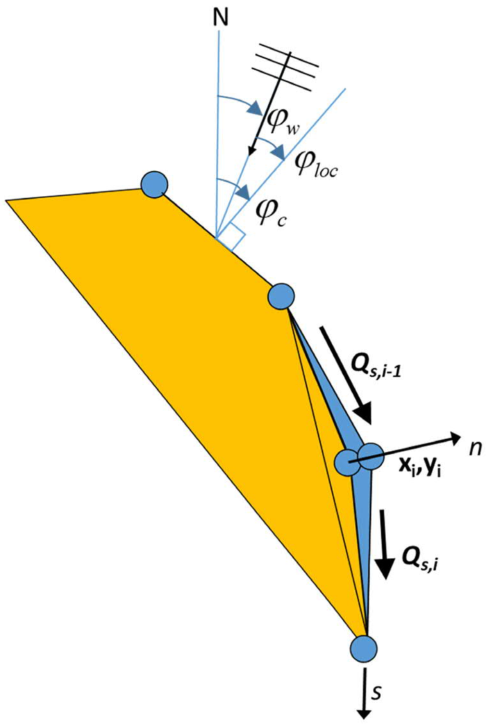

Figure 1-2 Coastline-following coordinate system and definition of wave and coast angles. ϕc is the orientation of the shore normal with respect to North; ϕw is the angle of incidence of the waves with respect to North and ϕloc the local angle between waves and coast, defined as ϕc − ϕw. Image sourced from Roelvink et al. (2020)

1.1.4 Adelaide's coastal management

This thesis applies numerical models to understand the medium to long term dynamics on Adelaide's managed beaches (see Figure 1-1) which have been defined as the 28 km stretch of beach between Kingston Park and Outer Harbour (Department of Environment and Water, 2021a). The majority of sand within the system originates from the shelf and deposited along the shoreline approximately 7000 years ago when the sea rose to its present levels (Tucker et al., 2005, Lewis et al., 2013). A dominant south-westerly wave direction causes sand to move in a net northerly direction (Harvey and Caton, 2012). Prior to urban development, the northern beaches on the LeFevre Peninsula featured dunes of up to 12m high and 500 meters wide (Bowman and Harvey, 1986). Sometime after sea level roughly stabilised at the present level, sediment supply from the shelf ceased and a net northerly longshore drift transported sediments from the south to the north. Since the urban development of the coastline and the construction of numerous coastal structures, supply of sediment from southerly sand dunes has been starved and the natural northerly littoral drift of sand around the LeFevre Peninsula which acted as a sediment sink was disrupted (Harvey, 2006). This has resulted in the deployment of the current sand nourishment regime that moves sand trapped by structures in areas of accretion back to areas of erosion (Department of Environment and Water, 2021a).

Coastal works have occurred along Adelaide’s managed beaches since 1837 when the stone pier at Brighton was constructed (Wynne et al., 1984). Between this time and 1945, the coast was managed in a largely ad-hoc manner without systemic considerations, resulting in a variety of coastal defences which interrupted the natural coastal processes. Post-World War II, the coast was managed by a newly established Seaside Councils Committee which saw to a more systematic approach, however the method largely involved the construction of hard engineering structures (Wynne et al., 1984). Following significant storms in the 1960’s, the coastal system was first studied and described by Culver (1970) in the report now termed the ‘Culver Report’. The Culver Report recommended beach replenishment as a management strategy, however the vulnerability of valuable coastal property led to the installation of rip-rap rock walls along a significant portion of the coastline. Since this initial study, Adelaide’s coastal studies have primarily been facilitated by the Coastal Protection Board which was established in 1972.

Wynne et al. (1984) conducted a review of coastal protection strategies which encompassed the findings of various studies on beach morphology and waves (Culver and Walker, 1983c, Culver and Walker, 1983b, Culver and Walker, 1983a). The review concluded that sand nourishment remained an effective coastal management tool to control coastal erosion hazard, but acknowledged the reluctance from coastal residents and made a recommendation to investigate offshore sand supplies. Following this review, a series of beach replenishment alternatives were investigated and summarised by the Coastal Management Branch (1992). Options to maintain existing practice, abandon replenishment and construct seawalls when necessary, perform major replenishment by dredge, perform major replenishment using a pipeline from North Haven, or a progressive construction of groynes were considered. It was concluded that an updated replenishment strategy with the addition of dredging at Port Stanvac was the most effective solution. This management strategy was formally reviewed by the Coastal Protection Board in 1997. This review found that sand nourishment remained the appropriate strategy, however urgent studies into the effect of nourishment on seagrass populations and investigations into alternative dredging locations to Port Stanvac were recommended.

The most recent coastal management review and strategy document presented by Tucker et al. (2005) outlines the details of a coastal management strategy for 2005-2025. This study includes discussion on geological setting, sand characteristics, wave climate, sediment transport, human interactions with the coast, history of coastal management and proposed coastal management. The plan outlines five main components that remain the current strategy utilised by the Coastal Protection Board:

- Continue beach replenishment by placing approximately 160,000 m^3 at strategic locations along the coastline
- Recycle sand more efficiently using sand slurry pumping and pipelines
- Add coarse sand from external sources
- Build coastal structures in critical locations
- Integrate sand bypassing at harbours with beach management

Since this review there have been numerous studies performed on Adelaide’s managed beaches as well as the implementation of the proposed recycling of sand using pumped slurry pipelines and sand sources from outside the system (Huiban et al., 2019, Deans et al., 2011, Townsend and Guy, 2017, Townsend, 2009, Townsend, 2005, Tucker, 2007, Tucker et al., 2013).

Recent studies have focused on the hydrodynamics of the gulf and long term morphological studies of West Beach and Henley Beach. Van Gils et al. (2017) developed the Adelaide Receiving Environment Model (AREM) which modelled the hydrodynamics of the gulf and was later updated by de Wit (2020) to include sediment for a sediment dispersion study. Kærgaard (2018) performed an in-depth coastal processes assessment of West Beach which included a 7.5-year wave hindcast and development on a one-line model of the beach. This study used a suite of DHI software including the MIKE 21 FM Shoreline model which was used for the 7.5-year morphological simulation. The model was calibrated using surveyed beach profiles, and then used to assess various design and management options. The Kærgaard (2018) study provides a comprehensive insight into West Beach shoreline change, however there remains a significant knowledge gap in the long term morphological change over the entire stretch of Adelaide's managed beaches.

1.2 Research aim and objectives

This thesis aims to assess the drivers of morphological change and efficacy of management techniques now, and into the future on Adelaide's managed beaches using novel numerical modelling techniques. To achieve this, the following objectives were adopted:

1. Characterise the wave climate of the Gulf St Vincent and investigate the role of large scale climate drivers in the region, utilising a numerical wave model capable of producing outputs fit for morphological modelling.
2. Develop a morphological hindcast model of Adelaide's managed beaches that can characterise shoreline movement over a seasonal to decadal timescale and assess the efficacy of shoreline management.
3. Assess whether drivers of wave climate variations in Gulf St Vincent can be linked to historic shoreline change and coastal management requirements.
4. Adapt morphological modelling software to dynamically apply sand nourishment in order to assess the future viability of sand nourishment along Adelaide's managed beaches considering a range of future climate scenarios.

1.3 Structure and scientific contributions

This thesis is comprised of a thesis introduction (chapter 1), 4 chapters written as manuscripts for publication (chapters 2-5) and a concluding chapter (chapter 6). Chapter 2 has been published in Frontiers in Marine Science (Perry et al., 2024a), chapter 3 is under revision in Coastal Engineering, chapter 4 has been accepted for a special issue of the Journal of Coastal Research and chapter 5 has been presented in manuscript form with intended submission post-acceptance of chapters 3 and 4. Chapters 2-5 all include novel contributions to literature with discussion of these contributions within each chapter.

CHAPTER 2.

Accepted article (Perry et al., 2024a)

Statement of co-authorship – I lead the research design and writing of this chapter. Mentorship, advice and editing of material was performed by co-authors. All contents of this chapter were ultimately my decision after consultation with PhD committee.

Perry (80%), Huisman (5%), Antolinez (5%), Hesp (5%), Miot da Silva (5%).

Impacts of large scale climate modes on the current and future bimodal wave climate of a semi-protected shallow gulf

2.1 Abstract

The bimodal wave climate of the semi-protected shallow Gulf St Vincent in South Australia has been analysed through a forty-year (1980-2020) wave hindcast and an investigation into the climatic drivers of wave climate anomalies is presented. The sea and swell partitions of the wave climate were modelled independently as well as using an integrated model with both partitions represented. The wave hindcast was validated against two wave buoys located off the coast of Adelaide's metropolitan beaches and key wave parameter anomalies were calculated across the gulf. Teleconnections were investigated, and the Southern Annular Mode is found to have the strongest correlations to wave parameter anomalies while the Southern Oscillation Index and the Dipole Mode Index fluctuations are found to correlate seasonally with wave parameter anomalies. Projected future trends of these climate drivers from literature have been related to the teleconnections found in this study to inform future trends of bimodal wave conditions in the gulf. The Southern Annular Mode is projected to trend positive which will reduce wave height and the westerly component of waves in the gulf, while the Southern Oscillation Index is projected to become more variable in the future which will lead to more extreme winter and spring wave conditions. An understanding of these trends allows coastal managers to pre-emptively manage

the impacts of waves on the coastline at a seasonal to annual basis and provides insight into future wave conditions beyond these time periods.

2.2 Introduction

Ocean waves play an important role in sediment transport and mixing in the coastal zone (Wandres et al., 2018). Wave-driven forces are an important driver for coastal erosion in nearshore areas in conjunction with beach profile retreat due to sea level rise and increased storminess (Hemer et al., 2007, Ranasinghe et al., 2023). Coastline changes are the result of a very delicate balance of small gradients in alongshore transports, which are determined mainly by the local wave climate where even subtle changes can result in large scale erosion or accretion (Splinter et al., 2012), and self-reorganization (Antolínez et al., 2018, Ashton et al., 2001). Understanding regional wave climates is therefore important for coastal planning, management and protection (Wandres et al., 2018).

The most common approach to assess the current influence of wave climates on beaches is through a combination of data analysis and numerical models (Smith et al., 2021). Numerical models are able to fill the temporal and spatial gaps in measured data and are relatively inexpensive in comparison to physical measurements (Albuquerque et al., 2021). Numerical models can go a step further, not only characterising the present-day conditions (seasonal, inter decadal and long-term trends), but also assessing future impacts on the wave climate and subsequent effects for the coastal management (J. Méndez and Rueda, 2020).

Not only the average climate conditions, but also the temporal variability of the wave climate is relevant for coastline changes, especially at seasonal to yearly time scales. Those ‘medium-term’ fluctuations and anomalies can be derived from wave hindcasts and can be compared to climatic indices which describe the variability of global circulation patterns. These studies have frequently been performed at a global scale using global wave hindcasts. Reguero et al. (2015) found correlations between wave energy and a range of climate indices across the globe to highlight wave power resources and assess their drivers. Odériz et al. (2020) found spatially dependent positive and negative correlations between ENSO with both wave power and wave direction anomalies globally. The study showed that ENSO is the primary driver affecting global wave climates on interannual timescales and suggested that the quantification of wave climate variability attributed to ENSO could aid in first-pass coastal risk assessments. Marshall et al. (2018) and Hemer et al. (2010) have shown that the Southern Annular Mode (SAM) is a primary driver for seasonal and interannual variations in wave climate in the Southern Hemisphere. An improved understanding of the global climate drivers that cause seasonal to interannual fluctuations at the coast has also been extended to morphological impacts on coastal areas (Barnard et al., 2015), which provides insight for coastal managers and practitioners to perform necessary pre-emptive planning or management.

Global studies can provide a broad insight into the climate modes which impact wave climates at a large scale, however there are nuances in regional wave climates that are not well represented at a global scale and require higher resolution analysis. For example, local winds which force more localised sea waves are often poorly represented in global reanalysis and forecasts but are captured more effectively in higher resolution regional wave models (Elshinnawy and Antolínez, 2023). Where coastal settings are complex, the interpretation of global wave climate data is sensitive to spatial and spectral resolution, as transformation of multimodal wave conditions become key (Hegermiller et al., 2017). A study of a bimodal directional wave climate in the Nordic seas showed that sea wave height anomalies and swell wave height anomalies can have a contrasting relation to the North Atlantic Oscillation (Semedo et al., 2015). The study showed that in areas where sea waves are more prevalent, a negative correlation was found while swell waves tended to correlate positively highlighting the benefits of analysing sheltered waters with a bimodal approach. Albuquerque et al. (2021) performed a partitioned assessment of the New Zealand wave climate where point location correlations were found between sea and swell wave conditions with the Southern Oscillation Index (SOI), Dipole Mode Index (DMI) and Southern Annular Mode (SAM). This analysis provided insight into the differing relationships between climate indices and both sea and swell waves from various directions around New Zealand and similarly to Semedo et al. (2015) highlighted the benefits of a multimodal analysis. Though there have been studies of the links between multimodal wave climates and large-scale climate drivers, there remains a lack of literature concerning the detailed correlation analysis of multimodal wave climates in localised semi-enclosed basins.

The study location for this current research is the Gulf St Vincent (GSV) in South Australia (see Figure 2-1), which is a semi-enclosed gulf. The gulf is characterized by a bimodal wave climate with a combination of swell waves from the southwest and a seasonally varying local sea waves (Short, 2020). The precise occurrence and properties of swell and sea waves are expected to determine the delicate balance of sediment transports at the eastern side of the gulf and are therefore essential for management practices along the Adelaide Metropolitan Coast. Though waves in semi-protected gulfs have been included in broader studies, they have not been assessed in detail using a bimodal approach. Such knowledge on their effects is very relevant for understanding the drivers for regional coastal change when the study location is subject to a nuanced wave climate that cannot be well represented in broader global studies. GSV provides a suitable study site to assess the impacts of large-scale climate modes in semi enclosed gulfs where both wave climate modes impact sediment transport of managed coastlines. Identifying these relationships will also provide an example of how identifying historic relationships between wave climate modes and climate indices can allow coastal managers to pre-emptively manage coasts based on projections of how these climate drivers may change into the future.

While in a national assessment Hemer et al. (2010) found that seasonal variations in South Australia offshore swell wave conditions related (with statistically significance at 95%) to the Southern Oscillation Index (SOI) and Southern Annular Mode (SAM), little is known if this correlation still holds for swells penetrating the GSV, or for local wave generation. Of note is that the Indian Ocean Dipole (IOD), which is due to the anomalous sea surface temperature gradient between the southeastern equatorial Indian Ocean and the western equatorial Indian Ocean, is of relevance for rainfall in the GSV area so may play a role in the generation of local seas (He and Guan, 2013, Kamruzzaman et al., 2020). This study presents a 40-year hindcast of the semi-enclosed GSV wave climate with an analysis of seasonal to interannual fluctuations of the bimodal sea state and locally relevant climatic indices. A novel understanding is provided of the correlations of the long-term global climate oscillations with the bimodal wave climate of GSV. These relations provide a basis for understanding the local coastal morphology of the Adelaide metropolitan coast and expected sensitivity of the coastal stability to climate change. The study site offers a suitable set of conditions to find correlations between the bimodal wave climate and large scale climate drivers, though it is expected that the methodology used in this study would be suitable to other semi-enclosed basins around the world.

2.3 Materials and methods

The methodology presented in this study develops a wave model to identify annual and seasonal trends in the bimodal wave climate that can be compared to climatic indices that describe the large scale climate drivers in the region. To perform this comparison, a correlation analysis can be performed at all points across the model domain in order to map areas in which significant correlations exist between wave parameter anomalies and climate indices. For the following sections, southern hemisphere seasons are defined as summer (December, January and February), autumn (March, April and May), winter (June, July and August) and spring (September, October and November).

2.3.1 Study area characteristics

The study site is Gulf St Vincent (GSV), a intercratonic shallow gulf (<40 m water depth) located in South Australia, bordered to the west by the Yorke Peninsula and to the east by the Fleurieu Peninsula (Figure 2-1). The gulf is part of the Great Australian Bight Shelf with seabed sediments composed of mixed terrigenous-carbonate sands (Short, 2020). The GSV’s area is ~7000 km^2 with a north to south fetch of ~150km and a west to east fetch of ~70 km at its widest point. It is largely protected from the Southern Ocean by Kangaroo Island which limits the swell contribution to the wave climate within the gulf.

Local prevailing winds are typically from the west quadrant with a higher prevalence of northwesterlies in winter and southerwesterlies in summer which generate sea waves within the gulf (Short, 2020). Seabreeze contributes to the wind climate with a net southwesterly direction as a result of westerly local gulf breeze and southerly continental sea breeze (Pazandeh Masouleh et al., 2016). Sea breeze intensities increase in the summer months with a greater southerly component. High-energy south/southwesterly swell waves that originated in the Southern Ocean with an annual mean significant wave height of approximately 3m (Smith et al., 2021, Young et al., 2020) dampen through refraction around Kangaroo Island. Some southwesterly swells can enter the gulf through Investigator Strait (between Kangaroo Island and the Yorke Peninsula, Figure 2-1) with less obstruction and consequently propagate high wave energy across the gulf (Short, 2020). The bimodal wave conditions are the dominant driver for sediment transport on the beaches which varies seasonally but has a net northerly transport. This imbalance requires active management techniques such as sand nourishment to maintain recreational beach widths (Townsend and Guy, 2017).

2.3.2 Wave model development

The wave climate hindcast was developed using the wave model SWAN (Simulating Waves Nearshore); an open-source, third generation wave model which implicitly takes into account the interaction between waves and currents through radiation stresses (Booij et al., 1996). Three models were created to assess the (i) swell partition, (ii) sea wave partition and (iii) integrated partition contribution to the GSV wave climate. The integrated partition model included both the sea wave component and swell boundary components described in the following sections, while the swell partition and local sea wave partition models only included their respective components. The development of these models allows for the common analysis of integrated conditions as well as extra insight into each mode of the bimodal wave climate in GSV.

2.3.2.1 Wave model grid and bathymetry

This study presents results across the full extent of GSV, however, the model grid is refined for greater accuracy offshore of the Adelaide Metropolitan Coastline which lies on the eastern side of the gulf (Figure 2-1). Nested grids of increasing resolution have been adopted to assess wave conditions with enough resolution to capture the dominant processes at the study site while keeping an efficient computational time. Grids are comprised of square grid cells with resolutions G1-4km, G2-2km, G3-500m and G4-100m.

Model bathymetry was developed using local surveyed beach transects and a coarser national bathymetric grid (Geoscience Australia, 2009). The national bathymetric grid is a comprised of numerous data sources, however the areas which lie within the model grids are sourced from multibeam surveys. Beach profile surveys which extend approximately 2km seaward of the foreshore are performed regularly by the state's environmental authority, the Department of Environment and Water. Recent profiles (2020/2021) captured using real time kinematic and single beam echosounder instruments were used to create nearshore bathymetry using triangular interpolation between profiles. The nearshore bathymetry from surveyed profiles was blended into the coarser national bathymetric grid to create the bathymetry used for the 40-years hindcast model (Figure 2-1).

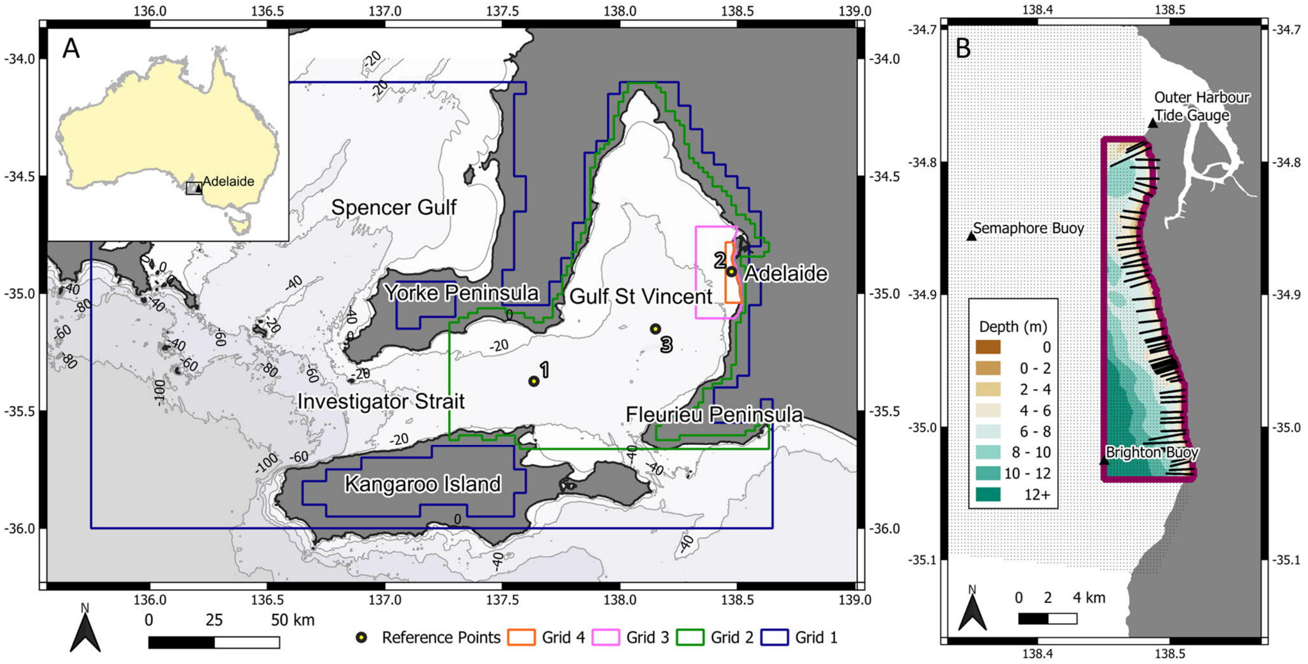

Figure 2-1 (Panel A) Study location (Australia boundaries from Australian Bureau of Statistics, July 2021) and bathymetric contours in metres (Australian Bathymetry and Topography Grid, June 2009, Geoscience Australia), computational grid extents for the wave model and result output locations 1 to 3 displayed as yellow circles. Australia boundaries from Australian Bureau of Statistics, July 2021. (Panel B) Model bathymetry of grid 4 adjacent to the Adelaide Metropolitan Coast (orange extent in Panel A), beach survey profiles (Department for Environment and Water, 2020/2021) displayed as black lines and national bathymetry points (Geoscience Australia, 2009) displayed as black dots, Australia boundaries from Australian Bureau of Statistics, July 2021.

2.3.2.2 Model boundary conditions

Wave boundary conditions were sourced from the Australian/Western Pacific WaveWatch III nested CAWCR (Centre for Australian Weather and Climate Research) wave hindcast (Smith et al., 2021). This model was developed to provide global data with increased resolution for applications in the Australian and West Pacific region. The forcing of this model varies through the simulation period with 1979-2013 generated using WaveWatch III v4.08 and 2013-2020 generated using WaveWatch III v4.18. The CAWCR model has been validated against wave data from the Cape du Couedic wave buoy which is located south of Kangaroo Island with a strong wave height of correlation of R=0.94 .Four-hourly integrated wave conditions were used from this model, applied to southern and western boundaries of Grid 1. These parametrised conditions are applied using a JONSWAP spectral shape with a default peak enhancement factor of 3.3.

Reanalysis wind data has been applied uniformly across the model domain at each four-hourly timestep from the ECMWF ERA5 model (Hersbach et al., 2020).

The effect of changes in water depth due to tides is represented using single uniform tidal levels for each four-hourly timestep, the tidal levels are sourced from the Outer Harbour tidal gauge, location displayed in Figure 2-1.

2.3.2.3 Time period and computational time step

The model simulation spans from 1980-2020 (40 years). This simulation length allows for medium term fluctuations in wave characteristic anomalies to be established. The computational timestep is four hours which was the minimum timestep able to be used while maintaining a reasonable computational expense. This time step is appropriate to assess trends and mean anomalies which is the focus of this study, however extreme events may not be adequately represented.

2.3.2.4 Settings

The SWAN model was run using third generation physics in stationary mode. Depth induced breaking was used according to Battjes and Stive (1985) with dissipation coefficient Alpha=1.0 and breaker parameter Gamma=0.73. Whitecapping was activated according to van der van der Westhuysen et al. (2007) and bed friction according to (Hasselmann et al., 1973). Quadruplets were considered for non-linear wave interactions, but triads were not included. The model domain for each grid used a default circular directional space and 24 frequency bins.

2.3.2.5 Verification of modelled data against buoy measurements

Output extraction points are shown for two measured wave buoy locations offshore of Semaphore (approx. 18 m water depth) and Brighton (approx. 12 m water depth) for model validation (Figure 2-1). Measured data from two SOFAR Spotter wave buoys deployed within Gulf St Vincent were used for these locations. At the time of model development, 1 month of measured wave data (September, 2021) was available. Pearson's correlation coefficient (R) was calculated to assess correlation, Root Mean Square Error (RMSE) was calculated to assess error margins, Scatter Index (SI) was calculated to standardize RMSE and bias was calculated to determine potential significant over or under prediction of modelled conditions. The wave buoys are located on the eastern side of the gulf (Figure 2-1), offshore of the Adelaide metropolitan coastline and provide half-hourly integrated parameters of wave height, period and direction.

2.3.3 Large scale climate modes

Southern Annular Mode (SAM), El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) are large scale climate drivers in the Southern Hemisphere (Cai et al., 2011a) with the potential to drive wave climate anomalies in GSV.

SAM is a widespread climate driver that encompasses the entire extratropical region of the Southern Hemisphere (Fogt and Marshall, 2020). It is defined as the zonal mean atmospheric pressure difference between the mid-latitudes (~40ºS) and Antarctica (~60ºS) (Marshall, 2003) and drives a westerly wind belt which moves between Antarctica and Australia. When SAM is positive, the belt of westerly winds moves closer to Antarctica, but when SAM is negative the belt of westerly winds moves closer to the southern regions of Australia (Swart et al., 2015). These fluctuations generally occur over a timescale of two weeks to a season and have been found to impact ocean waves in the Southern Ocean (Marshall et al., 2018).

The IOD represents the difference in ocean temperatures between the west and east tropical Indian Ocean and its negative phase is associated with an increase in northwest cloud bands over Australia (Cai et al., 2011b). When the Indian Ocean Dipole is positive there are warm anomalies in the equatorial western Indian Ocean and cold anomalies in the east (Cai et al., 2011b). Fluctuations in IOD are strongly seasonal with their impacts on Southern Australia predominantly felt in winter and spring (Ummenhofer et al., 2011). A negative IOD has been found to significantly correlate with increased rainfall, while a positive IOD was found to correlate to wetter conditions (Ashok et al., 2007).

ENSO describes the oscillations of El Niño, neutral and La Niña phases due to changes in intensity of the Walker circulation which modulates sea surface temperature in the central and eastern equatorial pacific (Cai et al., 2021a). These surface temperature oscillations are part of a feedback loop with trade winds across the Pacific. McPhaden et al. (2006) describes this feedback, during La Niña the trade winds elevate surface temperatures in western Pacific and induce cooler water to upwelling in the eastern Pacific. This creates an east-west pressure gradient that drives the trade winds. The trade winds weaken during El Niño when the pressure gradient reduces as atmospheric pressure increases in the western Pacific and falls in the eastern Pacific. Oscillations of ENSO occur at a time scale of approximately 2-8 years (Takahashi et al., 2011).

These three climate drivers have associated indices which quantify their variability. The Marshall SAM index tracks the SAM, Dipole Mode Index (DMI) tracks the IOD and the Southern Oscillation Index (SOI) tracks ENSO. SAM and SOI were selected based upon the correlations found in broader wave climate correlation studies (Hemer et al., 2010), while DMI was selected based upon correlations to other weather conditions local to GSV (Kamruzzaman et al., 2020).

2.3.4 Analyses of the wave climate and correlations with climate indices

Analyses of the modelled wave hindcast has been performed to validate, characterise, and identify climatic drivers for the integrated wave, sea wave and swell wave conditions.

The full 40-year hindcast wave climate results were analysed to characterise conditions in the gulf considering integrated, and sea and swell wave climates independently. Model outputs have been extracted and analysed across grid extents with detailed time series analyses performed at point locations shown in Figure 2-1. Points 1 is positioned to capture the wave conditions passing through Investigator Strait. Points 3 provides wave climate information for the central Gulf St Vincent. Point 2 is positioned adjacent to the Adelaide metropolitan coastline. Wave roses have been created to identify seasonality in wave direction as well as call attention to wave directions corresponding to more energetic conditions. Joint probability analysis was performed on integrated conditions to identify connections between wave parameters and highlight discrete sets of conditions.

The 40-year modelled wave climate was then processed to find seasonal and annual anomalies of wave parameters across the extent of grid 2 with the aim of relating these anomalies to climate indices. Significant wave height and mean values of period and direction were chosen for analysis to include the entirety of the wave spectrum for each partitioned model following Hemer et al. (2010). Anomalies of these wave parameters were then correlated against seasonal and annual fluctuations of DMI, SOI and SAM to find relationships that characterize the seasonal and interannual wave climate. These relationships were assessed by finding statistically significant correlations between each parameter and each climatic index across the entirety of grid 2 as presented in Figure 2-1. Statistically significant correlations for this study were defined as linear relationships between wave climate anomaly and climate index with a Pearson correlation coefficient $R>0.32$, relating to a 95% significance ($P>0.05$) level given 40 data points. The correlations found in this analysis were then investigated to understand the causation of these relationships.

2.4 Results

2.4.1 Model validation

Measured wave data from the two wave buoys in Gulf St Vincent (see Figure 2-1) were compared to model outputs extracted from the nearest grid cell over a 1 month period in September 2021.

Pearson’s correlation coefficient (R), Root Mean Square Error (RMSE), Scatter Index (SI) and bias were calculated and are presented in Figure 2-2.

Significant wave height correlations are R=0.88 when compared against the Semaphore buoy and R=0.89 when compared against the Brighton buoy. RMSE and bias results for significant wave height suggest the model is overestimating wave height which is also evident in the scatter plots presented in Figure 2-2. Correlations for both mean and peak wave periods range between R=0.30 and R=0.45 at Semaphore and Brighton respectively with high RMSE (>5 seconds) for peak period. These statistics indicate that the peak spectral conditions are not in consistent alignment between modelled and measured data. The peak period scatter, as presented in Figure 2-2, shows some occasions in which the modelled peak period is underestimated at Semaphore and overestimated at Brighton, which is supported by their corresponding bias statistic. The mean and peak wave direction statistics range between R=0.52 and R=0.8 suggesting that there are reasonable correlations between modelled and measured data with bias of less than 2 degrees. There is however, a more significant RMSE and poor SI for direction parameters.

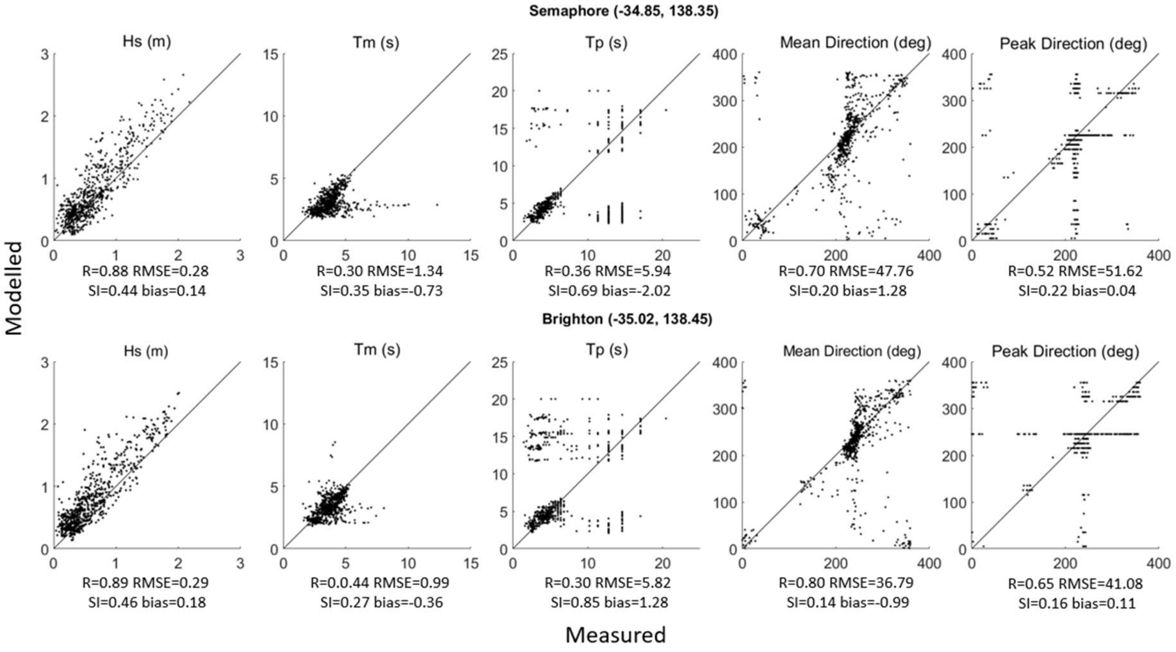

Figure 2-2 Model validation results of wave parameters (significant wave height (Hs), mean period (Tm), peak period (Tp), Mean direction and peak direction) from modelled waves plotted against measured data from wave buoys located offshore Semaphore Beach and offshore Brighton Beach. Validation statistics correlation coefficients (R), Root Mean Square Error (RMSE), Scatter Index (SI) and bias.

2.4.2 Mean wave conditions in GSV

Mean annual significant wave height has been calculated across the gulf with variation shown between integrated, sea and swell waves. The average annual significant wave height was computed for the (a) combined sea wave and swell model, (b) sea wave only model and (c) swell wave only model for the 40-year hindcast period (Figure 2-3). The local sea waves reach an annual significant wave height of approximately 0.5 m at offshore of the Adelaide metropolitan coast and are relatively homogeneously distributed across the gulf. Swell waves penetrate the gulf from the west through Investigator Strait with a mean annual significant wave height of approximately 0.8 m at point 1 (from Figure 2-1) and 0.3 m offshore of the Adelaide metropolitan coast and display a strong gradient in Hs that decreases towards the north. The combined sea and swell wave results (a) shows the characteristics of both results from (b) and (c) with an even distribution of mean Hs across the northern region of the gulf but an increase in Hs in the southern region is subject to greater swell wave influence.

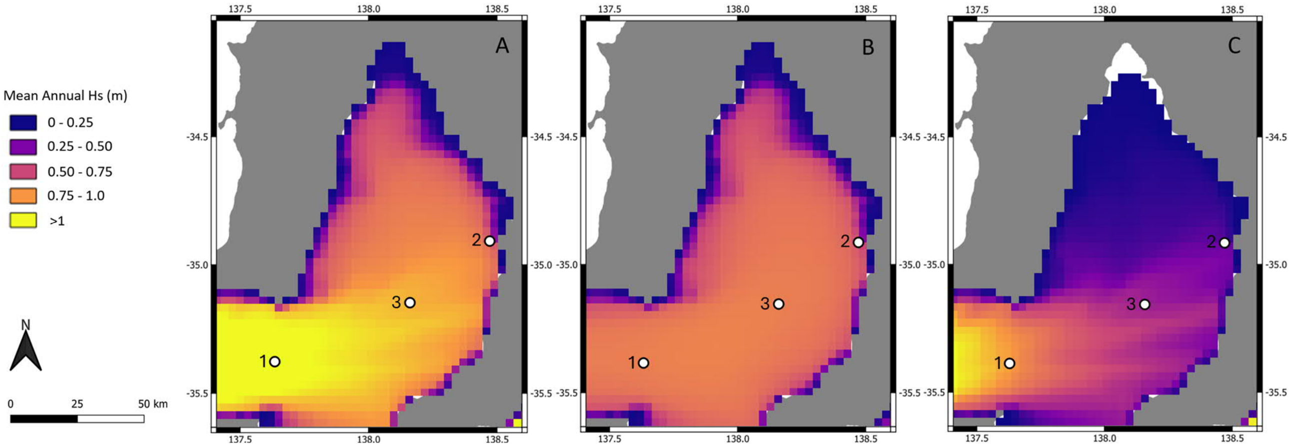

Figure 2-3 Annual mean Hs from modelled wave hindcast for the Gulf St Vincent. (Panel A) combined sea and swell waves, (Panel B) sea waves, (Panel C) swell waves.

Anomalies to mean conditions, extracted from points 1 and 2 from Figure 2-1 are presented below in Figure 2-7. Fluctuations of mean significant wave height at point 1 often exceed ±0.1m which at this location is 20%.Joint probability analyses displayed in Figure 2-4 show integrated wave parameters plotted against significant wave height for a location in Investigator Strait (P1) and a location adjacent to the Adelaide metropolitan coast (P2) (see Figure 2-1). The peak wave conditions at point 1 are largely from a southwesterly direction with a period of approximately 14 seconds. Wave heights exceeding 2 m at this location are swell waves with a peak period longer than 10 seconds from a direction of approximately 240 degrees North. Wave conditions at P2 are more varied with two distinct wave partitions displayed in panel (E) of Figure 2-4. Swell wave significant wave heights at this location are typically between 0.1-0.4 m and do not exceed 1.2 m. Sea waves at this location are typically between 0.3-1.1m and reach a significant wave height of 2.8 m.

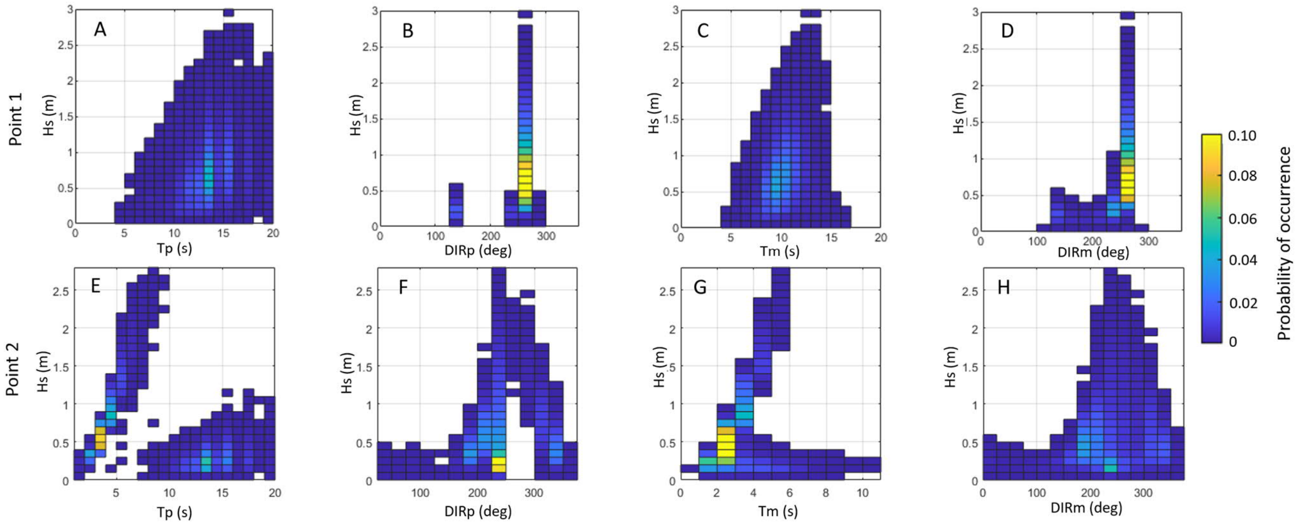

Figure 2-4 Joint occurrence plots at location P1 (panels A,B,C & D) and P2 (panels E,F,G & H) (see Figure 2-1) extracted from modelled wave timeseries. Significant wave height plotted against peak period (Tp) (A & E), peak direction (DIRp) (B & D), mean period (Tm) (C & G) and mean direction (DIRm) (D & H) using a probability of occurrence scale highlighting more common conditions (yellow) and less common conditions (blue)

Seasonal and annual wave roses for a location in the central part of the gulf (P3) (Figure 2-1) and adjacent to the Adelaide metropolitan coast (P2) (Figure 2-1) have been constructed from integrated conditions, swell wave partition and sea wave partition and are shown in Figure 2-5 and Figure 2-6, for P3 and P2 respectively. The integrated parameter results at location P3 show that the dominant wave direction is from the southwest with wave heights up to 3m entering the gulf. Significant wave heights greater than 2m are most common in winter, autumn and spring from a south westerly direction while the summer wave direction has a greater southerly component with less conditions exceeding a significant wave height of 2m. The seasonality of integrated conditions at location P2 follow a similar trend to location P3, however the seasonal signal is stronger with a greater contribution of northerly waves in winter. These plots show the uniform distribution of the swell component of waves within the gulf and highlight how this component accounts for a significant portion of wave heights below 0.5m, however they are not as energetic as the sea waves which are the dominant contributor to wave larger than 1m at both locations. These plots also highlight the seasonality of wave direction in the gulf with northerly sea wave conditions prevailing in winter only.

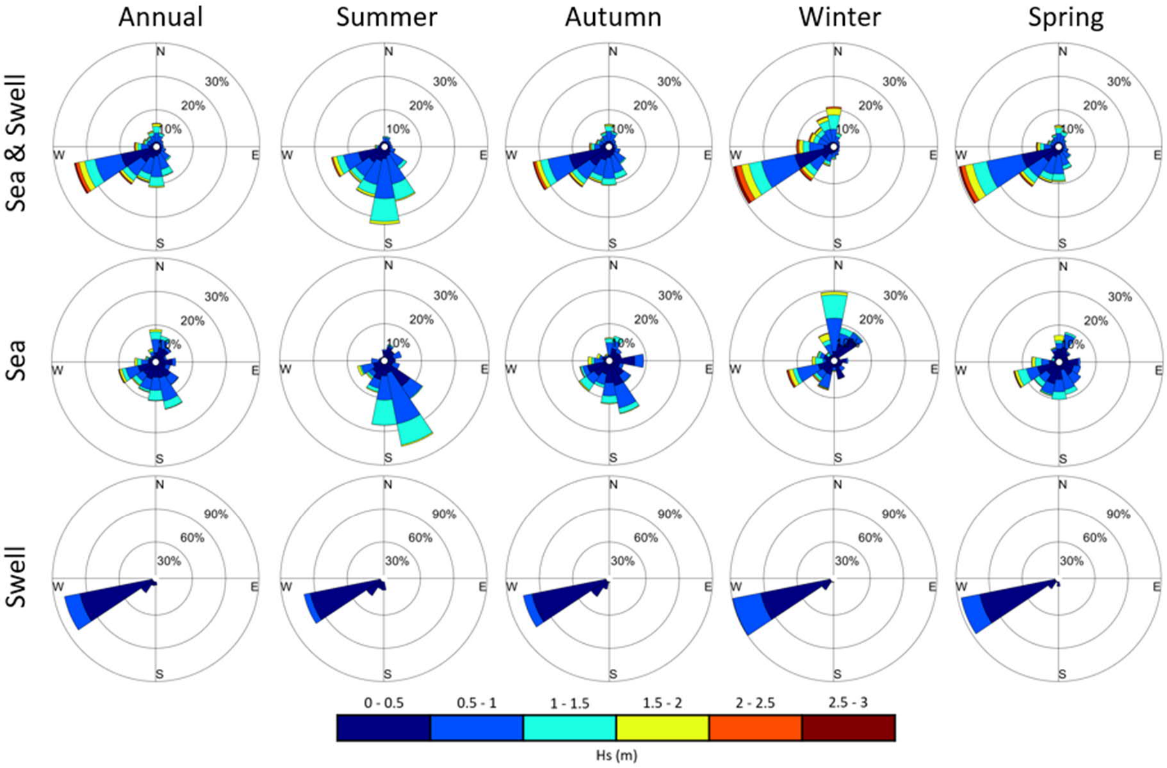

Figure 2-5 Annual and seasonal wave roses at location P3 in the central part of GSV (see Figure 2-1) extracted from modelled wave timeseries with integrated conditions, swell conditions and sea wave conditons

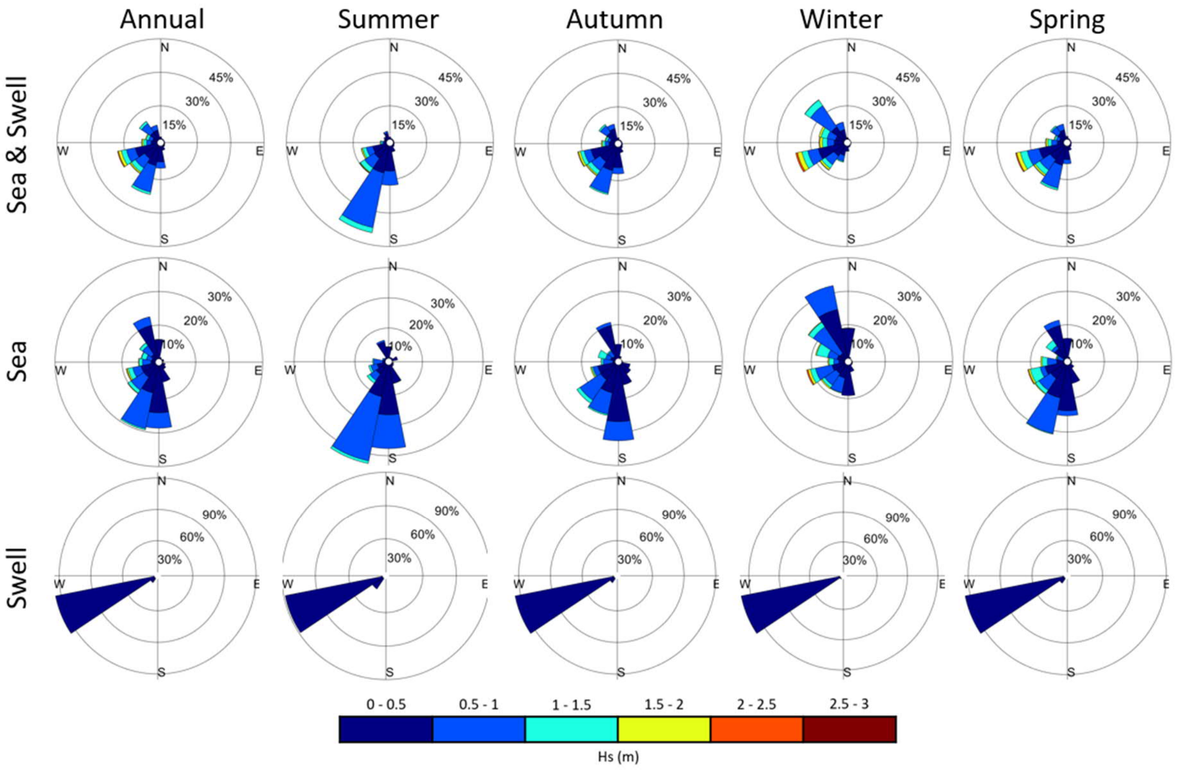

Figure 2-6 Annual and seasonal wave roses at location P2 adjacent to the Adelaide Metropolitan Coast (see Figure 2-1) extracted from modelled wave timeseries with integrated conditions , swell conditions and sea wave conditons

2.4.3 Seasonal and annual wave climate variability comparison to climate indices

Mean annual and seasonal significant anomalies of Hs, Tm and DIRm (using circular statistics) parameters were assessed at locations P1 and P2 from Figure 2-1. Given the annual (40 years) mean significant wave height at this location is 0.3m and 1m respectively, anomalies largely in the range of ±0.2 m are considered substantial. Mean direction anomalies of up to ±20 degrees were also found and considered significant, particularly when considering the potential effects of these anomalies on sediment transport. Anomalies of Tm were less significant with the biggest deviations from mean conditions being approximately 7%. Given the magnitude of anomalies and associated outcomes for longshore sediment transport, Hs and DIRm were the parameters selected to perform a correlation analysis with climate indices. The time series anomalies of this parameters for P1 and P2 are displayed in Figure 2-7.

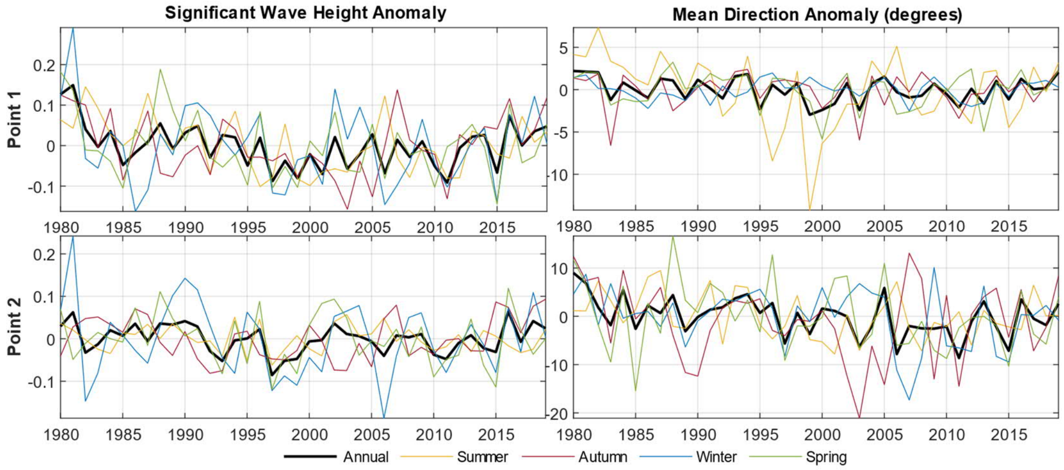

Figure 2-7 Time-series annual and seasonal anomalies of significant wave height and mean direction, extracted from locations 1 and 2 (see Figure 2-1)

The time series of climate indices used for analysis in this study are presented in Figure 2-8.

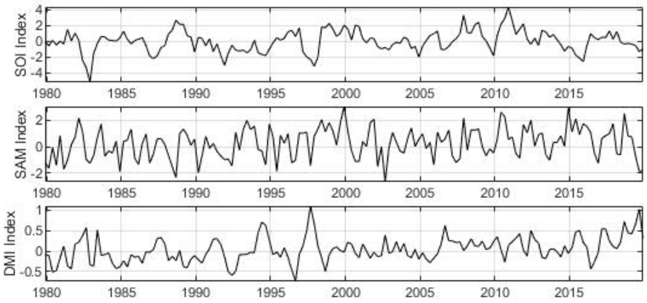

Figure 2-8 Time series of Southern Oscillation Index (SOI), Southern Annular Mode Index (SAM and Dipole Mode Index (DMI) from 1980-2020, sourced from the Physical Sciences Laboratory (PSL) of the National Oceanic and Atmospheric Administration (NOAA).

2.4.3.1 Annual variations

Correlations of wave parameter anomalies with individual climate indices are described below and presented in Figure 2-9.

Southern Annular Mode (SAM): Significant statistical correlations were observed between the SAM anomaly and wave conditions within the gulf. The annual mean significant wave height anomaly and annual mean wave direction anomaly for the integrated model both have significant negative correlations (R<-0.32) to SAM. The annual mean significant wave height correlation is stronger in the southern region (R<-0.5) of the gulf for integrated conditions, with the area of significant correlation extending further north for swell waves in particular. The annual mean wave direction correlation is generally stronger in the northern region for integrated conditions (R<-0.5), with the area of correlation spanning the entire gulf for the sea wave results. These correlations suggest SAM plays a significant role in annual swell direction and annual sea wave direction anomaly.

Southern Oscillation Index (SOI): No Significant correlations were found between the SOI annual anomaly and annual integrated significant wave height or annual integrated mean wave direction anomalies. An extent in the southern region of the gulf presents a correlation between annual swell wave direction anomaly and SOI annual anomaly, however no correlations were found between SOI anomaly and sea wave height parameters. This suggests that SOI only plays a minor role in influencing swell wave direction with no other significant teleconnections found at an annual scale.

Dipole Mode Index (DMI): A significant negative correlation (R<-0.32) was found between the annual anomaly in DMI and annual significant wave height anomaly in the southern region of the gulf. A small region on the eastern side of the gulf shows a significant correlation between annual anomaly in DMI and mean annual sea wave direction anomaly (R<-0.32). Given a significant correlation exists in the southern region between integrated wave height and DMI anomaly but not each partition individually, suggests that both partitions possess mild correlations which are insignificant at a 95% level but when integrated become significant. Mild correlations between annual DMI anomaly and annual wave parameter anomalies suggest that this climate mode influences swell wave heights in the southern region of the gulf and wave directions on the eastern side of the gulf.

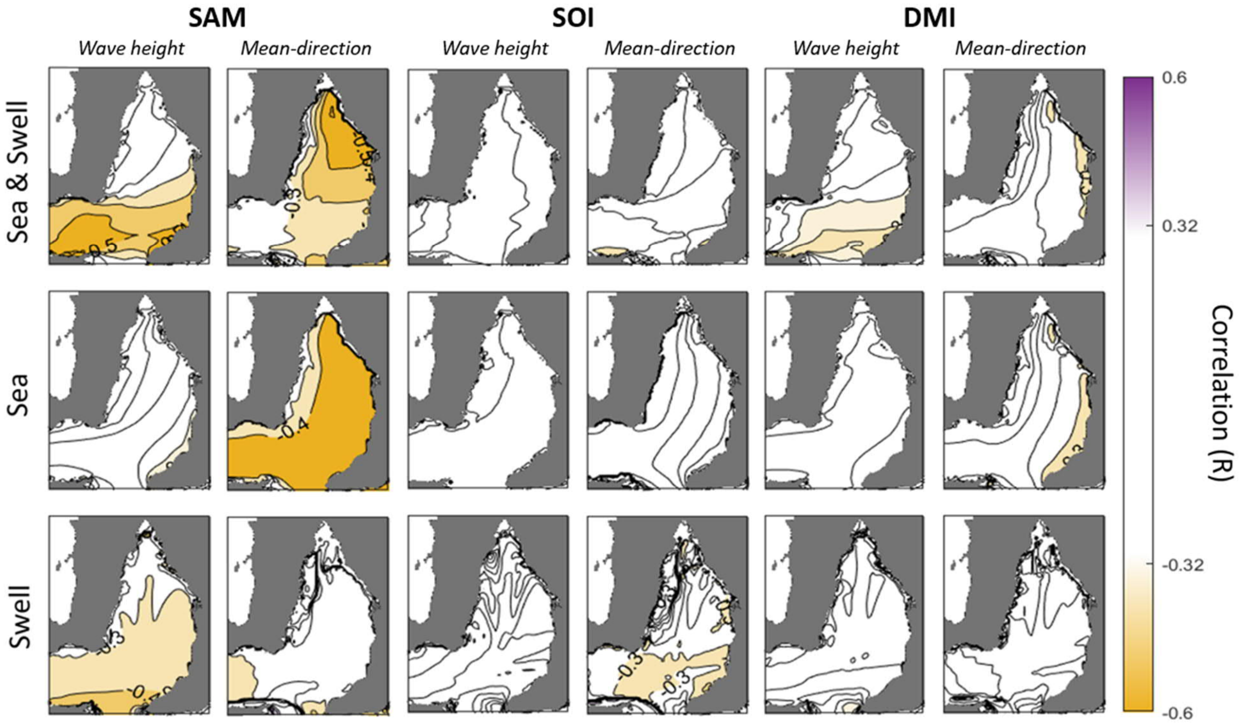

Figure 2-9 Correlation contour maps of annual modelled mean wave height and mean-direction with annual anomalies of Southern Annular Mode Index (SAM), Southern Oscillation Index (SOI) and Dipole Mode Index (DMI) for integrated conditions, sea waves only and swell waves only. Significant correlations occur when R>0.32 or R<-0.32.

2.4.3.2 Seasonal variations

Seasonal correlations between wave parameter anomalies and SAM anomalies are presented in Figure 2-10. The seasonal integrated conditions anomaly in significant wave height was found to have a significant negative correlation with SAM in winter (R<-0.4) and spring (R<-0.5) across most of the gulf. Both the sea and swell waves are affected by the SAM in the winter and spring season (R<-0.4). A smaller area of significant negative correlation was found across the southern region in summer (R<-0.32), which was affected just by the swell waves. The seasonal integrated (sea and swell) conditions anomaly in mean wave direction was found to have a significant negative correlation (R<-0.32) in summer and spring across much of the gulf with correlations as strong as R<-0.5. In smaller areas in the southern region of the gulf, these significant correlations (R<-0.5) also occur in winter. Significant negative correlations were found for the swell partition mean wave direction anomaly in summer (R<-0.5), spring (R<-0.4) and winter (R<-0.32) while significant negative correlations to the mean sea wave partition direction were found in summer (R<-0.32) and spring (R<-0.4) only. These correlations suggest that SAM has significant influence on wave conditions in GSV across all seasons except for Autumn.

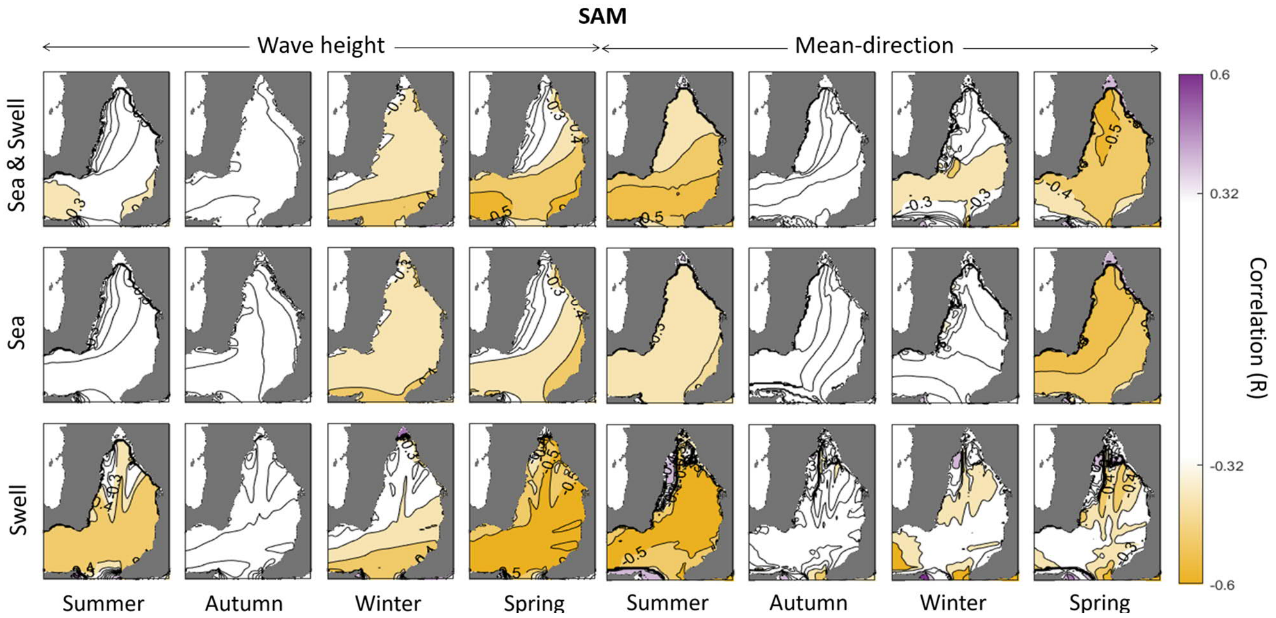

Figure 2-10 Correlation contour maps of seasonal modelled mean wave direction and height anomaly with seasonal anomalies of Southern Annular Mode Index for integrated conditions, sea waves only and swell waves only. Significant correlations occur when R>0.32 or R<-0.32.

Seasonal correlations between wave parameter anomalies and SOI anomalies are presented in Figure 2-11. A significant positive correlation was found between SOI and integrated significant wave height anomaly in the northern region of the gulf in winter (R>0.4). This winter correlation was found across the gulf in the sea wave partition (R>0.4) but was not present in the swell wave partition. A significant negative correlation is present for swell waves only during summer (Investigator Strait and western portion of GSV) and autumn in Investigator Strait. A significant negative correlation was found between SOI and integrated mean wave direction anomaly in the southern region of the gulf in summer (R<-0.4). This summer correlation was found across the gulf in the swell wave partition (R<-0.4) but was not present in the sea wave partition. Small areas within GSV show significant negative correlations during autumn and spring. These correlations suggest SOI has very little influence wave conditions in Autumn and Spring, however it has been found to influence winter wave heights where sea waves are dominant and swell direction in the summer.

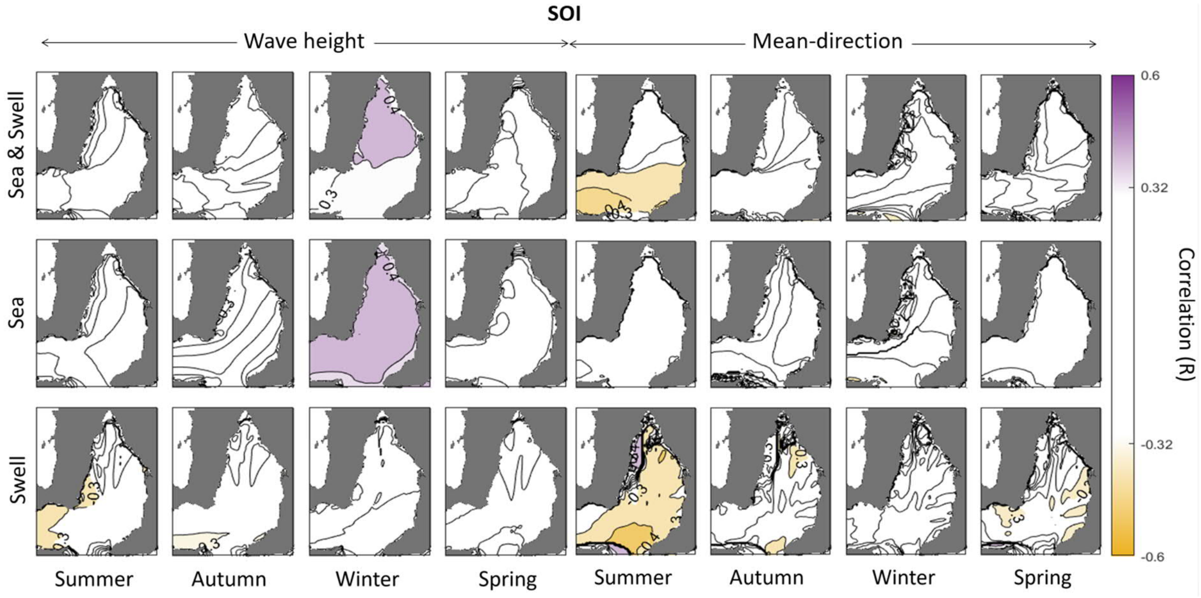

Figure 2-11 Correlation contour maps of seasonal modelled mean wave direction and height anomaly with seasonal anomalies of Southern Oscillation Index for integrated conditions, sea waves only and swell waves only. Significant correlations occur when R>0.32 or R<-0.32.

Seasonal correlations between wave parameter anomalies and DMI anomalies are presented in Figure 2-12. A significant correlation between DMI and significant wave height was found across the gulf particularly during winter (R<-0.4) but also during spring (R<-0.32), for both swell wave and sea wave partition anomalies. For mean direction seasonal anomalies, a significant negative correlation was found particularly in spring for sea wave conditions (R<-0.4) and the swell partition has some spatially sporadic correlation (R<-0.32) in winter and in autumn to a lesser spatial extent. These correlations suggest that DMI has a significant influence on wave conditions across the gulf in winter and spring but not in summer or autumn.

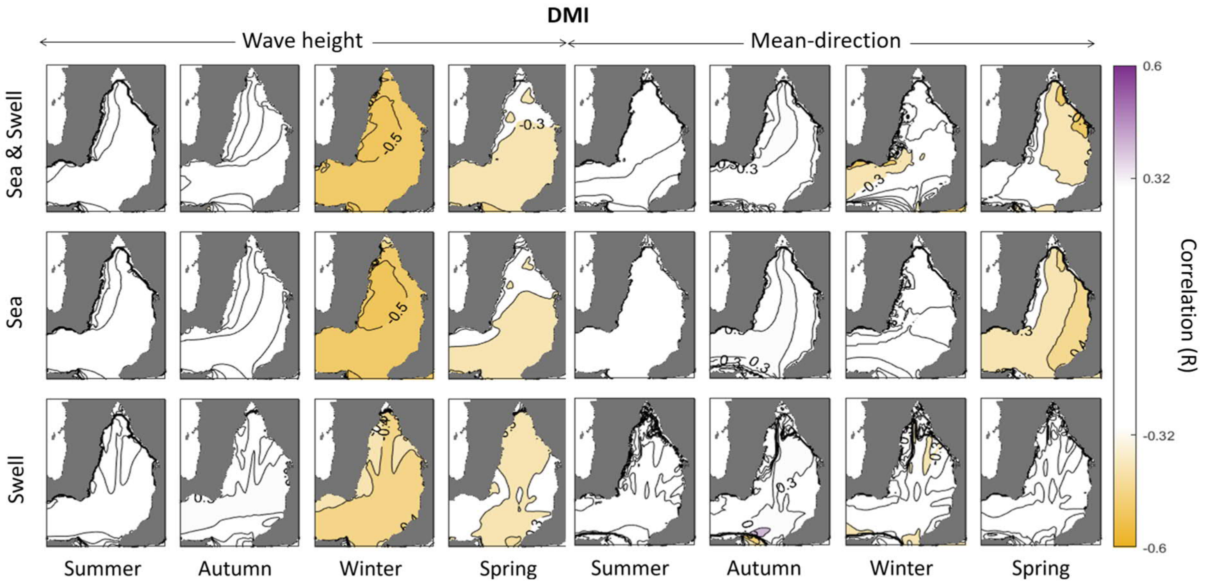

Figure 2-12 Correlation contour maps of seasonal modelled mean wave direction and height anomaly with seasonal anomalies of Dipole Mode Index for integrated conditions, sea waves only and swell waves only. Significant correlations occur when R>0.32 or R<-0.32.

2.5 Discussion

This study advances the understanding of bimodal wave climates at GSV through the development of a 40-year wave hindcast that captures medium term fluctuations which have been compared to various climate modes relevant to the region. The hindcast was developed to assess and compare sea waves, swell waves, and integrated conditions in GSV. The integrated conditions model was used for validation with measured integrated wave parameters buoy data over a one-month period. This one-month period is sufficient to validate model settings, however it is noted that seasonal and mode variations are not captured in the validation period. There was generally good agreement between measured and simulated wave conditions used for analysis in this study. There were strong significant wave height correlations of R=0.88 (Semaphore) and R=0.89 (Brighton), however the model was shown to overpredict wave heights with a bias of 0.14m (Semaphore) and 0.18m (Brighton). The agreement between modelled and measured mean direction was reasonable with correlations of R=0.70 (Semaphore) and R=0.8 (Brighton), however there was high RMSE values of 48 degrees (Semaphore) and 37 degrees (Brighton). The over prediction of wave height and wave direction error should be considered if assessing design wave conditions in GSV, however the model is appropriate for wave climate characterization as done in this study. In addition, the differentiation of wave directions from a bimodal wave climate is difficult for wave buoys to accurately capture.

Uniform wind was used as variations in the global model are not expected to significantly improve the representation of local conditions within the gulf. Resolution of Era5 outputs is 0.25° (~23km) and the width of the gulf is ~65km so the model will struggle to represent the nuances of local conditions. A possible improvement to the representation of winds could be to utilise a regional wind reanalysis such BARRA (Su et al., 2019), however this reanalysis is limited to 29 years (1990-2019). Another possible avenue for improvement of this model could include a spatially variable wind input through the development of a local wind model, capable of capturing coastal breezes, blocking of winds, tunnelling and convective processes. In addition, the computational timestep could be decreased and wind could be introduced in non-stationary mode, though this would come at significant computational cost. Limitations of boundary conditions used in this study should also be considered. Though outside the scope of this investigation, wave energy at the boundary could be corrected based on satellite altimeter data using the methodology suggested by Albuquerque et al. (2018). This correction could improve confidence in wave energy inputs, however uncertainties would remain in the wave direction and period which are not corrected by this approach. Limitations to the methodology used to introduce swell and sea waves should also be considered if the magnitude of these wave types is of interest. Given swell and sea waves were modelled using independent model simulations (as opposed to partitioned outputs of a single simulation) there is potential for differences in the energy of bulk conditions when compared to the summation of sea and swell. Any over or underestimates in wave energy from this limitation are likely minor and do not impact the conclusions of this study. An additional limitation to be considered in model applicability is the representation of tidal levels which were applied uniformly across the model. Kämpf (2014), found that tidal levels at the north of the gulf have an increased range of 4m when compared to the 3m tidal range at the entrance to the gulf. This is unlikely to significantly impact the investigation into climate driver correlations, however it should be considered if assessing nearshore wave conditions in the northern region of the gulf.

The results indicate that the wave climate on the eastern side of the gulf, adjacent to Adelaide's metropolitan beaches is impacted by both local sea waves and swell waves. This impact is nuanced, with the peak partition of the wave spectrum varying spatially and temporally which indicates bimodal peak conditions along the coast. This bimodal wave climate is a result of the unidirectional swell waves which propagate through Investigator Strait from the southwest and local sea waves generated by winds within the gulf. These modes are evident in Figure 2-4 (panel E) in which Hs and Tp model results extracted from the nearshore on the eastern side of the gulf show two clear wave climate modes of longer period (>10 seconds) with Hs between 0-1.2m and shorter period (<8 seconds) with Hs between 0-2.7m. Figure 2-13 further highlights the bimodal conditions present in the gulf. Panel A shows the percentage of time swell wave Hs exceeds sea wave Hs. This varies spatially across the gulf from approximately 50% swell dominance in the south, decreasing to less that 10% swell dominance in the north of the gulf. This highlights the spatial gradient of swell impact from south to north where there is a decreasing presence of swell waves. Panel B provides an example of the bimodal sea state adjacent to Adelaide's managed beaches at a single timestep of the model. The southwesterly swell partition of the wave spectrum has peak energy for the southern stretch of Adelaide's metropolitan beaches while the locally generated northwesterly waves have peak energy for the northern stretch of beaches.

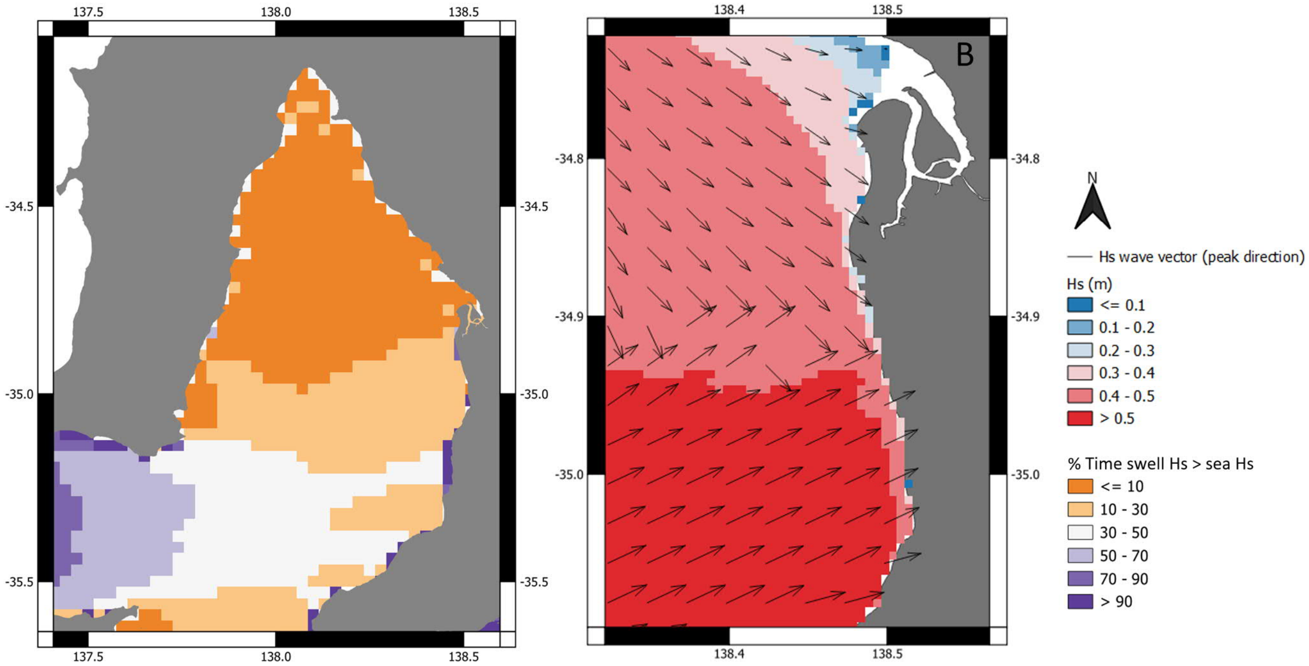

Figure 2-13 Bimodal integrated wave conditions from modelled wave hindcast. Panel A displayed the percentage of time swell Hs is greater than sea Hs. Panel B shows bimodal waves impacting Adelaide metropolitan coastline on December 20, 2019 – arrow vectors show peak wave direction and significant wave height magnitude.

The study of each spectral mode is important to the understanding of longshore sediment transport along Adelaide's managed beaches which lie on the eastern side of GSV and are subject to the bimodal wave climate. The net observed littoral drift of this coastline occurs from south to north (Huiban et al., 2019) driven by the southwesterly components of the swell and sea waves, while transport from north to south can be contributed only from the northerly component of the sea waves. This means that for Adelaide's managed beaches, a clockwise increase in wave direction or a decrease in Hs of swell SW waves may lead to a decrease in net south to north transport. In addition, the complex bimodal climate, often with waves from two sides at the same moment in time, will make it a challenge to assess the precise sediment transports in the region. This may even lead to opposite longshore transports at different depths driven by either the western swell or northeasterly wind sea conditions. The bimodality of the climate needs to be accounted for in morphological assessments in the region.

Significant correlations between both significant wave height and mean direction and the SAM index and SOI were observed for the GSV, which is similar to other studies in the southern region of Australia’s coast (Hemer et al., 2010, Reguero et al., 2015). In addition, correlations were found to DMI within the gulf. It is noted that these anomalies are of particular significance for the Adelaide metropolitan coastline, due to the relative magnitude of the anomalies and their impact on sediment transport.

The impact of the anomalies was found to vary over the seasons. Given the prevalence of the swell waves in the southern region of the gulf (see Figure 2-3), it was expected that stronger correlations in the southern region of the gulf may be related to the anomalies driving these swell waves, while stronger correlations in the northern region may be due to anomalies related to the sea waves. This was confirmed across several examples by analysing these modes separately, for instance the integrated condition correlations to SAM index, where there was a strong correlation in the southern region for Hs and a strong correlation in the northern region for mean direction. As expected, there is a significant negative correlation between the SAM anomaly and swell partition annual significant wave height anomaly as well as the sea wave partition annual mean wave direction anomaly (see Figure 2-9 and Figure 2-10).

The obtained understanding of the relationship between climate indices and key wave parameters in this study helps to give a sense of how the wave climate may fluctuate in the medium to long term. Forecasted climatic indices can, for example, be used to predict the anomalies at a monthly to seasonal timescale in the GSV. In addition, it will be possible to obtain insight into the long-term changes to the wave climate on the basis of the known trends in some climate indices (see Figure 2-14), which is relevant for climate adaptation of Adelaide’s coast. The long-term changes of SAM, SOI and IOD will impact the future wave climate of GSV, however, in different ways.

When SAM is positive, a belt of westerly winds moves closer to Antarctica, but when SAM is negative the belt of westerly winds moves closer to the southern regions of Australia (Swart et al., 2015). The impact of this shift in westerly winds on southern ocean waves has been documented by Hemer et al. (2010). This study has confirmed that relationships are also found within GSV. When the westerly winds tend closer to Australia (negative SAM) the results of this study show that this correlates to an annual and seasonal (summer, winter and spring) increase of significant wave height and a clockwise increase in wave direction. Given the dominant wave direction is from the southwest, this indicates waves tend more westerly with negative SAM. The nuances of the impact of SAM on the swell and sea waves within GSV can largely be attributed to the orientation of the gulf. Swell waves enter the gulf through Investigator Strait which is bound by the Yorke Peninsula to its north and Kangaroo Island to its south. This means that swell waves from a westerly direction enter the gulf less obstructed by Kangaroo Island and maintain their energy leading to increased wave heights in the gulf. The impact of the westerly wind belt controlled by SAM on sea waves within the gulf is more direct. Correlations of SAM anomaly with sea wave direction are prevalent across the gulf in summer and spring, while correlations with wave height are more prevalent of the eastern side of the gulf in winter and spring. The reason for this prevalence of wave height correlation on the eastern side of the gulf is likely the exposure to a longer fetch extending through Investigator Strait which allows for increased wind wave generation when westerly winds are more prevalent.

SAM has had a positive trend over the past 50 years, though forecasting it into the future is difficult due to the lack of understanding of the contributions of greenhouse gas increases, which would promote positive trends, while ozone recovery (greenhouse gas decrease) would promote negative trends (Fogt and Marshall, 2020). Studies of SAM which include ozone recovery have projected a range of scenarios from insignificantly negative trends (Arblaster et al., 2011, Polvani et al., 2011) to significantly positive (Miller et al., 2006). If the SAM continues a positive trend, the correlations to wave conditions in this study suggest that mean swell wave height will decrease in summer, winter, spring and annually whilst sea wave heights will decrease in winter and spring. The westerly component of swell waves would decrease in summer, winter, spring and annually whilst the westerly component of the sea waves will decrease in summer, spring and annually.

The SOI phases impact weather patterns in southern Australia with stronger La Niña phases leading to increased easterly winds and the westerly wind belt below Australia moving further south. Hemer et al. (2010) found a significant negative correlation between the SOI and winter significant wave height offshore of south Australia towards the south east. This correlation with offshore swell waves was not found to translate to swell waves within the gulf. Instead, significant correlations with SOI within the gulf were found for summer swell direction and winter sea wave height. The correlation between positive SOI (linked to La Niña) and positive anomaly in winter sea wave height across the gulf suggest an increase in wind stress. Though relationships between GSV wind anomalies and SOI have not been specifically investigated in literature, there has been studies that link La Niña periods to increased storminess across southern Australia (Ashok et al., 2007).

The SOI is predicted to show an increase in variability and magnitude associated to greenhouse warming (Cai et al., 2021a). This means there will likely be stronger El Niño and La Niña phases in the future. Given the correlations between wave conditions in GSV and the SOI, an increase in stronger La Niña events would lead to increases in extreme winters with increased wave heights, conversely stronger El Niño winters would lead to decreased mean wave height across the season. Correlations also suggest that stronger SOI fluctuations would also lead to an increase in swell direction variability between summer seasons.

The IOD impacts weather patterns in southern Australia in its negative phase when a cloud band extends from northwest Australia (Cai et al., 2011b). Ummenhofer et al. (2011) reports that IOD impacts rainfall across the western and southern regions of Australia during winter and spring. This seasonal phase lock was also found in this study where significant negative correlations with sea and swell wave conditions were identified in winter and spring. This suggests that the northwest cloud band associated to the IOD impact wave conditions in the gulf. This influence may arise from heightened wind strength during cloudier conditions, driven by increased pressure gradients.

The IOD is also expected to be influenced by the effects greenhouse gas emissions with the climate of the Indian Ocean projected to change significantly (Cai et al., 2013). The projected response of the IOD and associated DMI is a decrease in moderate positive events but an increase in the number of stronger positive events (Cai et al., 2021b). Though this trend has been identified for positive events, it largely remains unknown how negative IOD events will change or trend in the future (Rutlidge et al., 2023).

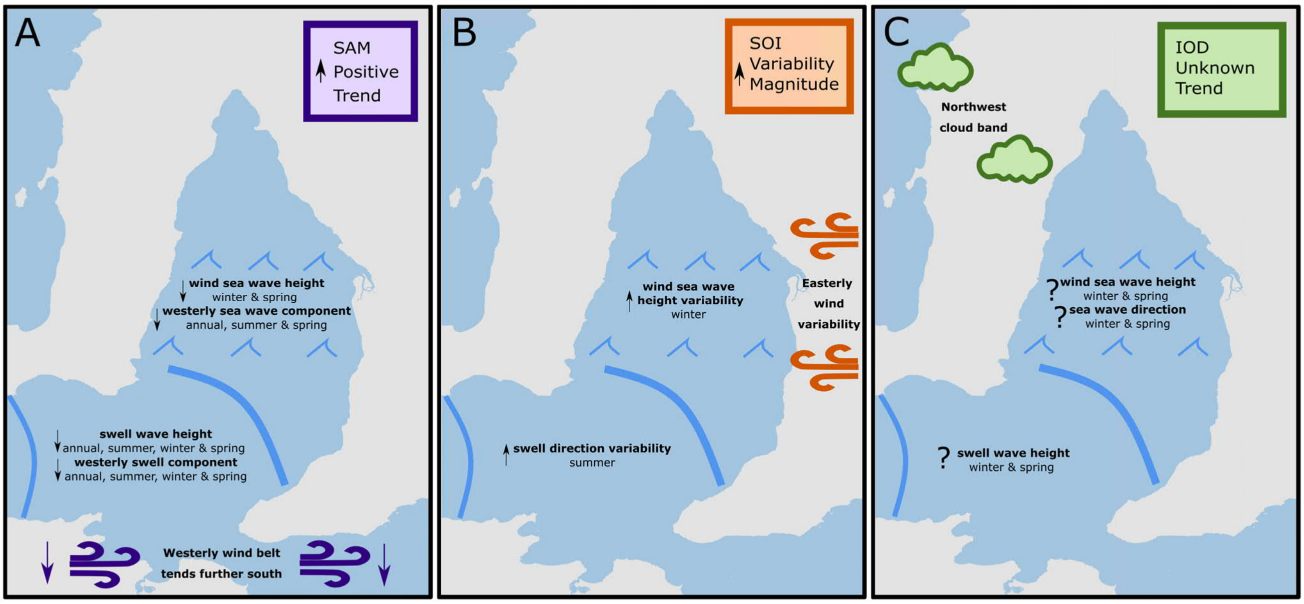

Figure 2-14 future impacts of climate drivers that influence the wave climate in Gulf St Vincent – Panels A, B and C show projected changes to SAM, SOI and IOD respectively (as per (Cai et al., 2021; Cai et al., 2021; Miller et al., 2006).

When considering the combined future effects of the drivers of seasonal to interannual fluctuations in GSV, it is important to consider underlying long term changes due to climate change. Reguero et al. (2019) investigated the impact of oceanic warming on global wave power and found a significant positive correlation in the Southern Ocean suggesting that wave power will increase as oceans warm which has also been reported by Young and Ribal (2019) who found that increases in mean wind speed and significant wave height over the past 33 years. This will have an impact on GSV, largely through an increase in swell energy from the Southern Ocean. This impact will have a contrasting effect on swell to the predicted decline in swell energy entering GSV due to a positive trending SAM. The contrasting and nuanced impacts of the seasonal to interannual fluctuations discussed in this study with interdecadal trends are critical to future wave climate forecasting. The results of this study highlight the importance of understanding downscaled impacts to more complex areas such as semi exposed gulfs where the application of offshore trends may not apply directly to the local area of concern.

The seasonal to interannual effects of climate drivers discussed in this paper are important to the future management of the coasts of the GSV. Of particular importance for GSV is identifying the combination of increased wave height and increased southerly component of the wave direction which leads to increased south to north sediment transport along the eastern side of the Gulf. Adelaide’s managed beaches require sand nourishments to maintain beach widths of southern beaches, and especially these south to north transports are responsible for the local sediment deficits.

The methodology used in this study to derive these regional correlations between large scale climate drivers and local wave conditions is expected to be applicable for semi-enclosed basins around the world. In these locations where swell waves only form part of the wave climate, it is crucial to consider the drivers for local sea waves to understand the drivers for conditions within the basin. It is expected that by understanding the nuances of the wave climates in these basins, coastal managers will be able to pre-emptively assess the possible severity of upcoming seasons on the coastal environment due to waves.

2.6 Conclusions

The factors that influence the seasonal to interannual timescale behavior of bimodal wave climates for semi-enclosed bays are better understood as a result of the comparison of modelled waves (over 40-years) with climate modes for the Gulf St Vincent, South Australia.

The eastern side of the gulf is influenced by a bimodal wave climate consisting of unidirectional swell waves from the southwest and sea waves generated within the gulf. The dominance of either the sea and swell climate varies spatially and temporally, which is of particular relevance for the coastal sediment transports and beach stability at Adelaide. The 3-month-averaged significant wave height and mean wave direction showed seasonal variations of up to 30% and ±20 degrees respectively. These seasonal anomalies of wave height and mean direction are significantly correlated ($R>0.32$ or $R<-0.32$) with the SAM index, SOI and DMI. SAM was found to have the strongest correlations with both wave parameters, especially having significant correlation with the swell wave height and sea wave direction.

The study highlights the benefits of considering modes of a bimodal wave climate separately when analysing wave parameter anomalies and their correlation to climate indices. It is predicted SAM, SOI and DMI will all be influenced by greenhouse gas emissions in the future so an understanding of how these projections relate to each mode of the wave climate is useful to give indications of how related coastal hazards may vary in the future. It is expected that the Southern Annular Mode will trend positively, resulting in a decrease in wave height and the westerly component of waves in the Gulf. Moreover, projections suggest that the Southern Oscillation Index will become more variable in the future, leading to more extreme winter and spring wave conditions in the gulf. The impact of greenhouse gas emissions on future trends of negative IOD events remains understudied, improved understanding would provide insight into future trends of winter and spring wave conditions in Gulf St Vincent. Understanding how these climate drivers impact the bimodal wave climate in the gulf will allow coastal managers to pre-emptively prepare appropriate management of a coast at a seasonal to annual timescale.

CHAPTER 3.

Submitted article (Perry et al., Under Review)

Statement of co-authorship – I lead the research design and writing of this chapter. Mentorship, advice and editing of material was performed by co-authors. All contents of this chapter were ultimately my decision after consultation with PhD committee.

Perry (80%), Huisman (5%), Roelvink (5%), Hesp (5%), Miot da Silva (5%).

Efficacy assessment of coastal structures and sand nourishment for managing Adelaide beaches using one-line modelling

3.1 Abstract

The efficacy of shoreline management with coastal structures, sand nourishments and sediment recirculation are evaluated at a decadal timescale for Adelaide's beaches in South-Australia, making use of the one-line numerical model 'ShorelineS'. The coast has been impacted not only by natural forces but is also managed by a wide variety of measures that were introduced in the last decades, such as (offshore) breakwaters, groynes, revetments, sand nourishments and regular sand recirculation. In this study satellite-derived shoreline change rates were used to verify modelled rates deduced from the one-line model wherein management and coastal structures were incorporated. Model simulations were then performed to assess the shoreline change rates and effective performance for the current management strategy as well as for alternative scenarios. The study found that beach nourishment is required on Adelaide's managed beaches to maintain beach widths. In some locations beach nourishment is required due to the natural longshore movement of sand; however, other locations require beach nourishment due to the presence of hard structures which restrict longshore transport. The methods adopted for Adelaide can also be applied to other managed beaches with complex structures and nourishment programs.

3.2 Introduction

Sandy beaches provide an amenity to coastal populations, defence against storms, and a range of ecological and social services to the surrounding environment and people (Barbier et al., 2011). Shoreline movement on sandy beaches can have significant impacts on coastal communities, hence, management is often required to mitigate commonly associated hazards such as coastal erosion. Engineers and scientists have studied shoreline evolution primarily using measurement and analysis of historic shorelines through photography or survey, one-line conservation of sediment models, coastal morphodynamic models and physical models (Thomas and Frey, 2013, Price et al., 1972). These measurements and models are typically used to understand historic shoreline evolution and, in some cases, predict future shoreline evolution based on historic rates. This means that often the effects of management are inherently incorporated into datasets and modelling results, which can make it difficult not only to evaluate the effectiveness of coastal management strategies, but also to justify investment and promote best management practice for the future. Evaluation methods that can account for the complex history are therefore essential for assessing coastal management strategies.

Shoreline management can be broadly divided into three standard strategies; defend, adapt, and retreat (Williams et al., 2018), all of which have varying impacts on the coastal environment. This study focuses on the assessment of hard and soft coastal defence strategies in relation to their efficacy to combat coastal erosion. Specifically, rock revetments, breakwaters and beach nourishment are investigated. The construction of rock revetments to armour shorelines was a typical response to coastal erosion for decades (Griggs, 2005) with the intention of protecting landward infrastructure and dissipating wave energy. Though they have been often successful in protecting infrastructure, they can have adverse impacts on the shoreline by occupying beach width, intensifying surf zone processes causing increased erosion, and reducing sediment input from the previously eroding upland (Nordstrom, 2014). Breakwaters and training walls can provide protection from waves and stabilise the entry to harbours, however, they interrupt longshore transport if there is a transport magnitude greater than zero (van Rijn, 2011).

Beach nourishment offers a ‘soft’ alternative to hard structures in which sand is placed in or downdrift of erosional areas to maintain beach widths (e.g. De Schipper et al., 2020). There are a number of techniques available to perform beach nourishment including direct placement, emplacement by longshore drift, bypassing, recycling, use of shoreward drift, backpassing, overfill and shore profile renourishment (Bird and Lewis, 2014). The method explored in this study is the recycling method, which involves collecting sand from an accreted updrift section of beach and backpassing it downdrift to an eroding section of shoreline. This method has been implemented at Noosa Beach in Queensland, Australia where a submarine sandshifter unit was installed to provide a constant supply of sand to the eroding beach (Nankervis, 2005). Perhaps the most elaborate beach recycling scheme exists in Adelaide, South Australia which is the location of this study. This scheme includes a sand recycling pipeline combined with trucked recycling and is discussed further in section 3.4.2.

A common tool used to assess shoreline movement over time scales of months to years is a one-line shoreline model. This type of model is typically used to assess shoreline change on coastlines where transport gradients dominate cross shore processes over extended time scales by representing a shoreline as a single line with a fixed coastal profile (Kristensen et al., 2011). Hunt et al. (2023) suggests that reduced complexity models such as one-line models are well positioned to benefit from advances in computational efficiency and increases in data availability. One-line models were first numerically presented by Price et al. (1972) with developments made throughout the 1970’s and 1980’s until the widely used model GENESIS was developed in 1989 (Hanson, 1989). This model provided a more generalised shoreline change model for coastal engineering applications to assess changes to sandy beaches in a long-term perspective (months to years). Since the development of GENESIS, several other one-line models have been developed including ONELINE (Dabees and Kamphuis, 1999), UNIBEST (Deltares, 2011), LITPACK (DHI, 2005), SMC (González et al., 2007) and GENCADE (Frey et al., 2012). More recently, Roelvink et al. (2020) presented a new one-line model, ShorelineS, which uses a flexible, vector-based approach that allows for unconstrained modelling of complex coastal features.

One-line shoreline models have been used in an array of engineering applications to inform coastal decision making, largely to predict shoreline behaviour with the introduction of a structure or nourishment. Whitley et al. (2021) used GENCADE to model a mega-nourishment known as the Sand Motor on the Holland coast. The study found that the model was able to represent observed shoreline morphological patterns and highlighted the importance of calibrating longshore transport coefficients. Tonnon et al. (2018) also modelled the Sand Motor but used UNIBEST-CL+ and LONGMOR to derive erosion rates and assess the life span and required maintenance nourishment volumes. Kuang et al. (2011) performed a small scale one-line shoreline modelling study using GENESIS. The model incorporated beach nourishment and proposed structures to explore the impacts of coastal management options including the impact of removing existing structures. Lim et al. (2021) presented a one-line shoreline study at seaports on the eastern coast of Korea to enable coastal managers to assess the impact of structure installation on shoreline position. Roelvink et al. (2020) presented two initial test cases of ShorelineS for the Sand Engine located at Ter Heijde, the Netherlands and Al-Gamil Beach located at Port Said, Egypt. The Sand Engine case highlighted the model’s ability to represent a significant nourishment regime with a complex shape. The results were positive with qualitative signs of realistic morphodynamic evolution and quantitative indications of excellent model skill according to a classification given by Sutherland et al. (2004). The Port Said case highlighted the model’s ability to represent a coast section protected by groynes with a sparse amount of local data, relying on Google Earth Imagery for shoreline location and ERA5 reanalysis wave data. Similar to the Sand Engine case, the model skill was found to be excellent when compared to the measured shoreline position. Though shoreline models have been used regularly in the literature to model shoreline dynamics, structure interactions and nourishment regimes, there is minimal discussion on the use of shoreline models to determine underlying shoreline change rates of managed coastlines that can help inform improved management practice. Furthermore, it is surprising that the use of one-line models to assess the performance of a management scheme with multiple measures over an extended period of time is rarely explored in literature.

One-line shoreline change models are most often verified by measured data. Methods such as beach topographic transects or LiDAR surveys offer accurate shoreline positions, however, often they do not offer the vast spatial extent or temporal coverage of satellite derived shorelines (Kelly and Gontz, 2018). Given that one-line models are generally used to assess shoreline movement across large spatial extents at a time scale of months to years, satellite derived shoreline positions are a valuable verification tool. Numerous studies have investigated the applicability of various satellite derived shoreline detection methods at various temporal scales around the world, showing that typical shoreline variability can be resolved using satellite derived data over a temporal resolution of 6 months to 30+ years using sub-pixel shoreline extraction techniques (Luijendijk et al., 2018, Vos et al., 2019). The satellite dataset selection and shoreline extraction techniques are not the focus of this study, but are considered a good basis for evaluating the performance of the coastline models (Vitousek et al., 2023). In addition, the hindcasted shorelines should be verified against local in-situ measurements where possible. In-situ measurements remain the most accurate capture method of shoreline position with modern in-situ surveys predominantly utilising RTK-GPS survey equipment, such as the rich survey record at Narrabeen, Australia (Splinter et al., 2018). In-situ beach profile surveys have been collected on Adelaide’s managed beaches since the establishment of a monitoring program in the 1970’s by the South Australian Department of Environment and Water. Huiban et al. (2019) used these observations in a study of shoreline change and performed a volumetric analysis on littoral drift. The study estimated annual transport rates between 50,000 and 150,000 m^3/year across the entirety of the Adelaide Metropolitan Coastline and noted the significant volumes of sand that have accumulated in the northern region. A study by Coastal Engineering Solutions (2004) used longshore transport formulations to estimate the annual net longshore transport to be approximately 75,000 m^3/year.

This study assesses the effectiveness of long-term coastal management strategies on a shoreline managed by multiple rock revetments, attached/detached breakwaters and beach nourishments. To achieve this, the one-line shoreline model ShorelineS (Roelvink et al., 2020) has been applied to Adelaide’s metropolitan coastline in South Australia (Figure 3-2). The model is calibrated for a hindcast period of 32 years using satellite derived shoreline positions sourced from Bishop-Taylor et al. (2021) available from the year 1988. This shoreline dataset was produced using a tidally constrained median composite approach to determine the position of the annual shoreline, where rates of change were validated against surveyed rates around Australia with MAE accuracy of 0.35 m/yr (Bishop-Taylor et al., 2021). The calibrated model is then used to explore the effects on beach stability (i.e. retreat rates) for the current maintenance plans as well as scenarios without beach nourishment and structures. The discerning aspect of this study is the presentation of a methodological framework for the evaluation of decadal timescale management strategies with a large variety of interventions. Hereby utilising a recently developed shoreline model that can also deal with complex structures and widely available satellite derived shoreline positions to provide insight into the effectiveness of management practices on Adelaide’s managed beaches.

3.3 Methods

3.3.1 General framework

A methodology is proposed for the assessment of underlying shoreline change rates in the absence of beach nourishment and structures. This methodology is designed to be computationally inexpensive through the implementation of a one-line numerical model ‘ShorelineS’. The approach is applicable to cases worldwide regardless of data scarcity. Though it’s possible to perform this methodology using locally collected survey data rather than satellite derived shoreline positions, it is rare to have access to sufficient temporally and spatially rich locally collected data. An overview of the proposed methodology is given in Figure 3-1.

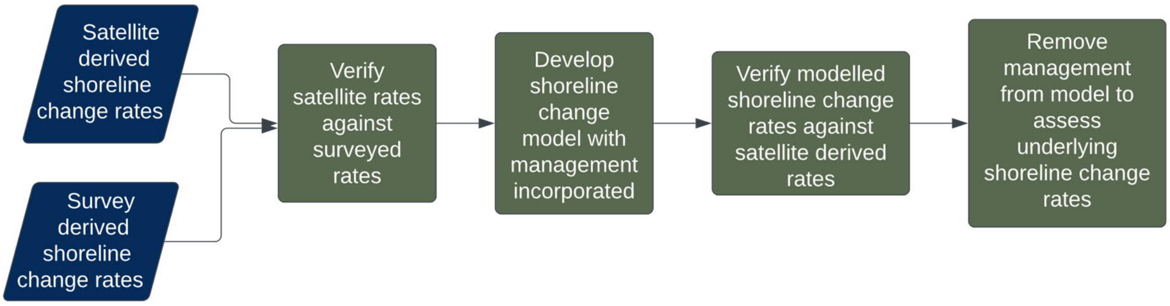

Figure 3-1 Methodology schematic for assessing underlying shoreline change for a managed coastline using a shoreline change model

The methodology has been applied to Adelaide’s managed beaches in South Australia (Figure 3-2) as a typical example of a highly managed coastline with nourishment regimes and coastal structures implemented to combat coastal erosion.

3.3.2 Scenarios and shoreline trend analyses

Three model scenarios are simulated with the aim of establishing the effects of beach nourishments and coastal structures on the coastline of Adelaide over the 32 year hindcast period. Scenario (i) is used as a model validation and baseline case to assess how well the model is able to represent observed changes and includes all beach nourishments and structures. Scenario (ii) is designed to quantify shoreline trends in a situation where nourishment is ceased, using the same model settings as scenario (i), but without nourishment. Scenario (iii) leaves out all nourishments and structures (i.e. groynes, revetments and breakwaters) in order to quantify shoreline changes in their absence. There are historic impacts of development near the coast, such as the construction of roads and houses which are not represented in these scenarios. In all scenarios the sediment transport model settings remain constant based on the calibration of scenario (i).

The effectiveness of the nourishments and coastal structures on the stability of Adelaide’s beaches are assessed from the comparison of the modelled shoreline change to observations across timescales of months to years. Surveyed shoreline trends are used to verify the satellite derived observations at the transects, which in-turn are used to verify the modelled shoreline change rates. The rate of change of the coastline is computed from the observed shoreline position changes along a cross shore transect through time. Using linear regression, an annual rate of change statistic is generated at each transect based on the (modelled and measured) shoreline positions. The gradient of the linear line of best fit to the shoreline positions then represents the shoreline change rate, which is then available for the in-situ profile-surveys, satellite-derived and modelled coastlines. These trends in shoreline position show the longer-term changes, while the impact of short-term shoreline changes due to storms or seasonality is minimized (Douglas and Crowell, 2000). These short-term changes are relevant for understanding the impacts of extreme events on the beaches but are not so important for the longer-term coastline changes explored in this study.

Root Mean Square Error (RMSE), Standard Deviation (SD) and mean difference are used to quantify differences in the satellite derived and surveyed rates of change as they offer a practical assessment of whether the differences are satisfactory, and the data is fit for purpose (Alvarez-Cuesta et al., 2021). Only statistically significant (P-value < 0.05) trends were considered. Seasonal and annual statistics were calculated with the southern hemisphere seasons defined as summer (December, January and February), autumn (March, April and May), winter (June, July and August) and spring (September, October and November).

3.3.3 Coastline modelling description

ShorelineS is utilised in this study with details of the model available in Roelvink et al. (2020). The model uses a series of free form vectors to determine shoreline position forced by waves. The governing equation for updating the coastline position used in ShorelineS is shown in equation 3-1:

$$\frac{dn}{dt} = -\frac{1}{D_c}\frac{dQ_s}{ds} - \frac{RSLR}{tan\beta} + \frac{1}{D_c}\sum q_i \tag{3-1}$$

Where, *n* is the cross-shore coordinate, *s* the longshore coordinate, *t* is time, D_c is active profile height, Q_s is the longshore transport rate, $tan\beta$ is the average profile slope between dune or barrier crest and depth of closure, RSLR is the relative sea level rise and q_i is the source/sink term used to incorporate cross-shore transport, overwashing, nourishment, sand mining and exchanges with tidal inlets (Roelvink et al., 2020).

Typically, one-line models assume a constant active profile height across the entirety of the model. This assumption may be valid in some cases, however, if the study case has a significantly variable active profile height, the response of the coastline to gradients in the transport may be under or over predicted. Given the importance of a suitable active profile height for model performance, a modification was made to ShorelineS to allow a space varying active profile. With this modification, the model user is able to specify the active profile height at various locations along the coastline. In this study, active profile heights varying between 6 and 15 meters are applied. These profile heights were determined by calculating the vertical difference between the active dune or back shore height and the inner depth of closure calculated according to Hallermeier (1980).

The model extends from Kingston Park to the North Haven marina (see Figure 3-2) with an initial space step of 100 m. The initial shoreline position uses the satellite generated shoreline position from Bishop-Taylor et al. (2021) as a basis but modifications were made to align with the 0m contour from survey transects from the same year collected by local government. The simulation period spans from 1988 to 2019 with structures including breakwaters, training walls and revetments introduced at the time of construction throughout this period. Breakwaters and training walls are specified to the model independently to the revetments to account for the appropriate processes. For breakwaters and training walls, wave diffraction is modelled according to the Roelvink approach (Elghandour et al., 2020) and bypassing is modelled according to Ghonim (2019). The treatment of revetments is such that transport reductions are applied when the shoreline is near to the revetment. As a result, the shoreline does not retreat landward of the revetment but at the same time allows for the bypass of sediment. The sediment bypass along the revetment is limited to the rate of updrift supply. When sediment has accumulated in front of the revetement, transport can only increase to the extent that the available sediment allows.

Beach nourishment including carted and piped nourishments has been applied in quantities and locations sourced from The Department for Environment and Water, the local government agency and presented in Figure 3-4. The nourishment extent, volume and time period is specified for each nourishment placement. Sand recycling is represented by retreating the shoreline position (in agreement with the nourishment rate) at the source locations and advancing the shoreline position at the deposition locations. When nourishment is applied to the model, the volume is added to the q_i term in equation 3-1, where it is divided across the active profile height to determine the distance the shoreline moves seaward (or landward for sand extraction).

Longshore transport is computed in the model according to Van Rijn (2014) (see equation 3-2), and as a reference compared to the performance for the CERC (Coastal Engineering Research Center, 1984) or Kamphuis formulations (Kamphuis, 1991) in the calibration phase of the model.

$$Q_{t,mass} = 0.0006 K_{swell} \rho_s (tan\beta)^{0.4} (d_{50})^{-0.6} (H_{s,br})^{2.6} V_{wave}^{2.6} \qquad 3\text{-}2$$

Where, $Q_{t,mass}$ is the transport rate (mass per unit time), K_{swell} is a dimensionless swell coefficient, ρ_s is sediment density, β is beach slope, d_{50} is median grain diameter, $H_{s,br}$ is the significant wave height at the breaker zone and V_{wave} is the wave velocity.

Waves sourced from a Delft3D wave model presented in Perry et al. (2024a) are introduced at 1km spacing from offshore locations in 4m water depth with a weighted distance method used to interpolate wave conditions between inputs. The ShorelineS model uses Snellius to compute the refraction from the wave condition extraction point (at the 4m depth contour) to the point-of-breaking at this site. The wave model includes swell boundary conditions from the CAWCR wave model (Smith et al., 2021) and reanalysis wind data from the ECMWF ERA5 model (Hersbach et al., 2018). The model outputs 4-hourly wave conditions using 4 nested grids with a 100m square grid cell size for the highest resolution grid in which results were extracted for the present study. The model was calibrated against measured wave conditions from wave buoys offshore of Brighton and Semaphore beaches on the Adelaide metro coast, data from these wave buoys is open source and publicly available at www.sawaves.org. Model validation compared modelled wave conditions with the Brighton and Semaphore wave buoys. For significant wave height, correlations of R=0.89 and R=0.88 were found for the Brighton and Semaphore buoys, respectively, with a bias of 0.14 m and 0.18 m. For mean wave direction, correlations of R=0.7 for the Brighton buoy and R=0.8 for the Semaphore buoy were found, with biases of 1.28° and -0.99°, respectively.

3.4 Shoreline evolution of Adelaide's managed beaches

3.4.1 Setting and wave conditions

Adelaide's managed beaches have been defined as the 28 km stretch of beach between Kingston Park and Outer Harbour (Department of Environment and Water, 2021a) (Figure 3-2). A dominant south-westerly wave direction causes sand to move in a net northerly direction (Harvey and Caton, 2012). There is minimal to no sediment supply from the nearshore and shelf in at least historic times, and likely for the past several thousand years (Short, 2012). The supply of sediment to Adelaide's beaches, originating from sand dunes and beaches to the south, has been starved in the last decades since the urban development of the coastline and the construction of numerous coastal structures. These structures interrupted the natural littoral drift of sand around the LeFevre Peninsula to the north (Harvey, 2006). This has resulted in the deployment of the current beach nourishment regime that moves sand trapped by structures in areas of accretion to areas of erosion (Department of Environment and Water, 2021b).

Figure 3-2 Study location (Australia boundaries from Australian Bureau of Statistics, July 2021). (A) Location within Australia, (B) Location with the Gulf St Vincent – South Australia, (C) Adelaide's managed beaches, (D-G) Photographs of select beaches along Adelaide's coastline (credit Department for Environment and Water (D – Semaphore Breakwater))

Adelaide's managed beaches are influenced by swell waves which diffract around Kangaroo Island and propagate through Investigator Strait into Gulf St Vincent (Figure 3-2) from a south-westerly direction, and local wind sea waves generated within the gulf. The mean annual significant wave height varies along the coastline between ~0.4m-0.5m at the 4m depth contour with associated annual mean period of varying from ~2.5-3.5 seconds (Perry et al., 2024a). Wave directions vary seasonally with local wind sea waves featuring a more significant northerly component over winter months and southerly component through summer months. Figure 3-3 displays modelled wave roses extracted from 3 locations along the coast (Perry et al., 2024a), showing the dominant south-westerly wave direction with a greater influence from northerly waves at the southern locations due to an increase in fetch across the gulf. The wave climate, including its spatial and seasonal variations in wave conditions along the coastline, is the driving factor for morphodynamic change.

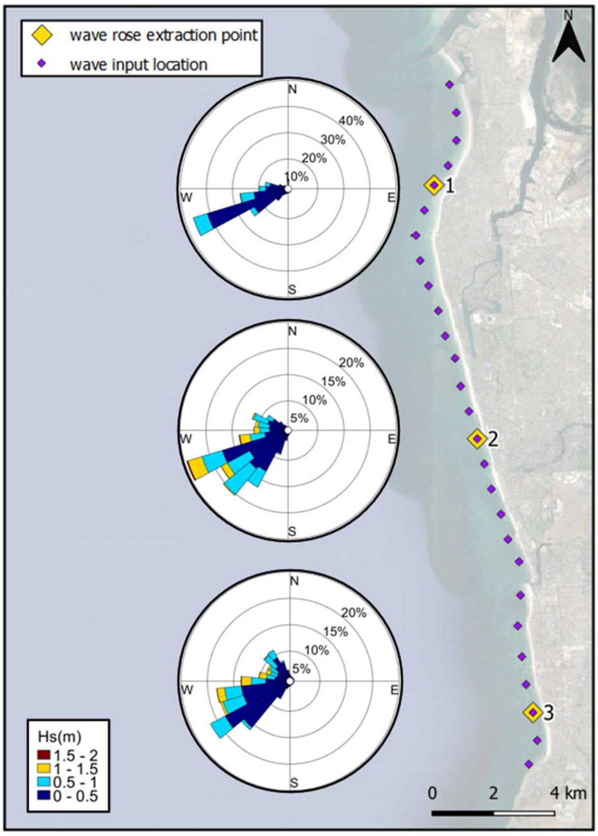

Figure 3-3 Wave climate along Adelaide's managed beaches. Extraction locations of modelled data (Perry et al, under review) shown by yellow diamonds and wave input locations for the shoreline model shown by purple diamonds.

3.4.2 Coastal management

Adelaide's managed beaches have undergone significant changes through time, some of these changes are due to the natural evolution of coast but change can also be attributed to human intervention. After European settlement in 1836, Adelaide's beaches, and particularly the adjacent dunes were used for mining, building and other activities with limited understanding about coastal processes (Department of Environment and Water, 2021a). Glenelg was formally settled in the 1840's with development extending to the rear of the beach. From the 1850's several timber and concrete seawalls were installed to manage erosion to these properties as well as jetties at Largs Bay, Grange, Henley, Glenelg and Brighton (Short, 2012). Development continued over the 20th century and by the 1970's the coastline had 12 km of seawall, six jetties, six groynes and two sets of training walls (Short, 2012). Beach nourishment became a key element of coastal management in 1973 following recommendations from Culver (1970) and has remained a key element of maintaining beach widths along the coastline, including a large-scale external source nourishment scheme in the 1990's. In 2013 a sand recycling pipeline became operational which is able to transport sand from Glenelg breakwater to southern beaches when required. The present-day coastal structures and beach nourishment locations along Adelaide's managed beaches are presented in Figure 3-4. Beach nourishment is performed regularly along the system with volumes rarely exceeding 100,000 m^3 with the notable exception of a series of larger nourishments (total of 1,150,000 m^3) applied to Brighton between 1990 and 1998 (Figure 3-4). The frequency of beach nourishment increased in late 2004 and has remained frequent to the present day.

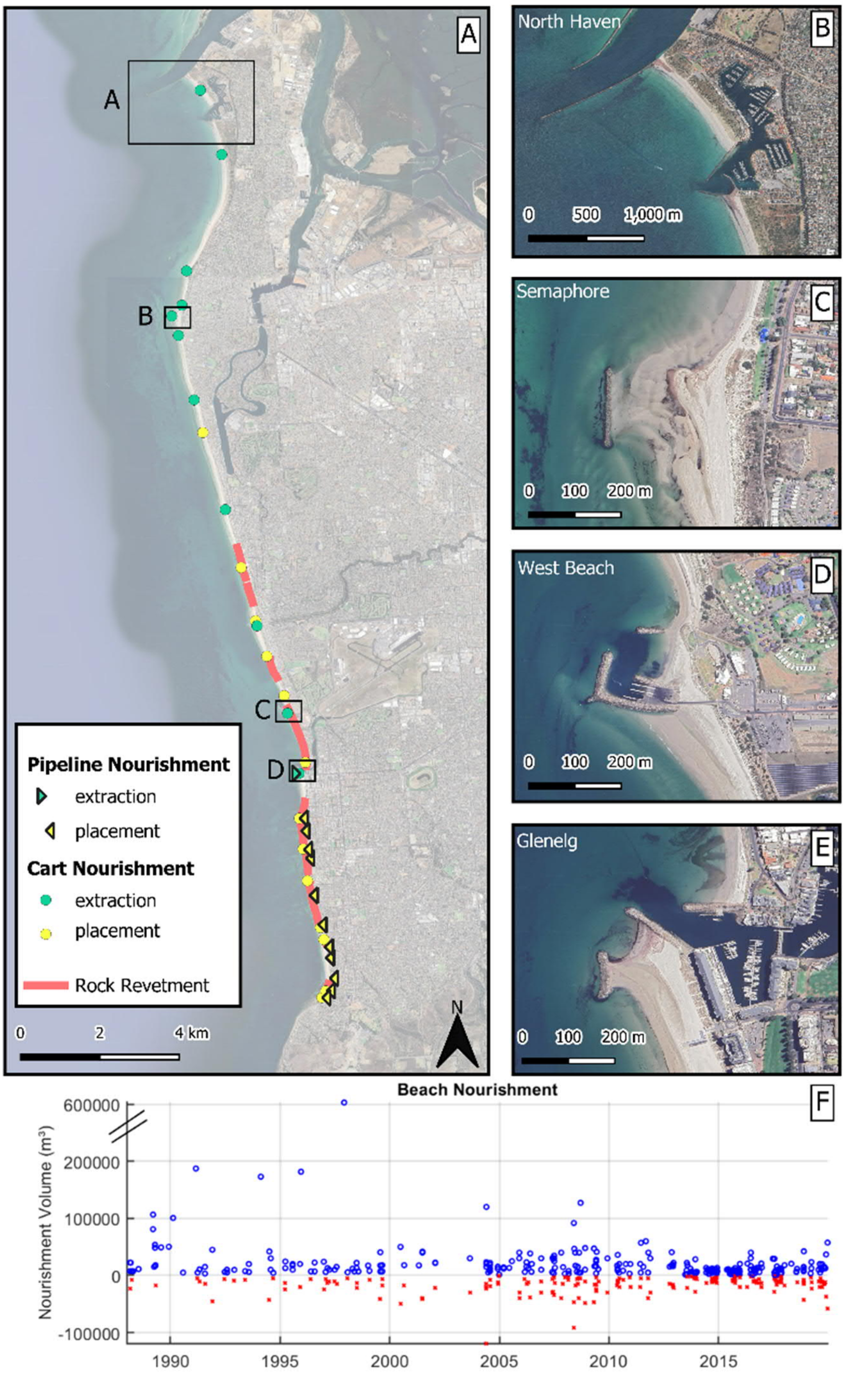

Figure 3-4 Coastal management of Adelaide's managed beaches – rock revetment extent, nourishment locations (A) and key structures (Outer Harbour and North Haven training walls (B), Semaphore offshore breakwater (C), West Beach boat ramp (D) and Glenelg marina (E)), panel (F) presents beach nourishment through time where negative (red) values represent sand extraction and positive (blue) represent sand placement from within the system.

3.4.3 Historical shoreline change

Shoreline observations have been performed on Adelaide's managed beaches since the establishment of a monitoring program in the 1970's by the South Australian Department of Environment and Water (Huiban et al., 2019). A series of beach transects are surveyed regularly and provide snapshots of shoreline location. Bishop-Taylor et al. (2021) presented an Australian continental data set of satellite derived shorelines, which included the Adelaide monitoring program as a validation dataset. This study found accretion rates as high as 3.5 m/year in northern regions near Largs Bay and erosion hot spots in North Brighton, Glenelg North, West Beach, Henley Beach South and north of the offshore breakwater at Semaphore.

Satellite derived shorelines provide spatially and temporally rich data, however, their accuracy and applicability to each site varies (Vitousek et al., 2023). For this reason, the satellite derived shoreline rates of change from Bishop-Taylor et al. (2021), as used in the current study, have been compared to rates from more accurate survey data collected on Adelaide’s managed beaches (see Figure 3-5) which provides more confidence in their use as a reference for modelled coastlines. Our finding was that of the 49 survey locations, 33 had a statistically significant shoreline change rate and were used in the verification process. Considering all survey locations, the Root Mean Square Error (RMSE) is 0.29 m/year with a Standard Deviation (SD) of 0.24 m/year and mean difference of 0.17 m/year. Zone 1 has the highest error across all metrics with a RMSE of 0.39 m/year, SD of 0.35 m/year and mean difference of 0.25 m/year. Zone 2 has a RMSE of 0.29 m/year, SD of 0.25 m/year and mean difference of 0.15 m/year. Zone 3 has the least error with a RMSE of 0.21 m/year, SD of 0.13 m/year and mean difference of 0.17 m/year.

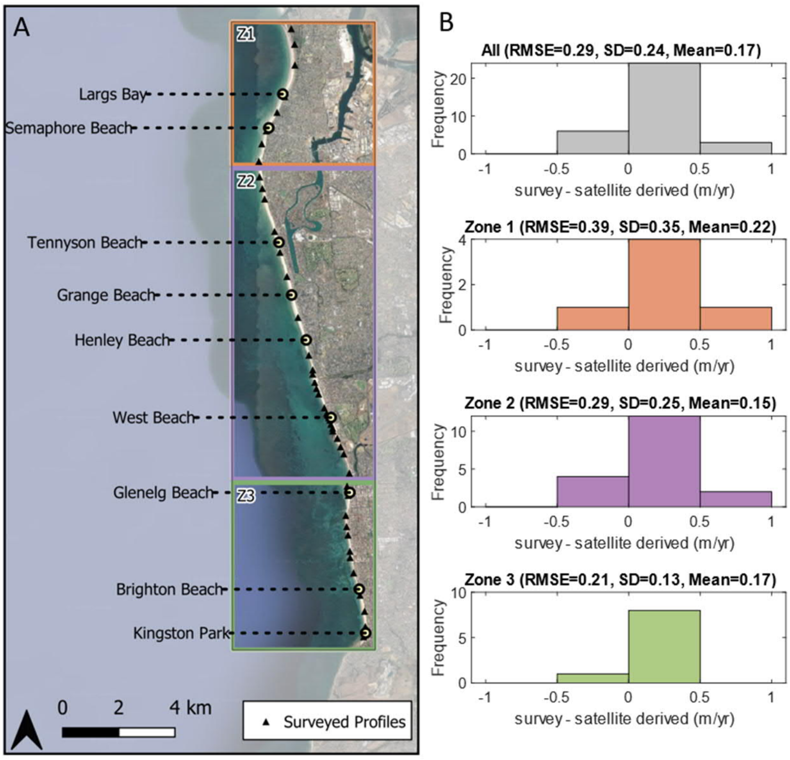

Figure 3-5 Satellite derived shoreline change rate verification histograms and statistics (Root Mean Square Error (RMSE), Standard Deviation (SD) and mean) – surveyed rate of change minus satellite rate of change at each survey location along Adelaide's managed beaches. Panel A shows zones and locations, Panel B presents histogram and statistics.

These linear trend analyses of survey and satellite derived shoreline positions describe areas with consistent changes through time with confidence. However, as standard practice when assessing shoreline change through a time period where development significantly alters the coastal processes, it is important to consider the temporal variability of shoreline change. Figure 3-6 presents the satellite derived shoreline positions around key structures on Adelaide's managed beaches. The trend at North Haven Marina is relatively stable with a consistent accretion of the shoreline throughout the 32-year time series. At the Semaphore breakwater the shoreline shape changed significantly post development of the offshore breakwater in 2005. After construction, the shoreline accreted significantly directly behind the offshore breakwater and to its southern side. This came at the cost of the beach North of the breakwater, which experienced significant erosion. A retreat of approximately 100 m was observed at a location about 300 m north of the breakwater. This interaction is likely influenced by both the offshore breakwater construction and the beach sand recycling strategy, which extracts the accreted sediment from behind the breakwater for nourishment of eroding beaches to the south. West Beach Boat Ramp and the Glenelg Marina experienced similar impacts to the shoreline position after their development in the late 1990's. In both cases sediment accumulates on the southern side of the structure and erosion has occurred on the northern side of the development, resulting in the need for sand bypassing and beach nourishment.

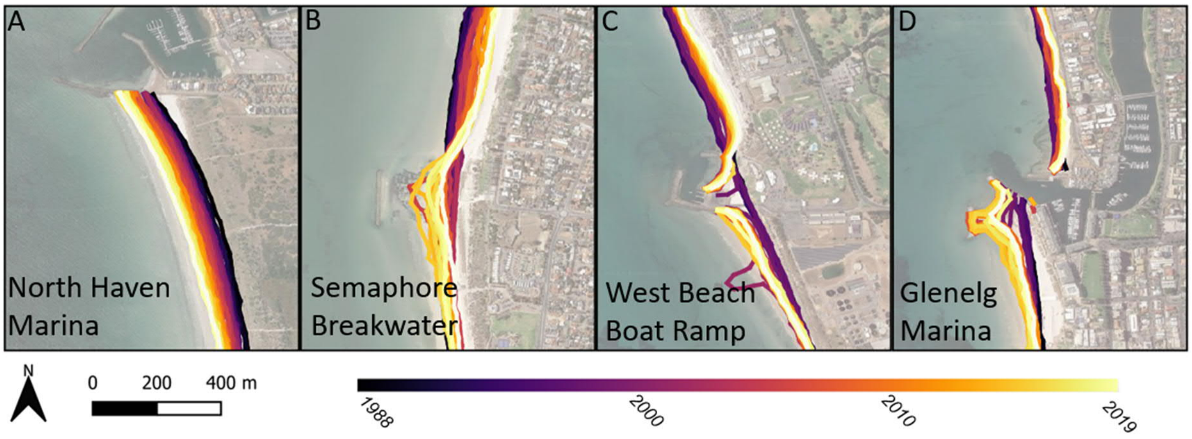

Figure 3-6 Satellite derived shoreline positions (from (Bishop-Taylor et al., 2021)), edited to remove shorelines across structures) at structures along Adelaide's managed beaches – (Panel A) North Haven Marina, (Panel B) Semaphore Breakwater, (Panel C) West Beach Boat Ramp and (Panel D) Glenelg Marina.

3.5 Results

3.5.1 Model calibration

Model parameters were calibrated to appropriately represent shoreline change at an acceptable computational cost. A significant contributing factor to computational cost is the choice of time step and initial space step, which also impact model stability. Several combinations were tested, but it was found that an initial space step of 100m and timestep of 0.001 years (~9 hrs) made for an appropriate balance of simulation time (less than 12hrs on desktop computer) and model resolution. Using smaller grid cells led to increased computational time and model instabilities. The appropriate longshore transport formulation was chosen based on a criterion of minimum required calibration to the model, which showed that VR14 (Van Rijn, 2014) was able to more accurately estimate transport without significant scaling compared to the CERC (Coastal Engineering Research Center, 1984) or Kamphuis formulations (Kamphuis, 1991). Using VR14 it was even found that model-wide calibration of transport scaling factors and modifications to wave directions only decreased model accuracy, which meant that the no calibration case of longshore transport formulation was in the end used. It is acknowledged that detailed interactions between the shoreline shape and individual structures could be improved, but these were not the considered the focus of this study and had limited larger-scale impacts. Although the bypassing of structures did influence shoreline change rates beyond the immediate impact of the structure, through the appropriate input of physical shoreline characteristics and structure properties (e.g. length, depth and conditions at tip etc) these bypass rates were represented reasonably without specific calibration. This is seen in the modelled volume changes in the different coastal cells of the Adelaide coast that aligned with measured total volume change. This brings confidence to the reliability of the simulations with structures removed as no shoreline change parameters required adjustment for the representation of structures.

3.5.2 Validation of modelled shoreline change

The validation of the modelling at Adelaide's managed beaches against satellite derived data shows that very similar shoreline trends are obtained by the model. The modelled and satellite derived coastline trends and data-set comparison statistics are presented in Figure 3-7. Across all validation zones, the RMSE is 1.22 m/year with a minimal bias of 0.14 m/year. The most significant bias occurs in in zone 3 where the model is underestimating landward shoreline change, which could be due to an overestimation of active profile height, an underprediction of sediment transport, or an over representation of beach nourishment. In most locations, the erosional or accretional trend is captured with the exception of Grange Beach and West Beach which lie in zone 2. At Grange Beach, a largely stable coastline was modelled, although an accretional trend has been captured in the satellite derived shoreline change rates. This discrepancy may be due to the under estimation of erosion at West Beach which is down drift of Grange Beach. This underestimation of erosion at West Beach could be due to a coastal process such as diffraction around the West Beach breakwater being inappropriately represented, or nourishment volumes have been misrepresented at this location (either by inaccurate historic records or model implementation) leading to an overestimation of seaward shoreline change.

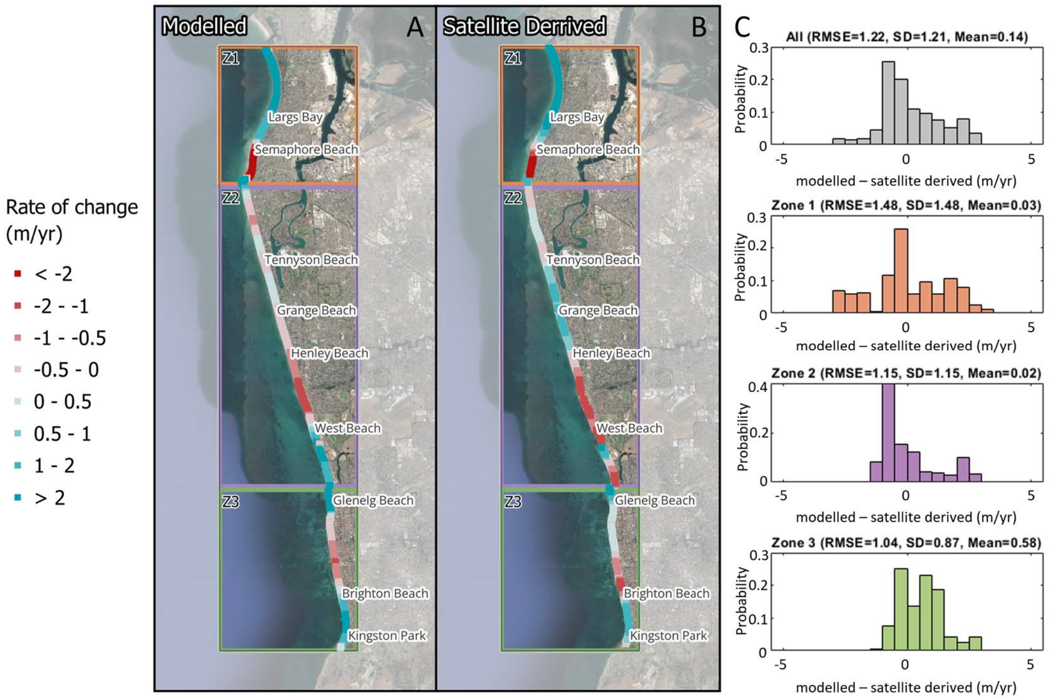

Figure 3-7– (A) Modelled and (B) satellite derived annual rate of shoreline change (m/yr) at 50 m transects along Adelaide's managed beaches, red indicates an erosional trend and blue indicates an accretional trend – (C) Modelled shoreline change verification histograms and statistics (Root Mean Square Error (RMSE), Standard Deviation (SD) and mean) presented for three zones

3.5.3 Variability of gross and net transport rates

Longshore transport rates are a critical input into the design of coastal engineering solutions (Sanil Kumar et al., 2003). Coastal structures which block longshore transport may result in down-drift beach erosion over hundreds of meters to kilometres with longshore transport rates playing a key role in the extent of this erosion (Leont'yev, 1999). In addition, longshore transport rates and gradients in combination with storm surge levels are the major design factors for beach nourishment design (Hanson et al., 2002).

Modelled longshore transport rates of the Adelaide system are presented in Figure 3-8. The spatially variable mean longshore transports in panel A were calculated as the mean transport at each node throughout the time series. The temporarily varying system-wide average transport rates presented in panels B-E were calculated as the mean value for each year or season considering all calculation nodes. Transport rates indicate that the net annual northerly median longshore transport for the system is between 75,000 m³/year and 98,000 m³/year. Mean transport rates vary significantly within the system, with areas such as Brighton Beach and Glenelg displaying a net northerly transport less than 40,000 m^3/year, while Semaphore Beach has a modelled net northerly transport of over 100,000 m^3/year. The significant spatial variation can largely be attributed to coastline orientation. Areas such as Semaphore Beach with a northwest shore normal orientation are more susceptible to high angle approach waves from the dominant southwest direction which increase northerly transport. The system transport rates align well with other studies of the annual longshore transport rates along the Adelaide coast (e.g. Huiban et al, 2019; Coastal Engineering Solutions, 2004). Huiban et al. (2019) estimated annual transport rates between 50,000 and 150,000 m^3/year for the system, while Coastal Engineering Solutions (2004) estimated the annual net longshore transport at 75,000 m^3/year for the system.

There is a considerable inter-annual and seasonal variability of the transport rates in Adelaide as a result of yearly varying impacts of atmospheric indices and the bi-directionality of the wave climate conditions (Perry et al., 2024a). Average-annual net transport rates for the considered period therefore vary between 44,000 m^3/year in 1997 and 144,000 m^3/year in 1989. Intra-year, the modelled median gross transport rate for the system is typically between 153,000 m^3/year and 199,000 m^3/year, but ranges from a minimum of 119,000 m3/yr in 1997 to a maximum gross transport rate of 232,000 m^3/year in 1989. Rates also vary seasonally with net northerly transport rates highest in summer (median 112,000 m^3/year to 151,000 m^3/year) and lowest in winter (-8,000 m^3/year to 57,000 m^3/year). In contrast, the gross transport rates are highest in winter (209,000 m^3/year to 282,000 m^3/year) and lowest in autumn (104,000 m^3/year to 171,000 m^3/year).

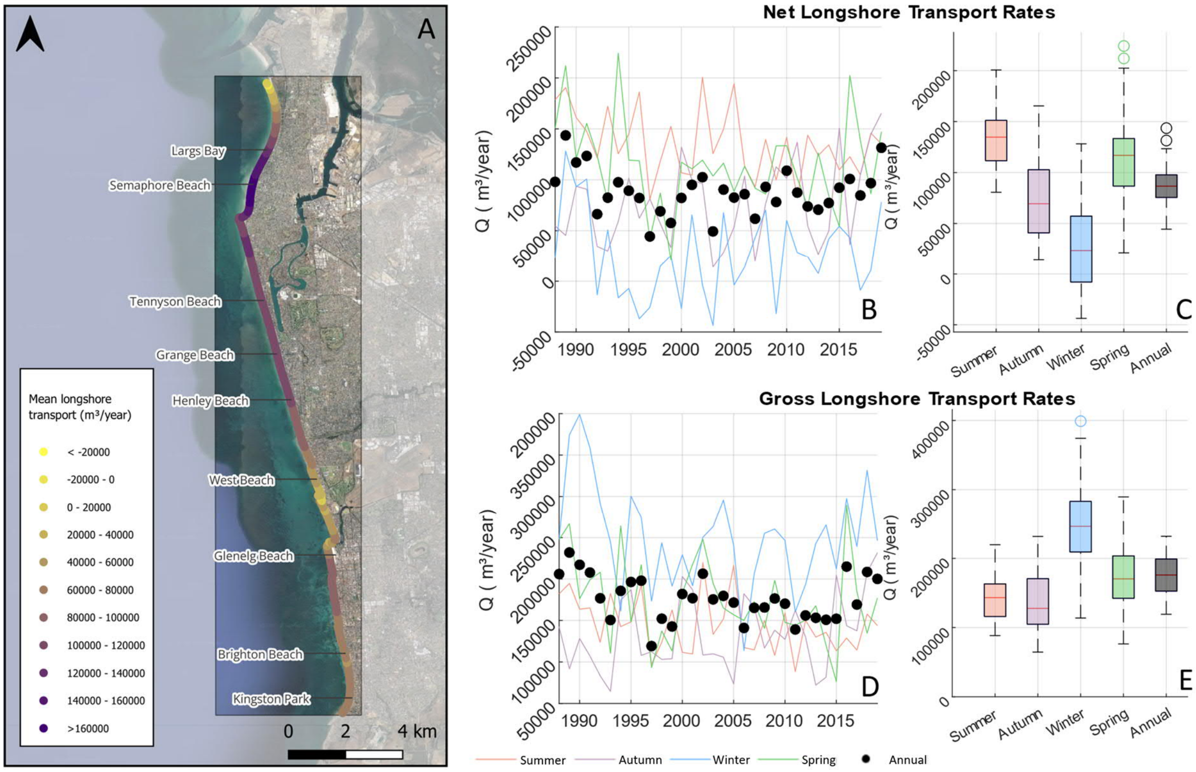

Figure 3-8 Modelled net and gross longshore transport rates along Adelaide’s managed beaches (1988-2019) where positive values of Q represent northerly transport. A: Mean net longshore transport at all locations. B & D: annual and seasonal northerly longshore transport rate variations (m³/year) through the simulation period for net and gross transport respectively over all locations. D & E: box plots of annual and seasonal transport rates (m³/year) for net and gross transport respectively over all locations.

3.5.4 Shoreline management assessment

The influence of coastal management measures on the stability of the coast is shown in Figure 3-9 for the scenario with all measures implemented (i), the scenario without nourishments (ii) and the scenario without any nourishments or coastal structures (iii). The mean rates of coastline erosion in the coastal segments are higher when nourishment is ceased (in scenario (ii)), with the exception of segment 6 on the updrift side of the Semaphore breakwater. This is most evident in segments 14- 16 and 22-24 which are frequently nourished locations. However, the accretion and erosion rates differ more significantly when structures are not included, with less obstructions such as seawalls to limit erosion extents throughout the simulation (scenario iii).

The most northern segments 1 to 4 show accretion trends in all scenarios with rates greater than 1.5 m/year in all cases. Segments 5-8 show erosion trends in all scenarios other than in the 1km segment where an offshore breakwater is present in scenarios (i) and (ii). The mean shoreline movement rate across this 4km stretch is -0.8 m/year in scenario (i) and (ii), while in scenario (iii), the mean rate is -1.1 m/year. Segments 9-14 are relatively stable across all scenarios with rates below 0.5 m/year. Segments 15-17 show erosion trends across all scenarios with the most significant erosion occurring in scenario (ii) where rates exceed 2 m/year without nourishment. This suggests that the presence of structures cause increased erosion in these segments, however, beach nourishment negates this impact. Segments 17-21 have erosion and accretion hot spots in both scenarios (i) and (ii) while without nourishment or structures in scenario (ii) the stretch has a dominant accretion trend. Segments 22-25 show an erosion trend across all model scenarios with the least erosion occurring in scenario (i) with rates below 0.3 m/year. Rates increase at hot spots in scenario (ii) without nourishment and significant erosion occurring in scenario (iii) without beach nourishment or structures with rates greater than 2.5 m/year. Segments 26 and 27 show accretion in all scenarios with the most significant accretion above 2 m/year occurring in scenario (i).

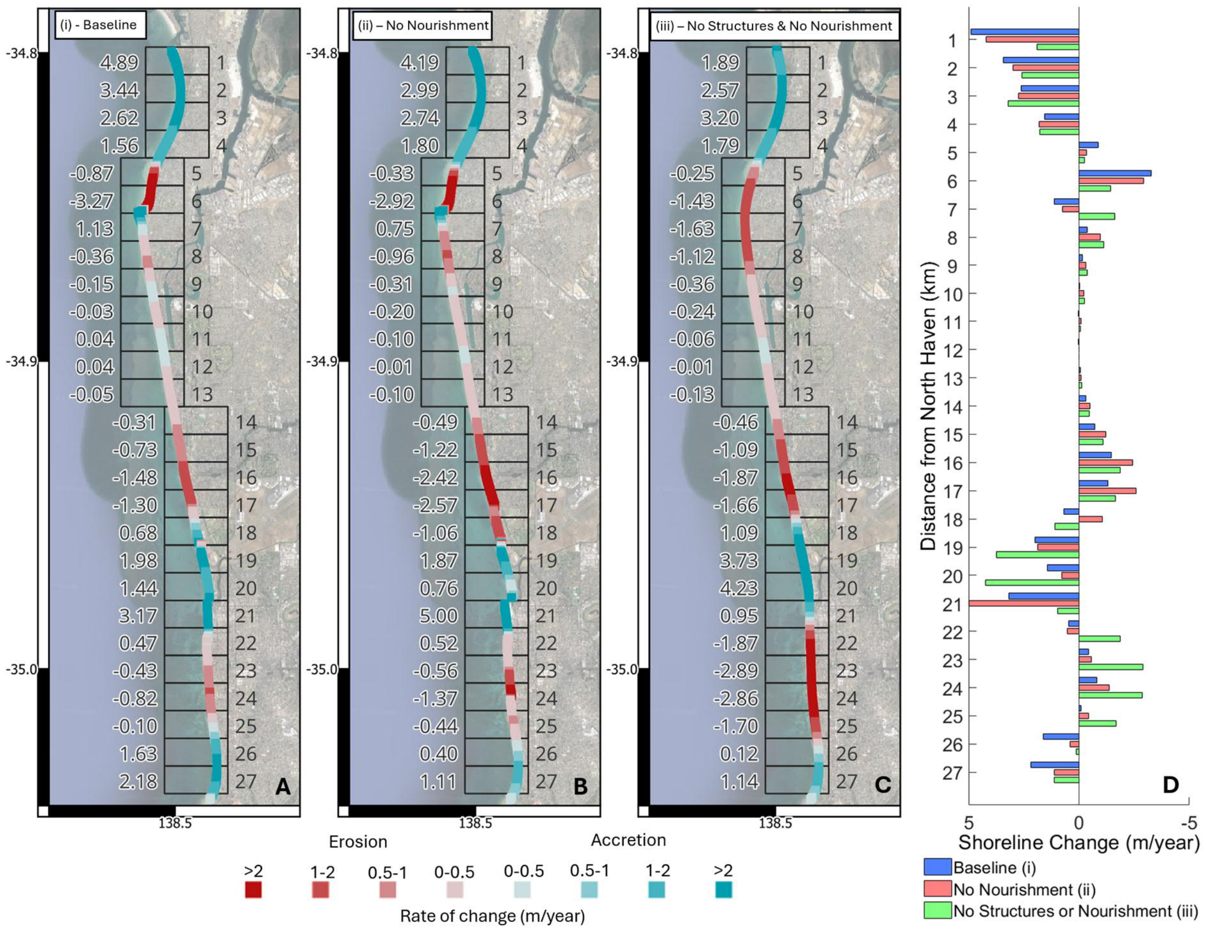

Figure 3-9 ShorelineS model derived rates of change (m/year) from 1988-2020 – (A) model scenario (i) baseline case including historic nourishment and structures, (B) model scenario (ii) baseline case without historic nourishment and (C) model scenario (iii) baseline case without historic nourishment or structures. Rates are plotted every 50m in panels A, B and C with mean values across 1km segments labelled in panels A, B and C. Panel D presents mean 1km segment rates from all scenarios.

Shoreline change at four locations has been presented in Figure 3-10 to highlight some varying impacts of shoreline management and show the temporal variation of shorelines throughout the simulation period. Location 1 highlights the net northerly migration of sand in this system with a steady increase in beach width over the simulation period regardless of management scenario. The results suggest that the implementation of structures has slightly decreased the accretion at this location, which is favourable as there is already sufficient sediment. Beach nourishments did not have a significant impact at Location 1.

Location 2 draws focus to the impact of building an offshore breakwater structure with significant accretion updrift of the structure and erosion just north on the downdrift side. This 220m long offshore breakwater was constructed in 2005 with the intention of protecting the eroding coast and trapping sand to be used for beach nourishment. Without the presence of the offshore breakwater, results suggest this location would still be eroding, however, with the breakwater, erosion rates are significantly increased. At this location, sediment mining associated to beach nourishment slightly increases the updrift erosion as sediment is removed from the lee of the offshore breakwater.

Location 3 shows the impact of the West Beach marina with significant accretion on the southern side of the marina and instability on the northern side. This marina offers protection to a boat ramp with a breakwater on the southern side extending ~270m seaward of the dune toe and a smaller breakwater on the northern side extending ~90m from the dune toe. At this location it is clear that without beach nourishment the beach width quickly erodes, however, with no structures blocking the northern flow of sediment, nourishment would likely not be required at this location.

Location 4 highlights a typical section of coast in the south of the system where there is an erosional trend, regardless of structures. At this location there are no downdrift, shore perpendicular engineered structures blocking longshore transport, however infrastructure has been built in close proximity to the coastal edge which is armoured by a rock revetment. Similarly to location 3, without beach nourishment, the beach widths in this section of coastline would erode and not recover. The impact of the large beach nourishments on the southern section of the coast in the 1990’s is also evident at this location.

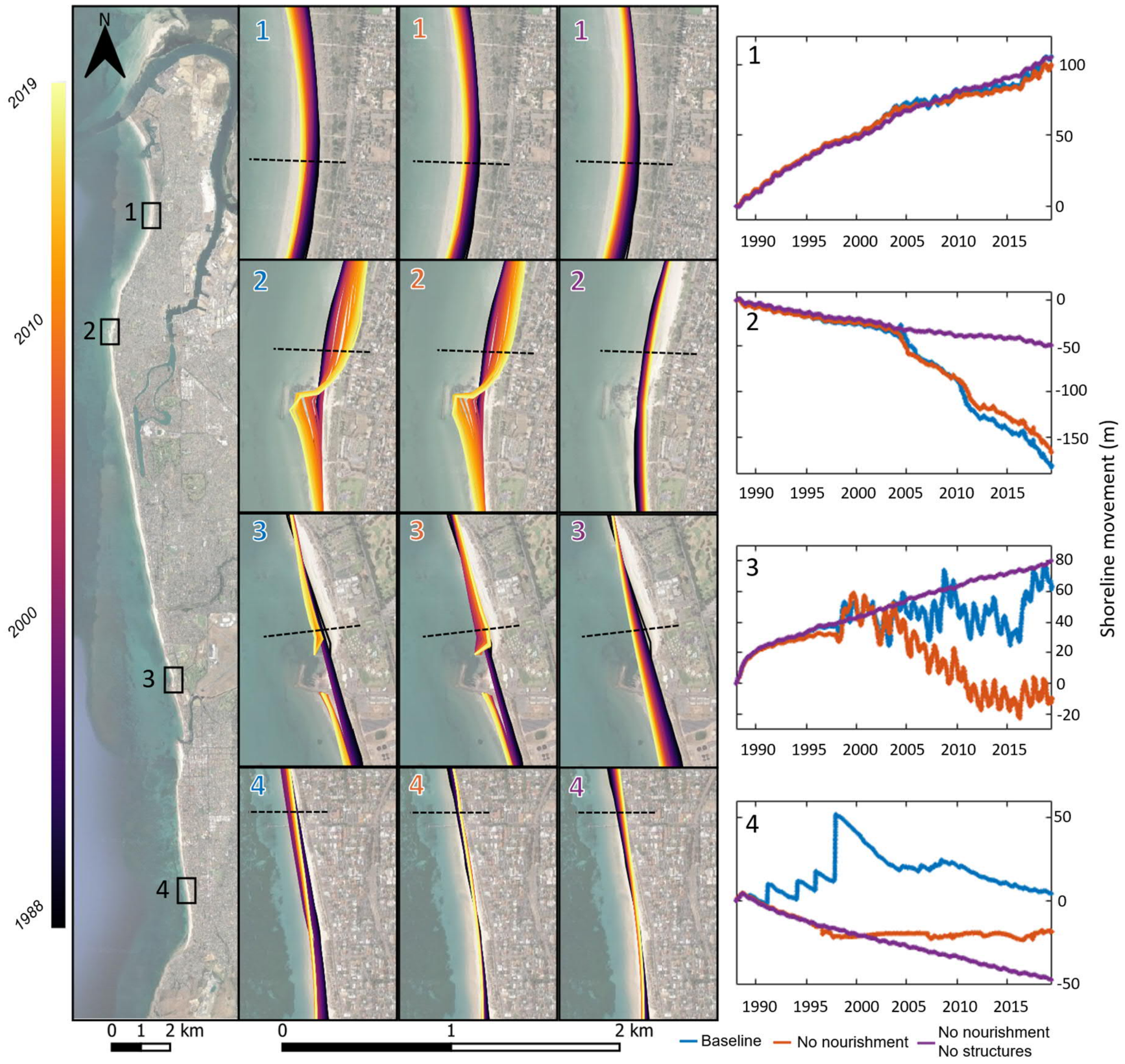

Figure 3-10 ShorelineS modelled shoreline change at locations (1 – Largs Beach, 2 – Semaphore breakwater, 3 – Glenelg North, 4 – Brighton Beach) between 1988 and 2019. Blue labelled panels/shoreline movement plots show baseline conditions with nourishment and structures implemented. Orange labelled panels/shoreline movement plots show the case with not nourishment implemented. Purple labelled panels/shoreline movement plots show the case with no nourishment and no structures implemented.

The mean shoreline change rates presented in Figure 3-9 and detailed examples presented in Figure 3-10 offer insight into the efficacy of shoreline management in Adelaide. Beach nourishment reduces the rate of erosion at the places where it is applied and seldomly causes an erosional trend in the accretional areas sediment is sourced from. The success of both mass nourishment campaigns in the 1990's and regular sand recycling are highlighted in these results and particularly evident in panels 3 and 4 of Figure 3-10. Coastal structures which block or impede longshore transport have a large impact on the local coastline trends, as the updrift beach typically accretes at the cost of amplified erosion on the downdrift side.

The modelled scenario without beach nourishment and structures highlighted sections of coast which are prone to erosion irrespective of structures, with the highest rates of erosion modelled in the southern region approximately adjacent to Brighton Beach (segments 22-25) with erosion rates of up to 2.5 meters per year. The section of coastline between Glenelg and West Beach (segments 18-20) has two key structures (shown in panels D and E of Figure 3-4) which modify the longshore transport of sand. The model results suggest that without beach nourishment in these areas, the shoreline would retreat to the revetment, as displayed in location 3 on Figure 10. However, the modelled scenario with no structures or nourishment suggests that without structures in this area, nourishment would not be required and the stretch of coastline would be accretional, but in this case the erosion is then taking place south of this area.

3.6 Discussion

This study presents a methodological framework to assess the shoreline change rates of a managed coastline. The outcomes from this methodology present coastal managers with an opportunity to understand the underlying rates of coastal change, independent of existing management regimes, to gain insight into the impacts of management decisions. It allows the efficacy of coastal management to be assessed against a true baseline rather than one impacted by existing management. For example, ongoing beach nourishment at a location which continues to experience erosion may be seen as a failure unable to revert the trend, while in practice it does reduce erosive gradients substantially compared to a no-management baseline. The methodology equips coastal managers with a tool that does not require extensive data collection or computationally expensive models to showcase the different outcomes of management strategies.

The shoreline evolution model used in this study is ShorelineS (Roelvink et al., 2020). Given the recent release of the open-source model ShorelineS, this study acts as a valuable validation case for a long coastline with narrow beach widths and complex management scheme. The methodological framework presented in this study can be executed with alternative shoreline models. In this case ShorelineS was considered the most suitable, as the model could be extended with a module that can realistically capture alongshore variation of the active profile height at

Adelaide. Another practical consideration was that coastal structures and their effect on wave diffraction and bypassing could be rather easily incorporated in ShorelineS. It is noted that the modelled structures were not calibrated, and as a consequence the coastline does not exhibit a precise resemblance in the shaded zone of the structure, but a slightly too large or too small local accretion did not meaningfully affect the larger scale behaviour of the coastline. It concerns only a part of the volumes in these shaded zones, which are relatively small (a few thousand m^3 uncertainty in the sand volume in these curved coastal areas) compared to the continuous longshore transport rates and nourishment efforts.

The focus in the current study on yearly to decadal timescales also alleviates concerns with respect to the ability of one-line models in representing short-term (daily) coastline variations and cross-shore variability of the shoreline, which are not a strong-point of one-line models. The inherent assumption in one-line modelling is that cross-shore processes are less significant at a sufficient time scale in which longshore processes are the primary driver for shoreline change, which is even considered the case for long-term development of sand nourishments.

The methodology proposes a two-stage verification process. First, verifying that the selected satellite derived shoreline change rates are suitable for the shoreline of interest based upon in-situ measurements (where available). Second, verifying that the shoreline model suitably predicts shoreline change rates consistent with rates determined from the satellite derived shoreline positions. In the case of Adelaide’s managed beaches presented in this study, satellite derived shoreline change rates from Bishop-Taylor et al. (2021) were favourably compared to 33 surveyed transects across the 28 km of coastline. A slight overvaluation of erosion or undervaluation of accretion was consistent over all three zones; This was most significant in zone 1 (Figure 6) where the error in the average rate of coastline change was 0.22 m/year. This slight overestimation of erosion is consistent with the validation results performed by Bishop-Taylor et al. (2021) where a bias of 0.08 m/year was found across 9 validation sites in Australia. Verified satellite derived shoreline change rates were compared to modelled shoreline change rates. As highlighted in previous studies including Huiban et al. (2019) the northern region of this coastline has had a steady accretional trend (segments 1-4) with a satellite derived rate of 2-3.5 meters per year in the area. The model results from this study largely captured this trend with modelled rates of 1.5-2.8 meters per year. As evident in Figure 7, the accretion and erosion patterns were generally in agreement along the coastline, other than a relatively stable area in the central region of zone 2 where some accretional areas were not represented in the model. Across all validation zones the RMSE is 1.22 m/year with a minimal bias of 0.14 m/year. However, a positive bias of 0.58 m/year was calculated for zone 3. This bias relates to an approximate modelled volume misrepresentation of 25,000 m^3 of sediment per year in this zone (~28% of net northerly transport) which is significant, but too small to meaningfully impact the conclusions of this study.

A limitation to the validity of the ‘no structure’ scenario is the assumption that shorelines are able to continue to retreat, regardless of the site setting. As in reality, shorelines may continue to retreat until they are starved of sediment and/or reach a geological constraint such as bedrock. In addition, the no structure case does not consider disequilibrium in the shoreline position and potential changes to active profile height compared to the case where structures had never been installed. Though these assumptions are relevant for the Adelaide coastline, the shoreline change rates derived from this scenario are informative nonetheless for comparison to rates with management incorporated. An additional limitation is the requirement for measured shoreline positions. Using the satellite derived shoreline positions in addition to available measured shoreline positions has improved the understanding of the temporal variations in coastline positions. Though it would be possible to execute this methodology without validating satellite derived shoreline positions, there would be significantly reduced confidence that modelled shoreline change rates are representative of reality.

This study assessed shoreline management on Adelaide’s managed beaches. Recommendations from the first formal coastal processes study by Culver (1970) suggested that beach nourishment should be used as an alternative to hard structures to maintain recreational beach widths along the coastline. Since this recommendation, there have been a number of studies and smaller scale modelling exercises which have reinforced this notion (Department for Environment and Heritage., 2006, Kærgaard, 2018, Tucker, 2007). The results of this study also suggest that beach nourishment is required in order to maintain recreational beach widths along the entirety of the coast. In all cells with an erosive trend (aside from cells 5 and 6) presented in Figure 3-9, the rate of erosion with nourishment included is reduced. The management induced an increase in erosion in cells 5 and 6 that can be attributed to the updrift impacts of the Semaphore offshore breakwater and associated nourishment source location. The results suggest that it is not possible to preserve the coastline with breakwaters alone, since they create downdrift effects. Due to the net northerly transport of sand in this system, significant erosion is experienced on the northern, downdrift side of these structures with beach nourishment required to maintain beach widths. They are useful for redistributing effects alongshore but cannot solve a deficit for the coastal cell. This is particularly evident on the northern side of Glenelg marina where (as shown in panel C of Figure 3-10), nourishment is required to maintain recreational beach widths. A key takeaway from the simulation with management removed, is that there are extents of this coastline which are subject to erosion without the impact of management. Though this conclusion is somewhat trivial to coastal practitioners with a knowledge of coastal processes, the ability to quantify this is critical in the communication of efficacy of management to the community. It allows coastal managers to show that there are dominant drivers for coastal change, outside of the coastal management strategy in question. For example, cell 24 from Figure 3-9 shows an erosional trend in all three simulation results. On the surface, it may seem that beach nourishment is then ineffective at this location, however quantifying the erosion rates without nourishment suggests that the nourishments and structures have been able to reduce shoreline recession rates from 2.86 m/yr to 0.82 m/yr.

The findings from this investigation on Adelaide’s managed beaches quantify the efficacy of management solutions on an actively managed sandy coastline. The modelled scenarios in this study provide a better basis for the evaluation of different management strategies, which is difficult to achieve on the bases of just the measured data, as measured rates are inherently impacted by nourishments and structures. Also, future scenarios can be assessed with numerical models. For example, to explore management pathways wherein nourishment is continued but a hard structure is removed as part of a managed retreat exercise. Although not explicitly investigated, even the options for managed retreat could be considered in some places based on the no nourishment scenario. The outcomes from the Adelaide case study highlight the success of an active nourishment strategy where relatively small volumes of sand are regularly applied to the coastline by sand carting and a sand pipeline to maintain recreational beach widths. Regular small-scale nourishments are effective at Adelaide to maintain beach widths and reduce erosion rates. An important consideration that also has to be taken into account in practice when deciding on a nourishment strategy is the availability of offshore sand sources, which is especially the case for large scale measures which may not be feasible due to limited sand availability or concern over ecological impacts. At the same time managed retreat policies, sometimes with removal of existing coastal defence structures, will be politically difficult to realize. Decisions on nourishments are therefore not only dependent on the local environmental characteristics and technical capabilities, but also related to local governmental policies.

3.7 Conclusion

This research advances the understanding of shoreline management for Adelaide’s managed beaches in South Australia. A numerical model-based methodology is used (using the ShorelineS model) to assess the historic changes of the coastline, which were verified against satellite derived shorelines and survey data. The recently released, open-source ShorelineS model was found to appropriately represent shoreline change rates at a yearly to decadal timescale with minimal calibration effort. The scenario with the historic management of the shoreline is compared to scenarios wherein the beach nourishment and coastline structures (i.e. groynes, breakwaters and revetments) are removed to assess the performance of these measures. For Adelaide’s managed beaches it was found that the sandy coastline requires active beach nourishment to maintain beach widths. In some locations, beach nourishment is only required due to the implementation of hard structures, however, other locations were found to require nourishment to maintain beach widths regardless of the presence of coastal structures. In addition, the study was able to quantify the spatial and temporal fluctuations in longshore sediment transport. The median net northerly longshore transport considering the entire system was found to be between 75,000 – 98,000 m^3/year with significant seasonal fluctuations as well as the mean annual transport varying spatially within the system by as much as 60,000 m^3/year. The novelty of this study does not lie specifically in a single element of the methodology, rather the integration of this process utilising the recently released ShorelineS model to inform the efficacy of coastal management at a yearly to decadal timescale. This kind of assessment is useful for coastal managers to gain a system perspective of their management, rather than a typical assessment of an individual structure or management practice, as local measures impact the regional scale sediment balance.

CHAPTER 4.

Accepted article (Perry et al., 2024b)

Statement of co-authorship – I lead the research design and writing of this chapter. Mentorship, advice and editing of material was performed by co-authors. All contents of this chapter were ultimately my decision after consultation with PhD committee.

Perry (80%), Huisman (5%), Roelvink (5%), Hesp (5%), Miot da Silva (5%).

Investigating Southern Annular Mode (SAM) as a driver for longshore transport on Adelaide's managed beaches in South Australia

4.1 Abstract

A one-line shoreline hindcast model has been utilised to investigate the temporal variability and climatic drivers of shoreline change on Adelaide's managed beaches in South Australia. This coastline is a 28km long, highly developed, sandy beach shoreline with a number of coastal management interventions including rock revetments, training walls, offshore breakwaters and beach nourishment aimed at maintaining beach widths. There is a seasonally varying longshore transport gradient with a net northerly direction, which results in the erosion of southern beaches and shorelines downdrift of hard structures. The bimodal wave climate, which drives the longshore transport, is significantly correlated with the climate drivers in the region (the Southern Annular Mode, Indian Ocean Dipole and Southern Oscillation Index). In this study a 32 year hindcast time-series of longshore transport rates have been deduced for the system as well as spatially along the extent of Adelaide's managed beaches and correlated with the Southern Annular Mode (SAM), which is the most relevant anomaly for the longshore transport. The correlation between SAM and (northerly) transports is typically weak to moderate, but varies spatially with correlation coefficients as strong as 0.6 for the beach section north of Semaphore. Visualizations are made for the

temporal and spatial relationship between the Southern Annular mode and the net, gross, southerly and northerly longshore transport, showing that gross and northward transport decrease with a strengthening of SAM, while southern transport increases with strengthening of SAM. This implies that less erosion of the recreational beaches takes place if SAM strengthens. Wave climate indices can thus have a substantial impact on coastal management requirements for the coastline. How SAM will change in the future as a result of climate change is, however, not understood well, and will be key for understanding future scenarios for Adelaide.

4.2 Introduction

Longshore transport plays a critical role in formation of sandy shorelines and is a key consideration in coastal management. It is of particular importance for the implementation of beach nourishment schemes or hard structures which block longshore transport. In the case of beach nourishment, longshore transport rates can inform the nourishment required to maintain shoreline position. For hard structures, the quantification of longshore transport rates can inform how much updrift accretion and downdrift erosion can be expected. Breaking down longshore transport rates into net transport, gross transport and directional transport at both annual and seasonal scales can give extensive insight into the requirements of coastal management for a system to maintain recreational beach widths.

In many cases the dominant driver for longshore transport rates on a coastline is the wave climate. Even subtle changes in wave climate can have the potential to result in erosion or accretion of sandy coastlines and impact communities (Splinter et al., 2012). A number of factors influence wave conditions at a variety of timescales. The focus of this paper’s analysis is to relate seasonal to annual fluctuations in longshore transport to the wave climate conditions, therefore the understanding factors influencing the wave climate at these scales is critical. Perry et al. (2024a) performed a study on various climate drivers, relevant to southern Australia to find relationships between these drivers and anomalies in the wave climate. The Southern Annular Mode (SAM), Indian Ocean Dipole (SOI) and Southern Oscillation Index (SOI) were correlated against annual and seasonal anomalies in wave height and direction spatially across the Gulf St Vincent in which

Adelaide’s managed beaches lie. It was found that SAM correlated most significantly with both wave height and wave direction anomalies in the gulf.

In order to evaluate the effects of wave conditions on seasonal to annual scale shoreline dynamics it is required to have either measured or modelled transports. In practice, directly measuring shoreline positions from survey data or satellite derived data is effective, however, it often lacks the spatial or temporal resolution required to understand seasonal fluctuations. In part this is due to the management of the beaches that is inherently incorporated into these measurements, which further complicates obtaining understanding of the underlying drivers from the measurements. Numerical models therefore offer a more useful tool to assess the influence of wave climate drivers on seasonal to annual transports. There are an array of numerical models available to understand morphodynamic change, all with a varying consideration of coastal processes at a range of computational expense. These complex processes are, however, not needed to assess the dominant longshore transports and may even complicate understanding. One-line models which simplify the coastline to a single line with fixed coastal profiles (Kristensen et al., 2011) can be used for this purpose. Perry et al. (Under Review) showed that ShorelineS (Roelvink et al., 2020) could be used to investigate the efficacy of coastal management schemes on Adelaide’s managed beaches.

This study explores relationships between the seasonal to annual anomalies and SAM for Adelaide’s managed beaches in South Australia (see Figure 4-1) using the longshore transport model by Perry et al. (Under Review). The aim is to link beach dynamics to climate indices as was done in other studies (e.g. Splinter et al., 2012), but in this case making use of directional transport from models. Finding relationships between longshore transport and SAM aims to assist coastal managers to understand the causations for seasonal to annual variabilities and help forecast potential nourishment requirements.

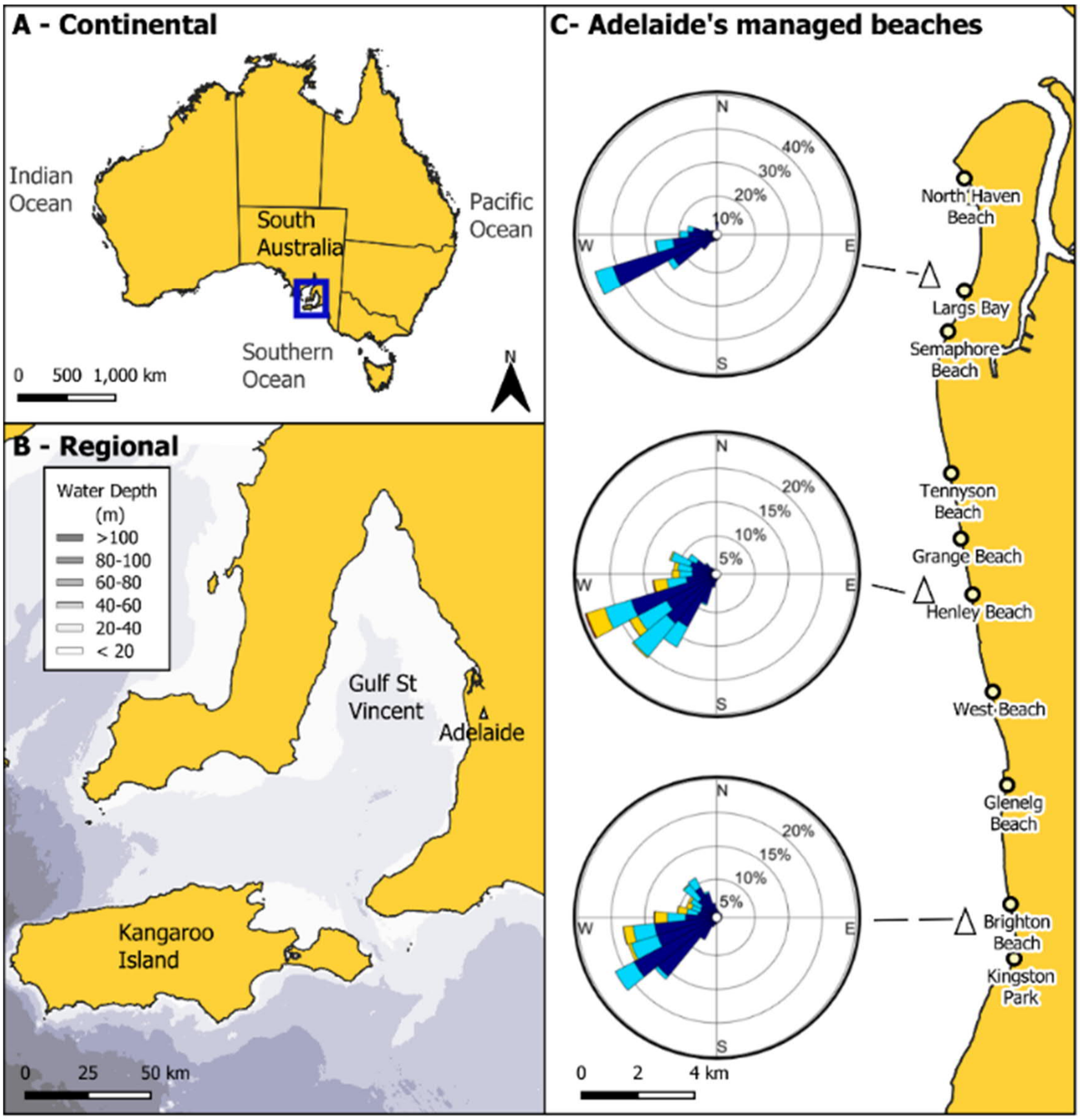

Figure 4-1 (A) Continental scale study location, (B) Regional scale study location including depth contours (from (Geoscience Australia, 2009)), (C) Local scale study location map including beach locations and modelled wave roses (from (Perry et al., 2024))

4.3 Methods

The study location is Adelaide's managed beaches which lie on the eastern side of the Gulf St Vincent in South Australia (see Figure 4-1). The Gulf St Vincent is partially protected from Southern Ocean swells by Kangaroo Island which lies to its south, however swells from a south westerly direction are able to propagate into the gulf and influence the wave climate on Adelaide's managed beaches. Locally generated sea waves from seasonally varying dominant wind directions also form part of the wave climate, where northerly conditions become more prevalent in winter than the summer months. The resulting wave climate is bi-modal with a south westerly dominant direction which drives a net northerly longshore movement of sand. This transport gradient leads to erosion of southern beaches and accretion of northern beaches which requires active management to maintain recreational beach widths. This necessity for management, along with requirements for ports and marinas has led to the construction of various coastal structures and a complex beach nourishment campaign.

4.3.1 Longshore transport model

Perry et al. (Under Review), developed a one-line coastline model using ShorelineS for Adelaide's managed beaches. A key output from this modelling exercise was the rate of longshore transport across the 32-year modelling period which is analysed further in this study. The model extends across 28km of shoreline from Kingston Park to North Haven with a space step of 100m and time step of 0.001 years (~9 hours). Structures including rock revetments, groynes and offshore breakwaters are implemented in the model, along with the beach nourishment regime. Longshore transport was computed according to Van Rijn (2014) with wave inputs every 1km along the shoreline extent.

4.3.2 Southern Annular Mode

The SAM index describes variations of the Southern Annular Mode which encompasses the extratropical region of the southern hemisphere (Fogt and Marshall, 2020). It encompasses the zonal mean atmospheric conditions between the mid latitudes and Antarctica which control a band of westerly winds that shift between Antarctica and Australia (Marshall, 2003). A positive SAM index relates to this westerly wind belt moving south towards Antarctica, while a negative SAM index relates to the westerly wind belt moving towards Australia. Perry et al. (2024a) found that the SAM index had an inverse correlation with annual wave height and direction anomalies. This suggests that when SAM is positive, wave heights decrease and wave direction becomes more southerly. This same relationship was also observed at a seasonal scale for the summer, winter and spring seasons.

4.3.3 Correlation analysis

Longshore transport rates from the shoreline model presented in Perry et al. (Under Review) were correlated against the SAM index with the aim of showing the impact of this climate anomaly on the magnitude and direction of the longshore transport. This analysis considers net transport, gross transport, northerly transport and southerly transport at seasonal and annual timescales. Note that southern hemisphere seasons are defined as summer (December, January and February), autumn (March, April and May), winter (June, July and August) and spring (September, October and November). Net transport is calculated as the mean transport, gross transport is calculated as the mean of absolute transport, northerly and southerly transport is calculated as the mean of only positive (northerly) or negative (southerly) transport divided by their prevalence. Annual anomalies for the system were calculated first as the difference between the annual mean and long-term mean of the longshore transport across the model nodes for each timestep. These regionally-aggregated transport rates were then plotted against the SAM index and correlations were calculated. Transport rates (net, gross, northerly and southerly) were then calculated also for each of the alongshore nodes of the shoreline model through the entirety of the hindcast to provide more detail in the alongshore differences in the response to the SAM index. Both the seasonal and annual anomaly time-series were computed and correlated with the SAM index to find correlations. These correlations were then mapped to investigate spatial variations in correlations.

4.4 Results

4.4.1 Annual system correlations

Relationships were found between the SAM index and system sediment transport anomalies with their time series presented in Figure 4-2. The mean anomaly of the longshore transport varied on average 12 to 19% from the mean, with max anomalies of up to 59% of their respective mean longshore transport type (Table 4-1).

Table 4-1. Longshore transport anomaly variations

Longshore Transport (m^3/yr)	Mean (m^3/yr)	Mean anomaly (m^3/yr)	Max anomaly (m^3/yr)
Northerly	137,763	18,224 (13%)	54,559 (40%)
Southerly	45,217	7,743 (17%)	20,679 (46%)
Net	92,546	17,462 (19%)	54,685 (59%)
Gross	182,980	21,487 (12%)	61,930 (34%)

Significant correlations were found with greater than 98% confidence for southerly transport and gross transport. For northerly transport the significance was ~90%, while the correlation with net transport was not found to be significant. Northerly transport decreases when SAM is positive, while southerly transport increases when SAM is positive. Gross transport has a negative correlation, suggesting that when SAM is positive, the absolute transport of the system increases.

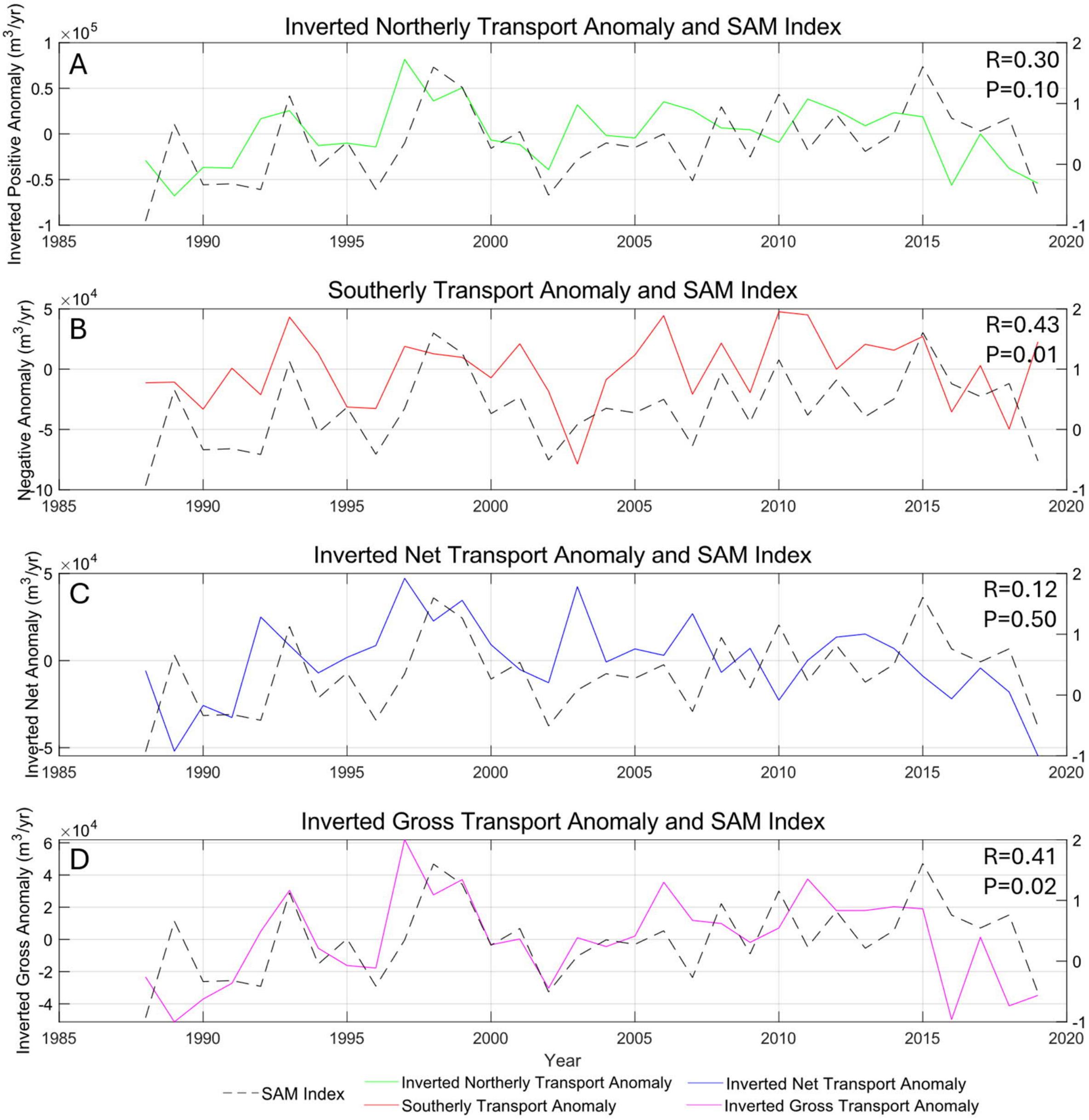

Figure 4-2 Time-series plots of system longshore transport anomalies and SAM index, including correlation between data sets (R) and associated P-value. (A) Presents the inverted northerly transport anomaly time-series, (B) presents the southern transport anomaly time-series, (C) presents the inverted net transport anomaly time series and (D) presents the inverted gross transport anomaly time series.

4.4.2 Annual spatial correlations

Relationships were found between the SAM index and annual sediment transport anomalies locations across Adelaide's managed beaches and presented in Figure 4-3. Significant correlations were found between all transport types and the SAM index, however the significance of these correlations varies. Considering net transport, the most significant correlations were found in the north westerly facing stretch of shoreline adjacent to Semaphore where inverse relationships as strong as R=0.55 are observed. Significant correlations greater than R=0.4 were also found at the northern and southern extents of the model where there are direct correlations in Largs Bay and inverse correlations at Kingston Park. Only relatively minor and insignificant correlations were found at other locations considering net transport. Considering gross transport, a relatively consistent and significant inverse relationship can be observed along the entirety of the shoreline. This indicates that when SAM is negative, transport rates increase at all locations across Adelaide's managed beaches. Considering the northerly and southerly directional transports, a spatially consistent inverse correlation is found for northerly transport while a direct correlation is found for southerly transport.

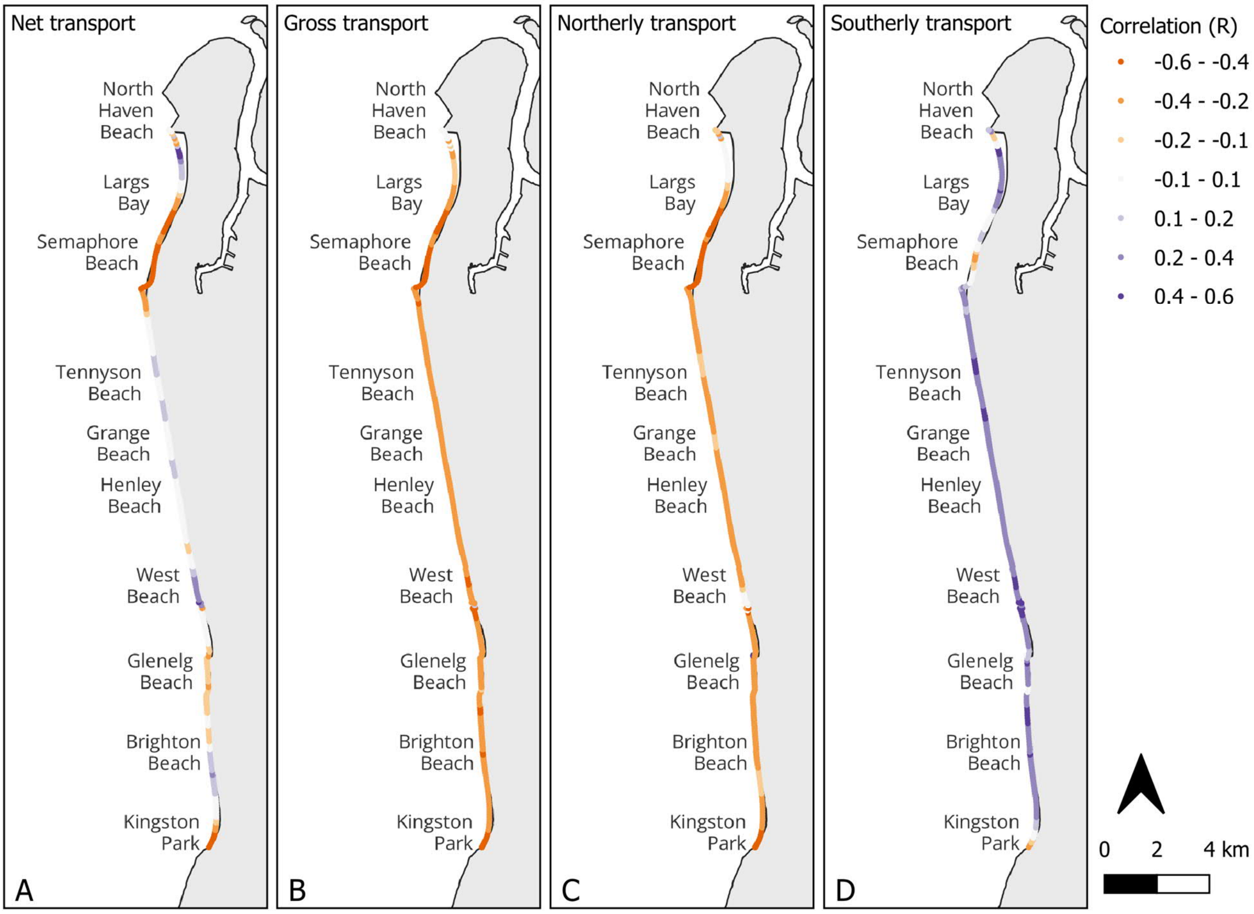

Figure 4-3 Spatial variations in correlations considering net (A), gross (B), northerly (C) and southerly (D) longshore transport with the SAM index.

4.4.3 Seasonal spatial correlations

Relationships were found between the seasonal anomalies in longshore transport and the SAM index, which are presented in Figure 4-4. Summer longshore transport anomalies have a weak inverse relationship with SAM. The north-westerly facing section of the shoreline adjacent to

Semaphore is most strongly inversely correlated to SAM. Only during summer is this inverse relationship observed between southerly transport and SAM. In general, no significant correlations between autumn longshore transport rates and SAM were found. Winter longshore transport anomalies were found to correlate directly with the SAM index, meaning that net transport decreases when the SAM moves southward due to a relatively stronger increase of the southerly transports than for the northerly transports. Consequently, the gross transport was found to be slightly larger (i.e. mild inverse correlations) with a more positive SAM, while net transport is decreased with SAM. Spring longshore transport anomalies were found to have significant inverse correlations with SAM considering net, gross and northerly transport, while a direct correlation was found for southerly transport.

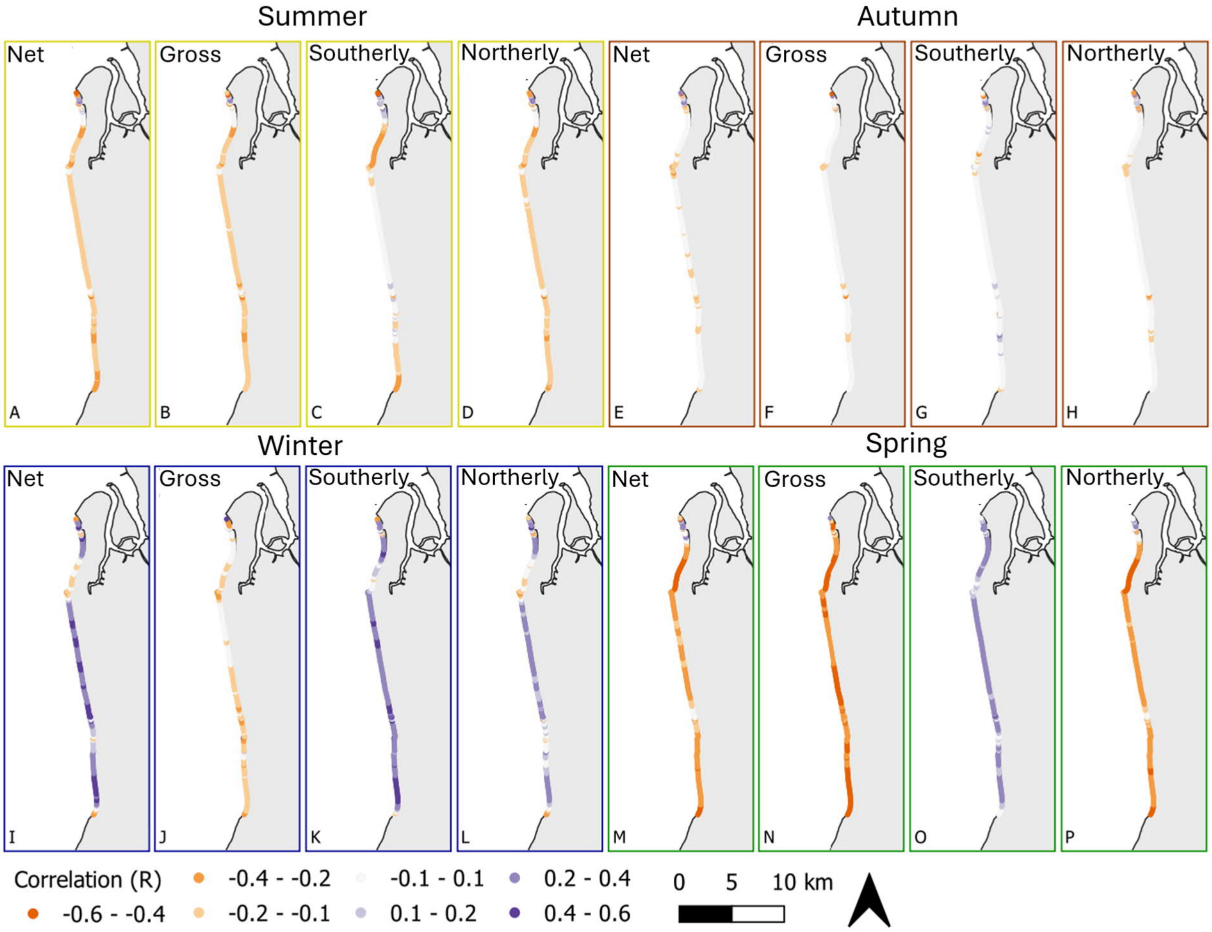

Figure 4-4 Seasonal correlations between longshore transport anomalies and the SAM index. Summer (A-D), autumn (E-H), winter (I-L) and spring (M-P).

4.5 Discussion

Correlations between longshore transport anomalies and the SAM index were investigated to identify relationships. An important first step of this investigation was determining the magnitude and variations of these anomalies (Table 4-1), as this sets the context and importance of relationships to climate drivers. For Adelaide’s managed beaches the timing and direction of transport is of critical importance for management, particularly for the use of beach nourishment on eroding beaches. Northerly transport is largely responsible for the erosion of southern beaches, while southerly transport can be seen as a ‘restoring’ transport which leads to less requirement for nourishment of southern beaches. Considering this context of beach nourishment, northerly system transport anomalies of up to about 50 thousand m^3/yr and southerly system anomalies of up to 20 thousand m^3/yr can occur due to variability in SAM. Net transport can provide information on combined impacts of northerly and southerly transport, but is considered less insightful than the transport components, as it is more difficult to associate the more nuanced impacts of climate to the conglomerate of two directions. Gross transport is more of interest as it can directly impact the frequency of nourishment operations.

The driver of longshore transport anomalies on Adelaide’s managed beaches is the wave climate. Perry et al. (2024a) presented an investigation into climate drivers and wave conditions. The wave height anomalies in that study vary by up to 20% of mean wave conditions, which is considerably less than the anomalies seen in the longshore transport. This is not surprising given that the relationship between wave height and longshore transport is exponential rather than linear (Van Rijn, 2014). In addition, the combined effects of wave direction and height anomaly can magnify or dampen the longshore transport rates. In general, the results presented in Figure 4-2, Figure 4-3 and Figure 4-4 show that northerly transport has an inverse relationship with SAM while southerly transport has a direct relationship with SAM. Considering annual anomalies, when SAM is negative, Perry et al. (2024a) suggests swell wave heights increase. In this case, the sea waves (which include a northerly component) form a less significant proportion of the bi-modal wave climate leading to increased northerly transport. In contrast, when SAM is positive, sea waves form a larger proportion of the bi-modal wave climate and a increase in southerly transport is observed.

The nuances effect of the Southern Annular Mode (SAM) on wave conditions and subsequent longshore transport in the gulf is further influenced by seasonal variations. This complexity is highlighted by the contrasting relationships between SAM and the season longshore transport anomalies, specifically the opposing interactions observed between SAM during spring (inverse) and SAM during winter (direct). In both seasons southerly transport has a direct relationship with SAM, however the relationship between northerly transport is different (direct in winter and indirect in spring). It’s possible that this could be attributed to SAM’s inverse impact on wave direction causing more idealised (tending to 45°) north westerlies in winter and south westerlies in winter. It’s also possible that SAM’s interactions with longshore transport in winter conditions can be attributed to interactions between SAM and other climate drivers during this season. Perry et al. (2024a) found that winter is the only season in which SAM, ENSO and IOD fluctuations correlate significantly with wave conditions in the gulf and this climate modes have been found to interact with each other (Cai et al., 2011a).

This investigation provides an insight into the relationship between SAM and longshore transport, however limitations to the methodology should be considered. The correlations identified in this study are significant, however there are limitations to the deductions of causation and consideration for autocorrelation. With complexities arising from both the interactions of climate drivers and nuanced relationship between SAM and wave direction, the physical causation is speculative. Regarding limitations due to autocorrelation, statistical robustness could be improved by using effective degrees of freedom. In addition, the limitations of the models which compute the longshore transport in this study should be considered. The modelled longshore transport rates analysed in this study are driven by modelled wave conditions from Perry et al. (2024a) which use key wind inputs from Era5 (Hersbach et al., 2018) and boundary wave conditions from the CAWCR wave model (Smith et al., 2021). Though these models, along with the downscaled wave model and shoreline model were validated against measured data, any misrepresented processes would carry through to this analysis.

The relationships between longshore transport and SAM identified in this study are useful for the forecasting of beach nourishment at a seasonal scale. There are a number of seasonal nuances as discussed above, however the results of this study indicate that increased longshore transport can be expected when SAM is negative. This is to be expected given a negative SAM brings a westerly wind belt, which in turn increases the prevalence of wave conditions that lead to increased longshore transport rates. The forecasting of SAM events remains a challenge, however studies suggest that SAM is displaying positive trends effectively moving the weather pattern southward (Fogt and Marshall, 2020). Excluding the influence of long-term trends beyond annual anomalies and short term storm events, this positive SAM trend suggests that (seasonal to annual) longshore transport may reduce in the future on Adelaide’s managed beaches.

4.6 Conclusion

Spatial and temporal changes in longshore transport determine coastline erosion at coasts with structures, which is relevant for the management of shorelines. Important drivers for these changes in transports are the not well understood climate indices which cause seasonal to annual timescale fluctuations in transport. More sand nourishments and coastal protection may be needed if some of the climate modes strengthen, while other climate modes are actually beneficial for the coast. An understanding of how these indices may change in the future therefore provides a direct insight into the expected longer term trends in longshore transport and subsequent coastal stability. A relationship between the Southern Annular Mode and longshore transport on Adelaide’s managed beaches in South Australia has been shown in this study. Net, gross and northerly transports were inversely correlated, while the southerly transport was positively correlated to the Southern Annular Mode (SAM) at Adelaide’s beaches. This implies that less erosion of the recreational beaches takes place if SAM strengthens, which directly puts this forward as one of the main items to be investigated in any studies on future climate impacts at Adelaide’s beaches.

CHAPTER 5.

Manuscript format article (unsubmitted) – will be submitted upon acceptance of (Perry et al., Under Review, Perry et al., 2024b)

Statement of co-authorship – I lead the research design and writing of this chapter. Mentorship, advice and editing of material was performed by co-authors. All contents of this chapter were ultimately my decision after consultation with PhD committee.

Perry (80%), Huisman (5%), Roelvink (5%), Hesp (5%), Miot da Silva (5%).

Assessing beach nourishment feasibility under a changing climate using a one-line numerical model

5.1 Abstract

The sensitivity of a beach nourishment scheme to a changing climate in Adelaide, South Australia is evaluated using a novel beach nourishment application tool implemented in the one-line numerical model ‘ShorelineS’. The tool detect when the shoreline has retreated behind a user defined trigger line and applies nourishment to user defined areas to determine the required nourishment volumes that maintain desired beach widths. The beach nourishment regime at Adelaide’s managed beaches is a sand recirculation scheme in which sand is regularly piped or trucked from accreting to eroding areas within the system. The analysis found that minor annual anomalies of significant wave height or wave direction have a significant impact on required nourishment volumes. A ±20% adjustment of wave height causes a 87% variation to nourishment requirements and ±10 degrees changes in wave direction causes a 82% variation to nourishment requirements when considering a typical year. Sea level rise rates impact required nourishment rates by up to 18% for a rate of 12mm/year in a single year simulation. When cumulative effects of sea level rise were considered over a 10-year period, the results suggest a 50% increase in nourishment requirement when considering a sea level rise rate of 8mm/year. The findings from

this study highlight the pressures that the cumulative impacts of sea level rise in addition to the year-to-year anomalies in wave conditions will have on the management of beaches. The study also presents an automatic nourishment extension to the ‘ShorelineS’ model which can be used to assess beach nourishment requirements for managed coastlines around the world.

5.2 Introduction

Beach nourishment is a commonly used coastal management strategy to combat coastal erosion that will likely play a critical role in maintaining beach widths under sea level rise (De Schipper et al., 2020). However, the effectiveness and practicality of beach nourishment under the pressures of sea level rise remains largely uncertain (Haasnoot et al., 2020). This uncertainty is not only related to various emission pathways and associated sea level rise response but also the local nuances of beach nourishment practicalities and changes to local wave climates. Robinet et al. (2018) suggests beach nourishment programs will face challenges under rising sea levels including borrow site limitations, native beach compatibility for external sand sources, construction costs, vulnerable geomorphic elements of the coastal zone and environmental impacts. The magnitude of these pressures are largely governed by the required increases to beach nourishment requirements due to sea level rise or changes in wave climates which are the focus of this study.

Numerical models offer coastal managers a tool to investigate the impact of beach nourishment and the ability to quantify some of the uncertainties and sensitivities to changing conditions on the coast, rather than relying on engineering experience or simplified empirical rules (Karambas and Samaras, 2014). These models vary in detail and computational expense, with more detailed models generally suited to simulate impacts at a short temporal scale while more generalised models are able to capture longer time periods by simplifying model physics (De Schipper et al., 2020). A common type of model to capture longer time periods are one-line models which represent the coastline as a single line in the cross-shore profile (Whitley et al., 2021). With simplified model physics, these models are able to capture time periods of years to decades with minimal computational expense (Chataigner et al., 2022). Splinter and Coco (2021) provide insight into the opportunities of such models, suggesting that they are best suited to coastlines with significant gradients in alongshore transport over long-term time periods.

One-line models have been applied to beach nourishment investigations and designs at various locations across the world. Weathers and Voulgaris (2013) performed a comparison of linear erosion (Verhagen, 1993), Verghagen (Verhagen, 1996) and one-line (Dean, 2002) model’s ability to represent the impact of beach nourishment at Folly Beach and Huntington Island in South Carolina, USA. Their study found that the one-line modelling approach provided the most versatile method to predicting beach volume evolution at both locations. Bergillos et al. (2018) used an integrated modelling approach, where waves are downscaled from deep water conditions to inform sediment transport in a one-line model over the period of 2 years in Guadalfeo, Spain. This study was able to effectively inform the most efficient coastline shape, required beach nourishment volume and grain size. Stronkhorst et al. (2018) combined Delft3D-WAVE (Booij et al., 1999), Ntool (Huisman et al., 2013) and one-line model UNIBEST-CL + (Deltares, 2011) to investigate sand nourishment strategies on the shores of the Dutch coast and the Aveiro coast in Portugal over the period 2010-2100. Their findings confirmed beach nourishment as a viable strategy on the Dutch beaches due to the population set to benefit from the strategy and large sand resource availability from the North Sea. However, for Aveiro, the outcomes was more nuanced where a combination of beach nourishment and managed retreat was recommended. Despite numerous one-line modelling investigations into beach nourishment, there remains an opportunity to sufficiently develop a one-line model capability to automatically apply nourishment through a timeseries to eroding beaches without the need for a model ensemble.

The present study uses a one-line model to assess future beach nourishment requirements under sea level rise pressures and uncertainty of future wave conditions. Research of this type has been identified as a priority in coastal geoscience and engineering, with the outcomes of an Australian priorities setting study finding: ‘Quantify shoreline change over varying spatial and temporal scales’ as the most critical research gap in coastal dynamics and processes, ‘impact of wave climate on coastal dynamics as the most critical modelling gap, and ‘sand sources for beach nourishment and impacts on extraction' as the most critical gap in engineering solutions (Power et al., 2021).To achieve this, an existing shoreline model developed in Perry et al. (Under Review) for Adelaide's managed beaches in South Australia has been adapted and model capabilities have been developed.

5.3 Materials and methods

5.3.1 Study site

5.3.1.1 Physical setting

The study site for this model application is Adelaide's managed beaches in South Australia (Figure 5-1). This site sits on the eastern side of Gulf St Vincent where Southern Ocean swell waves propagate into the gulf from a south westerly direction with Kangaroo Island providing protection from more southerly swell directions. These south westerly swell waves have the greatest influence on conditions in the south eastern quadrant of the gulf, with a reduction of impact in the northern regions of the gulf. In these regions, the local wind generated sea waves are most prominent (Perry et al., 2024). Adelaide's managed beaches are impacted by both the south westerly swell waves and locally generated sea waves, resulting in a bi-modal wave climate which has been discussed in detail by Perry et al. (2024a). The locally generated sea wave component of this wave climate is seasonal with an increase in northerly conditions in winter months and a southerly prevalence in summer months. The combined bi-modal wave climate results in a south westerly prevalence of wave direction which causes net northerly longshore transport along Adelaide's managed beaches. The seasonality and trends of this longshore transport have been discussed in detail by (Perry et al., Under Review, Perry et al., 2024b) where a 32-year shoreline hindcast was investigated for the area. The study estimated that the median net northerly transport in the area is 75,000-98,000 m^3/year which was consistent with previous studies in the area (Huiban et al., 2019, Coastal Engineering Solutions, 2004). Beach widths vary along coastline with generally narrower beaches in the south and wider beaches in the north, due to this net northerly transport. An overview of the physical setting is provided in Figure 5-1.

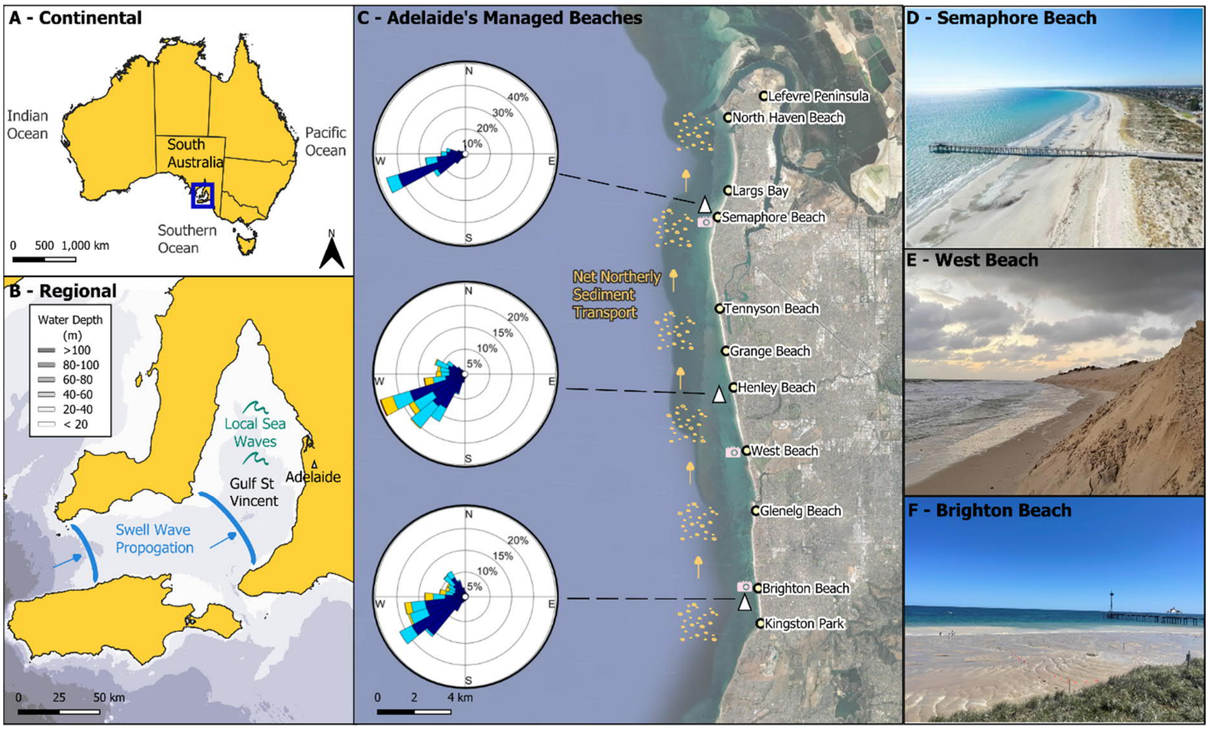

Figure 5-1 - Study site overview. (A) Continental scale study site location. (B) Regional scale study site location and bi-modal wave climate schematic. (C) Adelaide's managed beaches including longshore transport schematic and wave rose outputs from modelled wave conditions (Perry et al., 2024a). (D-F) Photographs of Adelaide's managed beaches.

5.3.1.2 Coastal management

Rock revetments, shore perpendicular training walls, offshore breakwaters, groynes and beach nourishment are all present on Adelaide's managed beaches. The longshore transport gradient produces an erosive trend at the southern beaches and shore perpendicular structures blocking longshore transport are required as part of the management strategy to maintain recreational beach widths and protect infrastructure (Townsend and Guy, 2017). Rock revetments armour a significant portion of the southern beaches between Henley and Kingston Park (Figure 5-2C) as the last line of defence against erosion hazard and beach nourishment is used to maintain beach widths. The beach nourishment scheme in Adelaide is unique, utilising quarried and dredged sand form outside the system as well as a sand recycling scheme where sand from accreting beaches is transported by pipeline or truck to eroding beaches.

Annual beach nourishment volumes from 2010 to 2019 have been plotted against net northerly and gross transport rates derived from the Perry et al. (2024b) study in Figure 5-2. The plots show that the net northerly longshore transport during this time period is ~90,000 m³/year and gross transport is ~170,000 m³/year. A relationship between net northerly transport rates and beach nourishment is observed, with greater northerly longshore transport generally resulting in an increase in nourishment volume. Gross transport which considers southerly movement of sand shows less of a relationship, however it is noted that the significant storms in 2016 (Townsend and Guy, 2017) which led to the largest requirement for nourishment correspond to the highest gross transport rates during this period. The storms in 2016 did not respond to the highest net longshore transport rate, as significant southerly transport also occurred in that year.

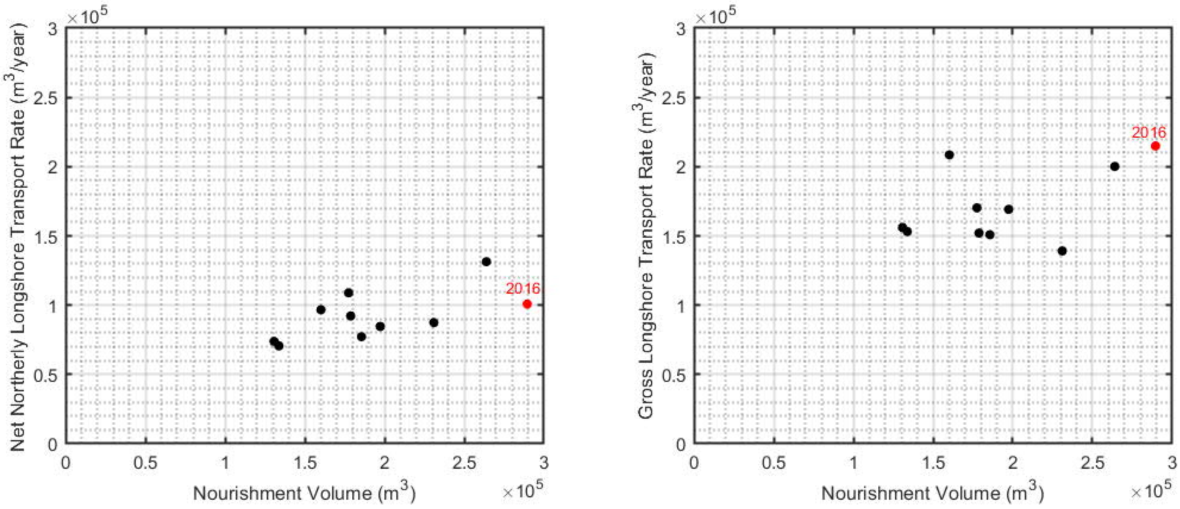

Figure 5-2 - Annual beach nourishment volumes from 2010-2019 on Adelaide's managed beaches plotted against net northerly longshore transport (A) and gross longshore transport (B). Transport rates from (Perry et al., 2024b). 2016 highlighted as the year with most significant storms from observation (Townsend and Guy, 2017)

5.3.2 Model description

5.3.2.1 ShorelineS model

The one-line model 'ShorelineS' has been utilised for this study with details of the model available in (Roelvink et al., 2020). Prior to this study, the user was able to input beach nourishment into the model at user defined locations and times in in a simulation. Equation 5-1 below presents the basis for coastal change in the one-line model.

$$\frac{dn}{dt} = -\frac{1}{D_c}\frac{dQ_s}{ds} - \frac{RSLR}{tan\beta} + \frac{1}{D_c}\sum q_i \qquad 5\text{-}1$$

Where, *x* is the cross-shore coordinate, *s* the longshore coordinate, t is time, D_c is active profile height, Q_s is the longshore transport rate, $tan\beta$ is the average profile slope between dune or barrier crest and depth of closure, RSLR is the relative sea level rise. This q_i is the source/sink term used to incorporate additional processes, including sand nourishment and sand mining. The nourishment/mining volume is divided by the length of beach in which it is being applied/removed and distributed over the relevant timesteps to result in the nourishment area over the cross shore profile ($\frac{m^2}{t}$) which is applied across the active profile height to result in the beach change (m) per timestep. The model's ability to simulate nourishment and sand mining allows for sand recycling to be represented by subtracting volumes and of sand from a location and redistributing this as nourishment to other locations.

5.3.2.2 Automatic nourishment tool

This study builds on the ShorelineS model's capability by proposing a tool to automate beach nourishment based upon modelled shoreline position, user defined nourishment trigger line and a user defined sand source trigger line. Note that the tool can also be utilised for locations where the source location is external to the system. In this case, no sand source would be prescribed and sand would be applied to the predefined nourishment areas without extraction from the system. At each timestep any intersections between the trigger lines and the shoreline are identified (see Figure 5-3 panel A). Each trigger line has an associated nourishment location where sand is deposited if the associated trigger line is crossed. Nourishment is applied through the q_i term in equation 5-1 where it is divided by the active profile height (assumed to spread across active profile), subsequently the seaward accretion of the shoreline is calculated. The volume of nourishment applied is predefined for each location and should be based on practical limitations and expected rates of erosion. To represent a sand recycling scheme, a sand source can also be allocated to each trigger line to be mined if an intersection occurs. To avoid excessive and unpractical mining of a sand source, an additional user defined trigger line is considered where sediment is only extracted if the shoreline is seaward of the sand source trigger line. An additional practicality represented in the model is a lag time between nourishments. This lag allows time for the applied nourishment to disperse along the beach to updrift locations which may have triggered the nourishment. The lag can also be used to represent the practical limitations of nourishment rates and volumes that coastal decision makers would pose. A schematic of this tool is presented below in Figure 5-3.

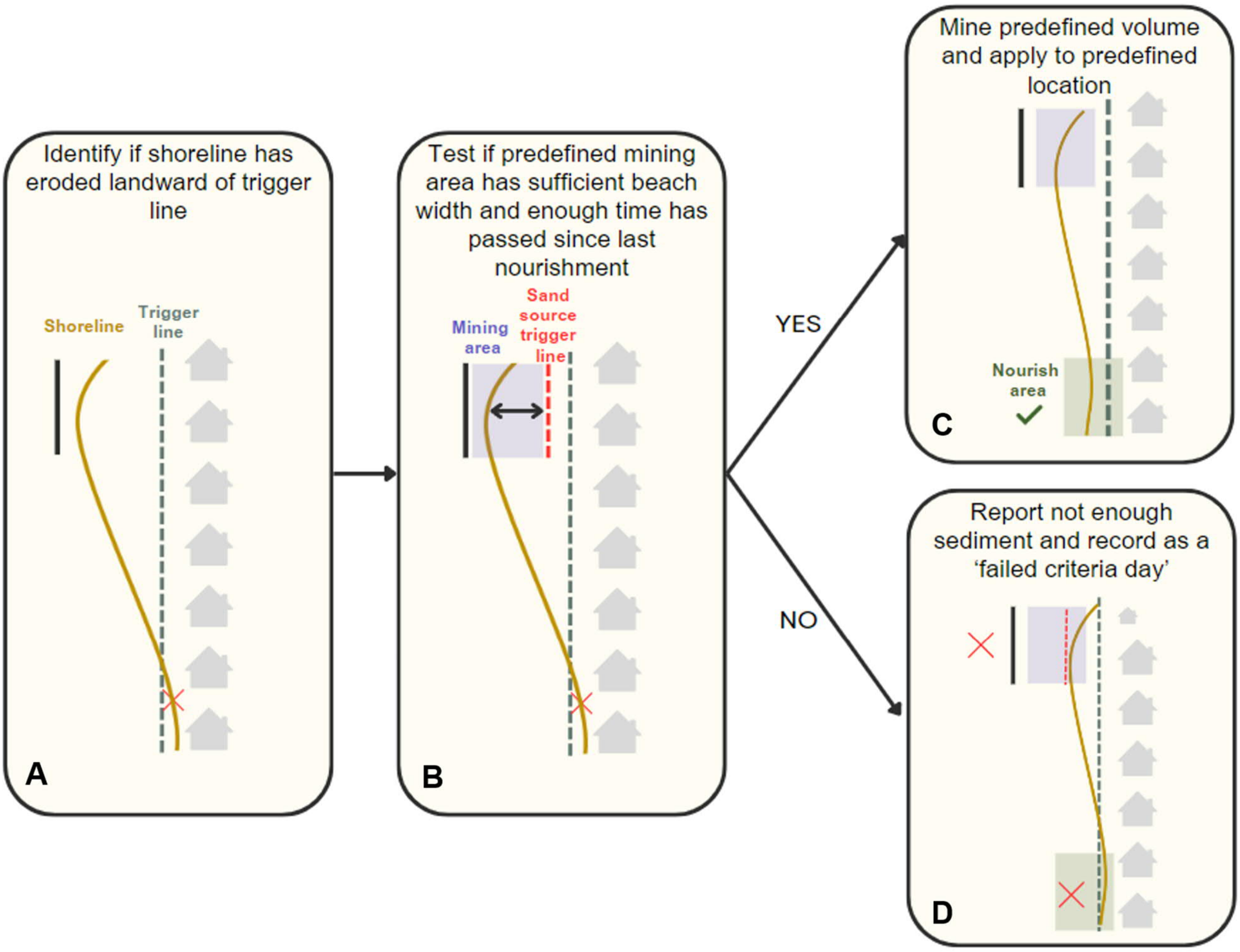

Figure 5-3 Automatic nourishment tool schematic. Panel A shows a situation where the modelled shoreline has eroded behind the user defined trigger line (red cross), Panel B shows the test to find if sufficient sand at the source location (if it is desired to recycle sand from within the system), Panel C shows nourishment applied given sufficient source sand and Panel D shows when there is insufficient source sand the eroded coast is not nourished.

5.3.3 Model application

The shoreline model including the automatic nourishment tool outlined in section 5.3.2 has been applied to Adelaide's managed beaches. A ten year model validation has been performed to confirm that nourishment volumes predicted by the tool are of similar magnitude to historic nourishment volumes. A variety of future scenarios have then been developed to test the sensitivity of the management scheme to changing future conditions, including sea level rise.

5.3.3.1 Model Setup

An extended shoreline hindcast was developed in Perry et al. (Under Review), via application of ShorelineS to Adelaide’s managed beaches. This model was built upon and adapted in the study, while maintaining key validated input parameters. A summary of parameters used in this model are presented below in Table 5-1.

Table 5-1 - Key shoreline model parameters and setup (summary from Perry et al. (Under Review))

Parameter	**Value**
Wave input	4-hourly modelled wave conditions introduced at 1km spacing in 4m water depth with modelling description in Perry et al. (2024a).
Longshore transport formulation	Van Rijn (2014)
Gamma breaking coefficient	0.72
Grain size	0.2 mm
Percent swell correction factor	25%
Active profile height	Variable between 6 m and 15 m(specified in Perry et al)
Initial space step	100 m
Diffraction formulation	Elghandour et al. (2020)
Bypassing formulation	Ghonim (2019)
Timestep	0.001 years (~ 9 hrs)

The previous study (Perry et al., Under Review) included a verification of model parameter suitability based on shoreline change comparisons between modelled shorelines and satellite derived shoreline positions. The study found that shoreline change rates had a root mean square error of 1.22 m/year with 0.14 m/year bias when compared to the satellite derived rates.

The model developed for this current study uses the same model parameters as outlined in Perry et al. (Under Review), however rather than applying historic nourishment, the automatic nourishment tool is utilised. Nourishment and sand source trigger lines have been applied with the intention of maintaining recreational beach widths along the coast. In this case, recreational beach widths have been set at ~10-20m adjacent to sea walls and ~30-40m adjacent to dunes (from dune toe). Sand source locations in the model mirror those frequently utilised in practice by coastal decision makers in the area. Each time a trigger line is intersected, a fixed volume of 5,000 m³ is applied to nourishment recycle locations and removed from a source recycle location. A lag time of 14 days is applied at all locations as the minimum time between nourishments at each location.

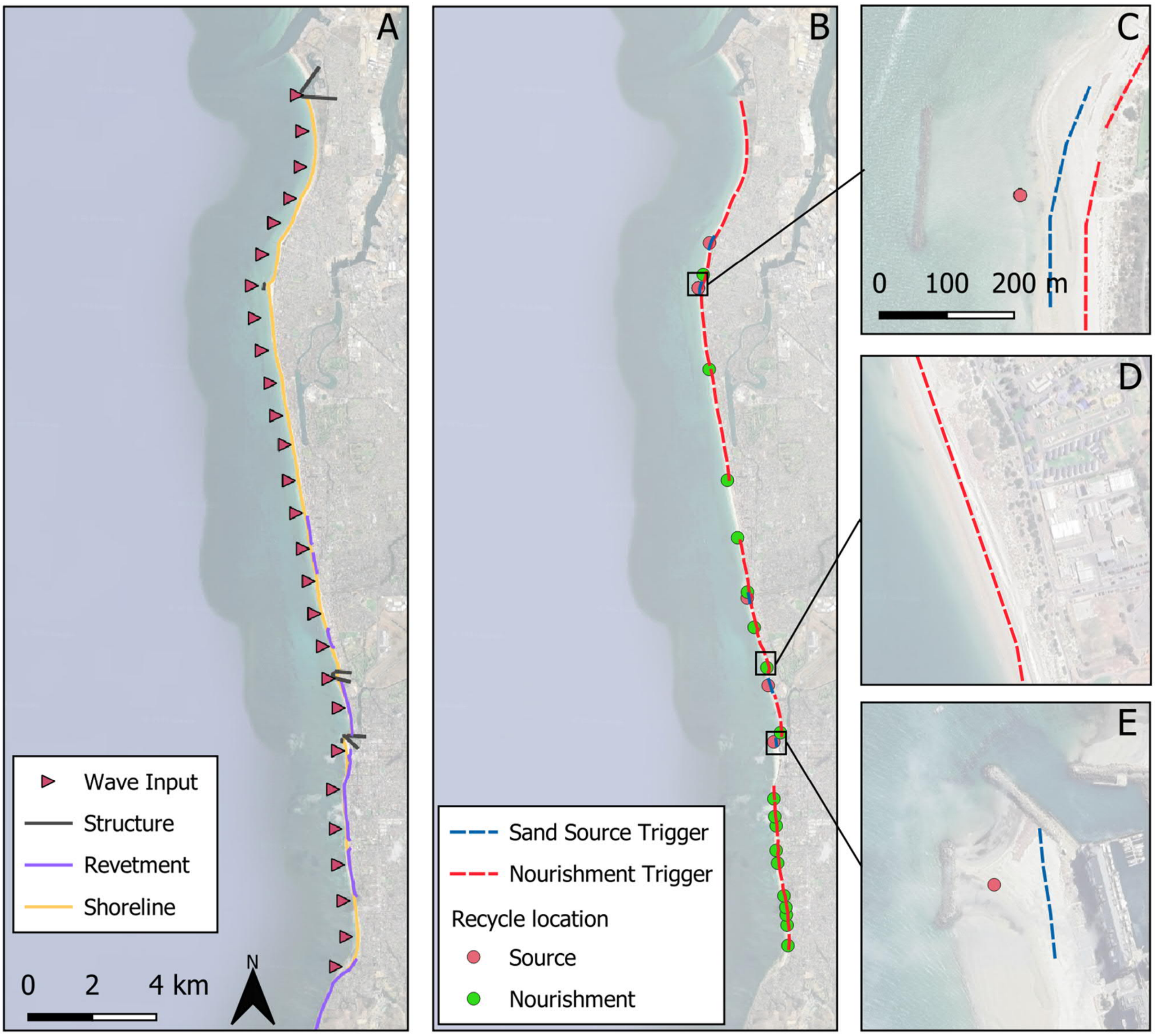

Figure 5-4 ShorelineS model application to Adelaide's managed beaches. (A) model setup showing initial shoreline position, structure locations, revetment extent and wave input locations. (B) Automatic nourishment tool setup showing the nourishment trigger lines and sand source trigger lines. (C-E) Zoomed examples of sand source and nourishment trigger lines.

Model settings and inputs outside of nourishment input have been validated in Perry et al. (Under Review). The model validation in this study focuses on the ability of the automatic nourishment tool to adequately model the required nourishment in order to maintain beach widths along the metro coast. To achieve this, a 10-year hindcast (2010-2019) is presented where historic nourishment records are compared to the required nourishment volumes simulated using the shoreline model. It is not expected that the nourishment volumes will be completely consistent with recorded volumes. This is due to a number of factors including times where recreational beach widths have not been maintained, restrictions to nourishment operations due to operational constraints or political factors, external sand sources brought into the system and potentially mis recorded nourishment records. A 5 year spin up time is used for this simulation (prior to 2010) as it is expected that initial nourishment volumes and shoreline movement is related to the model reaching a steady state, rather than purely from erosion pressures.

5.3.3.2 Sensitivity scenarios

A number of scenarios have been developed to test the sensitivity of the system to changes in environmental conditions. The sensitivities considered in this analysis are the addition of sea level rise, changes in significant wave height and changes in wave direction. Sea level rise rates are applied to the model at each timestep, wave heights have been adjusted by multiplying all input wave heights by a constant and wave directions have been adjusted by adding or subtracting all input wave directions by a constant. A single year, in this case 2018 is re-simulated using the same model settings as in the validation simulation but with sea level rise added to the first scenario, significant wave heights multiplied by a constant in the second scenario and wave directions modified by a constant in the third scenario. It is of note that the impact of a given sea level rise rate is explored without cumulative effects in these initial scenarios.

A summary of the scenarios investigated is presented in Table 5-2 below. SLR rates are based upon rates presented in the IPCC’s Assessment report 6 (Arias et al., 2021), these rates have been extracted from the National Aeronautics and Space Administration (NASA) portal for Port Stanvac. In this case, 0.004 m/yr corresponds to the ‘Very Low’ SSP1-1.9 rate at both 2050 and 2100; 0.008 m/yr corresponds to ‘Intermediate’ SSP2-4.5 rate at 2100; 0.012 m/yr corresponds to the ‘High’ SSP5-8.5 rate at 2100; and 0.016 m/yr has been used as an additional sensitivity above these projections. Significant wave height variations of up to ±30% and wave direction adjustments of up to ±20 degrees have been adopted to based upon the seasonal and annual anomalies reported by Perry et al. (2024a).

Table 5-2 – Sensitivity test simulations

Sensitivity test	Values tested
Sea Level Rise (SLR)	0, 0.004, 0.008, 0.012, 0.016 (m/yr)
Significant wave height (Hs)	0.7, 0.8, 0.9, 1, 1.1, 1.2, 1.3 (multiplied by constant)
Wave direction (degrees)	-20, -15, -10, -5, -3, -2, -1, 0, 1, 2, 3, 5, 10, 15, 20 (degrees)

To quantify the cumulative impacts of sea level rise, an additional sensitivity test has been performed using the full 2010-2020 simulation with the addition of the sea level rise rates presented in Table 5-2.

5.4 Results

5.4.1 Model verification

Modelled nourishment requirements have been compared to placed nourishment in Adelaide over the 10-year hindcast period to ensure that the proposed required nourishment volumes are appropriate. The modelled annual beach nourishment requirements for Adelaide’s managed beaches are similar to recorded volumes over the model validation period with only a 21% difference over the 10-year period. Yearly volumes are presented in Figure 5-5, the mean annual recorded nourishment volume is 195,000 m^3/year and the modelled annual nourishment requirement is 247,500 m^3/year. No failure days were recorded during the model simulation which means that sediment was always available at downdrift source locations when nourishment was triggered.

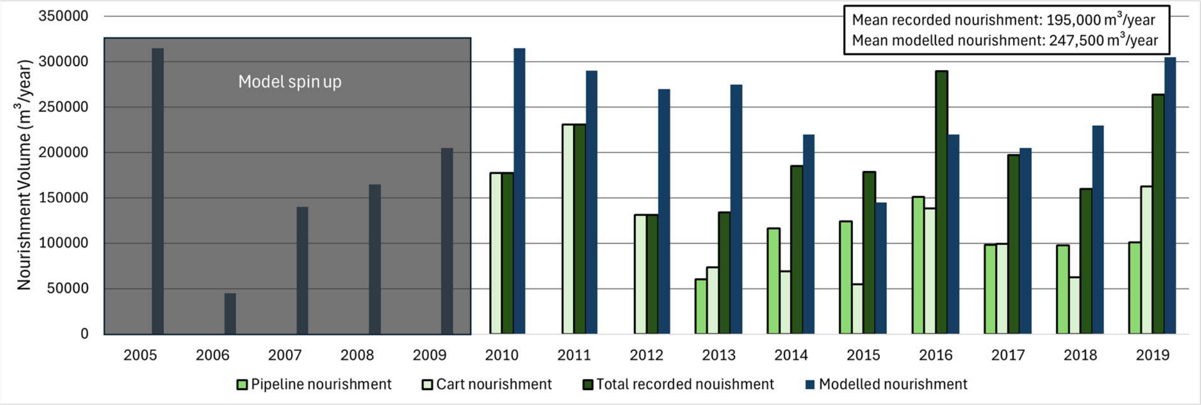

Figure 5-5 - Annual beach nourishment volumes for Adelaide's managed beaches. Green bars show the recorded volumes with a breakdown of pipeline and carted nourishment and blue bars show modelled annual volumes.

Year to year the modelled and recorded nourishment volumes vary more significantly. These variations can be attributed to both model limitations and constraints on recorded nourishment volumes during this period. A key model limitation which can likely describe the under estimation of modelled volume in 2016 is the model's ability to represent erosion of the 0m contour during storms. Adelaide's beaches experienced significant storms in 2016 which caused a significant cross shore transport of sand that is not represented in the one-line model. An additional cause of variation between modelled and recorded nourishment is the maintenance level of recreational beach widths. In reality, there were beaches which experienced erosion and reduced beach widths throughout the 10-year time period, while in the modelled scenario idealised beach widths are maintained throughout the simulation. Figure 5-6 highlights this at 3 key cross shore transects, where in all cases beach widths are maintained during the model simulations but are reduced by up to 15 meters in the surveyed beach profiles. These surveys were all performed annually in January (with exception of additional survey performed in mid-2016) so the fluctuations are not the result of seasonal beach width patterns.

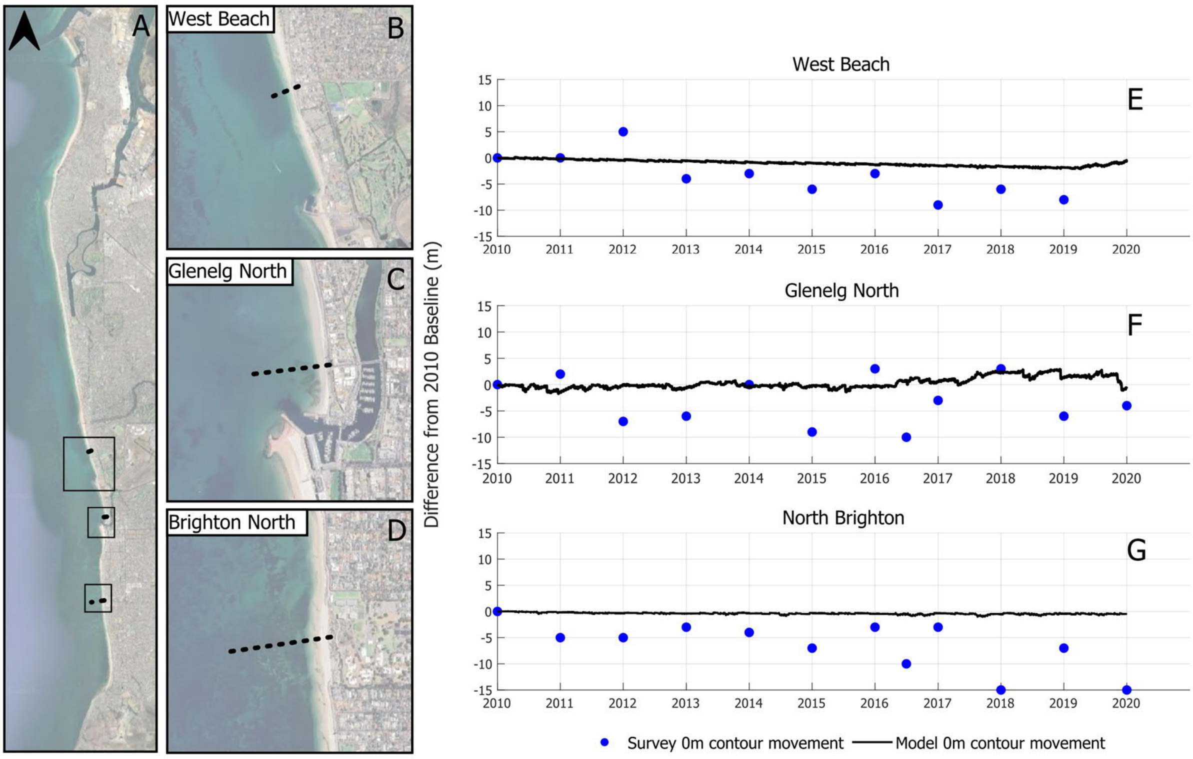

Figure 5-6 - Time series surveyed and modelled 0m contour movement between 2010 and 2020. Panels A-D provide transect locations while panels E-G present modelled and surveyed 0m contour movement for West Beach Dunes, Glenelg North and North Brighton respectively.

5.4.2 Forecasted nourishment sensitivities

Forecasted nourishment sensitivities to SLR, significant wave height and wave direction have been plotted in Figure 5-7. SLR rate of 4mm/yr was found to increase nourishment requirements by 4%, 8mm/yr increased requirements by 9%, 12mm/yr increased requirements by 18% and 16 mm/yr had the largest increase of 27%. Changes to significant wave height were found to have a close to linear relationship with nourishment requirements, however reductions in wave height corresponded to a slightly larger reduction to nourishment requirements than the relative increases in nourishment requirements from an increase in wave height. Changes to wave direction had a more nuanced impact on nourishment requirements. When wave direction was adjusted anticlockwise (negative), nourishment requirements increased, this increase was similar (~7%) for adjustments of -1, -2 and -3 degrees but increased to 13% when adjusted by -5 degrees. Nourishment requirements increased significantly (42%) when wave direction was adjusted by 10 degrees with only relatively minor increases thereafter. When wave directions were adjusted clockwise (positive), nourishment requirements decreased. Substantial reductions to required nourishment were found for only minor increases in wave direction, with a 1-degree adjustment corresponding to a 13% reduction in required nourishment, 2 degrees corresponding to 20% reduction and 3 degrees corresponding to a 22% reduction. Changes greater than positive 3 degrees had less impact on the required nourishment

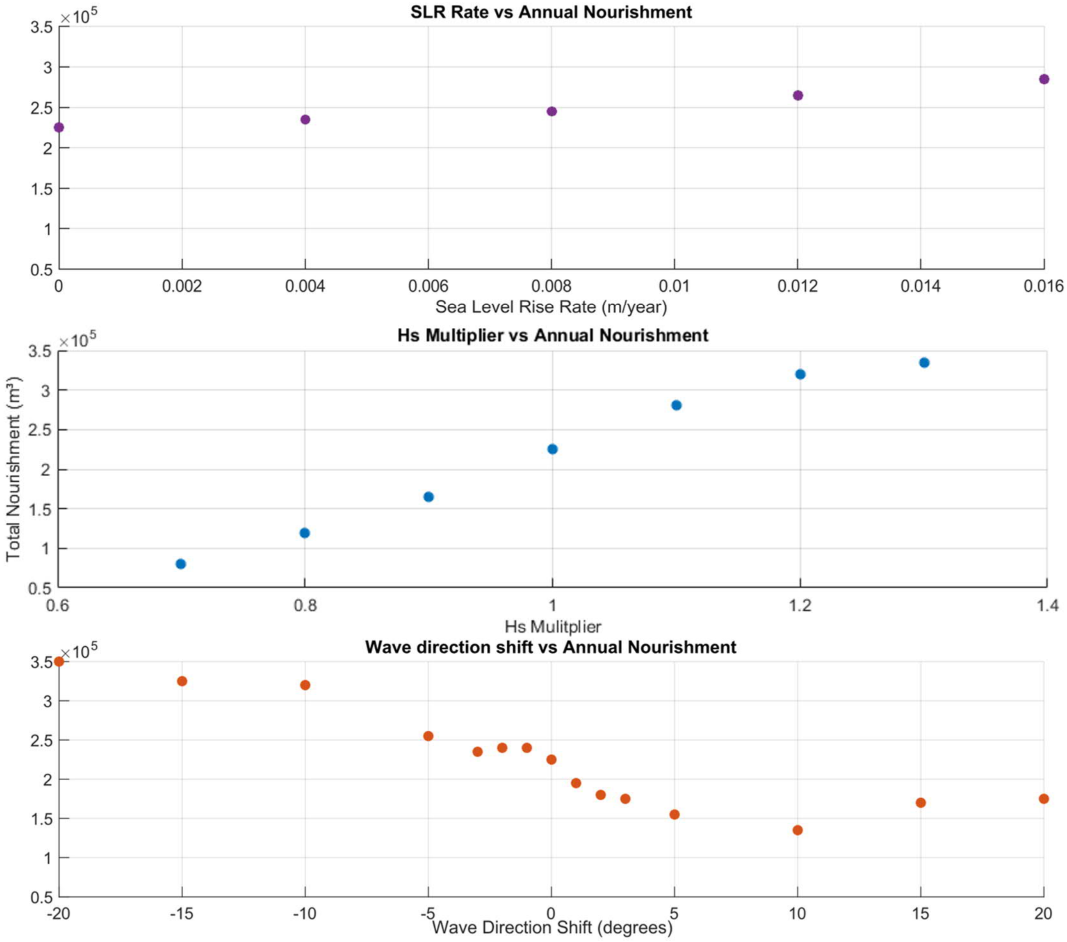

Figure 5-7 – Nourishment requirements sensitivity to Sea Level Rise (SLR), Significant wave height (Hs) and wave direction

To assess the compounding impacts of SLR an extended 10-year simulation was performed with SLR applied throughout the simulation. The results presented in Figure 5-8 show that the cumulative effects of sea level rise compound through time with more significant impacts of increased SLR rates occurring at the latter end of the 100-year simulation. This is due to the reduced beach widths across the entirety of the coastline causing additional nourishment locations to be triggered and increasing pressure on erosion hot spots with increasing SLR rates. For example, the average difference in nourishment requirement for 4 mm/yr of SLR compared to 12 mm/yr from 2010-2014 is 14%, however from 2015-2019 this increases to 34%. Across the full 10-

year time series the total required nourishment for the 10-year period increases by 27% for a SLR rate of 4 mm/yr, 51% for 8 mm/yr, 71% for 12 mm/yr and 88% for 16 mm/yr.

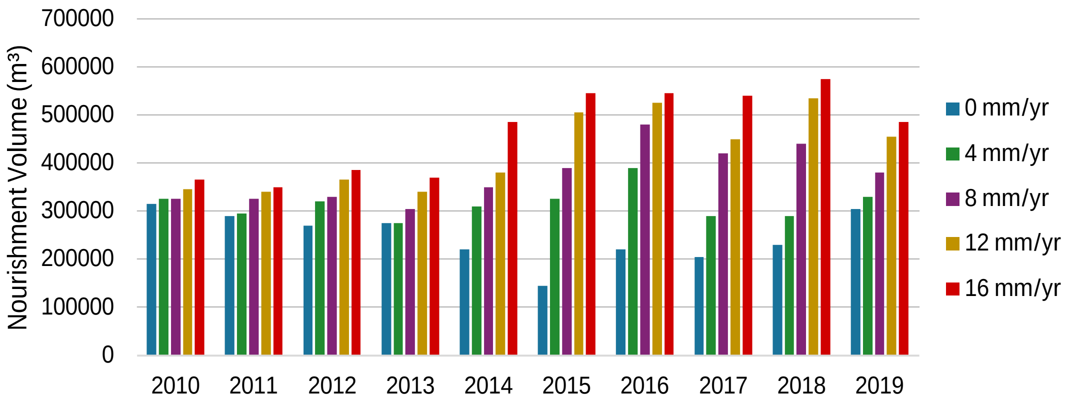

Figure 5-8 – Required nourishment volumes through a 10-year simulation for various rates of sea level rise

5.5 Discussion

This study presents a tool to understand sensitivities to future beach nourishment requirements due to changing environmental conditions. The focus of this study is on the high level feasibility of nourishment considering the pressures of a changing climate rather than an assessment of nourishment campaigns at a detailed level. The study does not attempt to prescribe a forecasted time series of forcing conditions, rather the sensitivities to these conditions are tested and assessed to understand their relative impact. The study site is Adelaide’s beaches which have experienced ongoing erosion of beach widths. To maintain beach widths in Adelaide, a beach nourishment regime based around sand recirculation within the system has been utilised. Though the technique has had historic success at this site, the impact of a changing climate on the strategy’s future viability has remained uncertain.

The automatic nourishment tool described in Figure 5-3 has been successfully implemented through additions to the ShorelineS one-line numerical model (Roelvink et al., 2020). Though possible to implement this tool into other existing one-line models, ShorelineS was chosen due to its previous application to this study site (Perry et al., Under Review) and ease of modification through MATLAB implementation. The tool offers a simple way to predict nourishment requirements at a timescale of months to years in situations where cross shore processes due to storms become less significant at this timescale. It allows coastal managers to understand the influence of sensitivities directly on required nourishment rather than a typical approach where environmental sensitivities are tested on a predefined nourishment.

To assess the suitability of the tool to model required beach nourishment, a hindcast was first simulated to compare modelled nourishment to actual nourishment between 2010 and 2019. Results from this simulation are presented in Figure 5-6 which show that the model generally over predicts required nourishment with a bias of 21%. There are a number of possibilities as to why this bias exists, including that the model keeps beaches at a desired width, where as in reality some beach extents experienced erosion (as presented in Figure 5-6). Considering this as the dominant source of bias provides insight into current management practice, suggesting that a 21% increase to nourishment is required to stabilise beach widths. The result also suggests that this can still be achieved without the addition of external sand. A location of particular concern in Adelaide is the northern (updrift) side of the West Beach boat ramp at West Beach which, as highlighted in panel E of Figure 5-6 has experienced ongoing erosional trends. Kærgaard (2018) performed a detailed modelling study of West Beach utilising an array of modelling tools from the MIKE 21 model suite (Warren and Bach, 1992) including shoreline modelling of this extent. Through an optioneering exercise, their study suggests that West Beach would require ~100,000 m^3/year to maintain beach widths. This aligns with the required nourishment at West Beach modelled in this study where an average of 96,000 m^3/year was the simulated requirement from 2010-2019. Though not a comparison to measured volumes, this alignment of modelled nourishment requirements from two approaches at West Beach suggests that the automatic nourishment tool can appropriately model nourishment requirements.

The relationships between SLR rates and nourishment requirements presented in section 5.4.2 have significant impacts for coastal management at this study site with useful insights for other coastlines around the world. The cumulative impacts of sea level rise causing an increased requirement for beach nourishment in order to maintain beach widths is well documented but found to be site specific (Stronkhorst et al., 2018, Houston, 2020). These cumulative effects can be offset by sourcing sand externally to the nourished system, however in many cases practical external sand sources are scarce. For Adelaide’s beaches the cumulative effect of SRL is likely to play a significant role in future feasibility. Considering only a 10-year accumulation of SLR effects, a rate of 8mm/year would result in a ~50% increase in required nourishment volume. Despite this increase in required recirculation volume, there were no failure days reported throughout these simulations, indicating that source locations were not depleted. This means that for Adelaide’s managed beaches there will need to be careful decision making when comparing options to increase recirculation rates or source external sand. In addition to the cumulative effects of SLR, Figure 5-7 presents the impacts of sea level rise rates on an individual year. This can be seen as nourishment required in a given year due to a SLR rate assuming the cumulative effects of SLR have been offset by external sand. These impacts were found to be less substantial for low SLR rates (4% increase corresponding to 4mm/year increase) but becoming more significant for higher SLR rates (18% increase corresponding to 12mm/year increase).

In addition to the investigation of SLR rates on required nourishment volumes, variations to wave heights and directions were explored. These variations were found to be impactful with small adjustments leading to relatively large changes to nourishment requirements. Perry et al. (2024a) found annual mean significant wave height anomalies of up to ~20% and mean annual wave direction anomalies of up to ~10 degrees adjacent to Adelaide’s managed beaches. Anomalies of this magnitude were found to have significant impacts with a ±20% change in input wave heights causing variations of 87% to nourishment requirements and ±10 degrees causing variations of 82% to nourishment requirements. Perhaps even more significant than the impact of these relatively large anomalies is the impact of minor anomalies of wave conditions. Just a 1-degree clockwise adjustment of incoming wave direction was found to reduce nourishment requirements by 13%. Linking the variations to wave parameters explored in this study to projected changes into the 21st century under various climate change parameters cannot be performed directly, as these projections use global models in which Gulf St Vincent may not be well represented. Despite this, studies such as Lobeto et al. (2021) and Morim et al. (2018) have found significant trends in the increase of Southern Ocean wave energy which will likely contribute to the fluctuations in wave parameters explored in this study.

Though the impact of wave direction anomalies on nourishment requirements has seldom been investigated in literature, the high sensitivity of beach changes to mean direction has been found in other studies. For example, Chataigner et al. (2022) found that mean wave angle biases had a more significant impact on shoreline change than biases in wave height, with modelled results at Narrabean Beach (north of Sydney, Australia) suggesting a 1 degree bias in wave direction impacted shoreline positions by up to 5m over a 10-year simulation. Contextualising the impact of annual anomalies of these wave conditions on nourishment requirements with the impact of SLR provides insight into the important drivers of feasibility. Assuming an operational or economic cap of recirculating beach nourishment, it is critical that the impact of wave condition annual anomalies is considered in addition to the cumulative impacts of SLR. The results of this study indicate that the cumulative impacts of SLR will cause the most significant increases to nourishment requirements if not offset by external sand sources, however year to year fluctuations in addition to this cumulative pressure from SLR may pose the most significant threats to recreational beach widths. In some instances this may result in tolerable loss of recreational beach space, however in other instances this may leave assets or infrastructure vulnerable to storm induced damage.

This study provides insight into future nourishment requirements, however it is important that the method is adopted considering the appropriate time scales. Though possible to use this method as a first pass assessment of individual nourishment campaigns, there are important processes that one-line models do not capture which should be considered at a finer timescale. Most critically is the distribution of sediment across the active profile which becomes more important on a finer timescale. This is particularly important for coastlines with prominent seasonal profiles in which sediment distributes seaward during energetic seasons and is deposited on the beach face during less energetic seasons. In these cases, it is likely that increased pressure on recreational beach widths occurs in the energetic season leading to an increased requirement for nourishment. This can be seen in the application to Adelaide’s beaches in this study. Significant storms occurred in

2016 and as a result, beach widths were reduced due to cross shore movement of sediment resulting in a significant nourishment campaign to maintain beach widths. Though an increase in longshore transport due to increased wave energy is modelled, the pressure due to the short term reduction in beach widths from cross shore transport is not modelled. This resulted in an underestimation of beach nourishment for 2016. This limitation should also be considered when forecasting future nourishment requirements. While climatic sensitivities which impact longshore transport have been included in this study, any future changes to storminess has not been considered. In addition, it is important to note that the method utilising a one-line model in this study is useful to determine volumes and timing of beach nourishment, however the specific nourishment approach is not considered. Such studies of nourishment approach are better suited to cross shore models. A possible extension to this methodology could include the coupling of a one-line model and storm response model which includes cross shore profile interactions, such as methods used in Baldock et al. (2021). This would allow the fit for purpose model to be utilised based upon the input conditions, though it would come at the cost of computational expense.

An additional extension of the modelling approach used in this study could include the synthesis of future wave conditions to simulate extended future time periods. Forecasting erodible coastlines at a the extended timescales of sea level rise is limited by the uncertainty in the forecast of forcing conditions (De Schipper et al., 2020). This was considered for this assessment, however the compounding uncertainties of developing a future wave climate in addition to shoreline modelling uncertainties were considered too significant to provide insightful results. To capture these compounded uncertainties, a probabilistic approach could be adopted to quantify uncertainty, however computational expense of this approach with the model developed in this study would be immense given a simulation time of approximately 12 hours on a desktop computer. It’s possible that this approach could become viable as the model becomes more efficient through continued development and computational abilities continue to improve.

5.6 Conclusion

The pressures of sea level rise and wave climate anomalies will play a prominent role in the feasibility of the sand recirculation nourishment regime on Adelaide's managed beaches. The sensitivities of the regime were tested through the development of an automatic beach nourishment tool implemented in the ShorelineS one-line model. The tool highlighted the year-to-year sensitivities posed by anomalies in mean wave height and direction parameters, with annual significant wave height anomalies of ±20% and annual mean direction anomalies of ±10 degrees causing changes to nourishment requirements for a given year of 87% and 82% respectively. Perhaps more significant than these relatively large anomalies, was the impact of just a 1 degree clockwise adjustment of the south westerly dominant wave climate causing a 13% reduction to required nourishment. The tool was also used to test the sensitivity of Sea Level Rise (SLR) rates, with results indicating that even when excluding cumulative effects, a SLR rate of 8mm/yr increases nourishment requirements by 9%. When cumulative effects are considered through a 10-year period, the results suggest that nourishments requirements will increase by 50% considering a SLR rate of 8mm/yr if not offset by nourishment from external sand sources. It's expected that the combined effects of cumulative sea level rise impacts and year-to-year anomalies will define the future viability of beach nourishment on Adelaide's coast. While regular beach nourishment from within the system remains a viable option moving forward, it's likely that significantly increased recycling rates and external sand sources will need to be considered for the system. The automatic nourishment tool applied in this study should be considered for other coastlines around the world where beach nourishment is used as a strategy to combat the effects of longshore transport induced erosion. Though used to test the sensitivity of nourishment requirements to environmental factors in this study, the tool could also be utilised for numerous other applications including the quantification of nourishment requirements after the introduction of a structure or nourishment design.

CHAPTER 6

6.1 Summary of findings

This thesis assesses the drivers of change and efficacy of management techniques now, and into the future on Adelaide’s managed beaches using numerical modelling techniques. Time scales of months to decades were considered through the development of a hindcast wave model which was able to be utilised to assess the importance of climatic drivers on wave anomalies in Gulf St Vincent. The outputs from the wave model were then used as a critical input to the shoreline hindcast model (ShorelineS) for assessment of the efficacy of historic beach management. Longshore transport rates from the shoreline hindcast model were then analysed to investigate if the climate drivers found to correlate with wave anomalies could also be related to the shoreline dynamics. Finally, the capability to assess future beach nourishment requirements with the ShorelineS model was developed in order to understand the future viability of beach management practices on Adelaide’s managed beaches. The core findings of this thesis contribute to the enduring questions that guide how beaches are understood and managed worldwide, with the primary focus of predicting how they will change. The ability to understand and predict beach change is a rapidly developing field of research which has been driven by increased understanding of the impacts of a changing climate, increased data availability from a range of sources, increased computational ability, and the development of models with greater capability to cope with more complex shores. This thesis uses and builds upon numerical models seeking to capitalise on the increase in computational ability and quantify the impacts of a changing climate with increased certainty due to availability of satellite derived observations. The questions explored and key findings from each of the chapters presented in this thesis are as follows:

Can climate drivers be related to a bimodal wave climate of a semi-enclosed gulf?

- Chapter 2 involved the development of the first extended wave hindcast of Gulf St Vincent to characterise the complex bimodal wave climate. The analysis proceeded to identify and investigate significant relationships between wave height and direction anomalies with climate drivers anomalies relevant to Gulf St Vincent through a spatial correlation analysis.

The study is the first to assess climate driver relationships to a bimodal wave climate within a gulf with results that highlight the importance of the consideration of bimodal conditions. Seasonal correlations were identified for the Southern Annular Mode (SAM), Southern Oscillation Index (SOI) and Dipole Mode Index (DMI) with the bimodal wave conditions in the gulf. SAM was found to have a significant inverse correlation with annual and seasonal fluctuations of both swell and sea wave parameters. With positive trends expected for SAM under climate change, the impact on the gulf will likely be a reduction of wave height and westerly component of wave direction. SOI and DMI were found to correlate seasonally wave parameter anomalies with the most significant correlations in winter for both indices. The projected increase in SOI variability and magnitude suggests that winter wave heights in the gulf will have increased year-year variance, while the relatively unknown IOD future projections remains a cause of uncertainty for the future of winter wave conditions in the gulf.

Can a one-line model be used to show the efficacy of coastal management at an annual to decadal timescale and be applied to Adelaide's managed beaches?

- Chapter 3 uses a hindcast shoreline model setup using ShorelineS to assess the efficacy of Adelaide shoreline beach management practices. A 32-year shoreline hindcast developed for Adelaide's managed beaches and validated using satellite derived shoreline change rates was first used to deduce longshore transport rates for the system and show erosion and accretion temporal dynamics along the shoreline. Simulations were then performed without the inclusion of management practices to show the significant impact of their absence. It was found that beach nourishment is required to maintain beach widths. In some locations, beach nourishment is only required due to the implementation of hard structures, however, other locations were found to require nourishment to maintain beach widths regardless of the presence of coastal structures. The median net northerly longshore transport considering the entire system was found to be between 75,000 – 98,000 m^3/year with significant seasonal fluctuations. In addition, the mean annual transport varies spatially within the system by as much as 60,000 m^3/year. Though there are several novel model applications in this study, what sets it apart from existing research is not any single methodological element, but the integration of processes to form an efficacy assessment of historic shoreline management.

What is the relationship between the seasonal and annual anomalies in directional longshore transport on Adelaide's managed beaches and climatic drivers?

- Chapter 4 investigates the climate drivers identified as relevant in chapter 2 to the temporal variations in longshore transport deduced from the Shoreline S modelling conducted in chapter 3. SAM was found to correlate significantly with longshore transport with nuanced seasonal interactions. Positive correlations were identified in winter, while inverse correlations were found for summer and spring. This means that a positive SAM contributes to greater net northerly transport in winter but less net northerly transport in summer and spring. Identifying these correlations allows coastal managers to understand the seasonal to interannual impacts of SAM on the net northerly transport which governs the requirement for beach nourishment on Adelaide's managed beaches. Though climate drivers have been linked to shoreline dynamics in existing literature, this study is the first to assess directional transport 'detrended' from the impacts of management through the analysis of modelled longshore transport.

Can a one-line model be adapted to test the future beach nourishment requirements of a managed coastline under a changing climate?

- Chapter 5 utilises the newfound understanding of shoreline dynamics and drivers from chapters 2-4, in combination with an innovative model development to assess the future sensitivity of nourishment requirements on Adelaide's managed beaches to a changing climate. An automated nourishment application tool developed as an addition to ShorelineS is presented as a tool to predict beach nourishment requirements. In this case the tool was used to assess the cumulative impact sea level rise and the year-to-year impact of wave climate anomalies and sea level rise on sand recirculation rates in Adelaide. The study found that year-to-year impacts of wave climate anomalies will play a significant role in nourishment feasibility moving forward. It’s likely that the heights of these year-to-year fluctuations in combination with the cumulative impacts of sea-level-rise will introduce the most risk to beach widths if not offset by external sand sources. The study offers a blueprint for investigations into nourished coastlines around the world, with the tool developed suitable for a number of applications in which medium to long term sensitivities and feasibility is of interest.

6.2 Recommendations

There are several future studies which should be considered based on the findings of this thesis. These studies would contribute to the collective knowledge of beach dynamics as well as improve the understanding of management requirements on Adelaide’s managed beaches. Future work for consideration is outlined in the following sections:

6.2.1 Further investigation into climate drivers impacting Adelaide’s managed beaches

Chapters 2 and 4 in this thesis identify several relationships between climate drivers and wave conditions which drive coastal change on Adelaide’s managed beaches. To identify these relationships, the seasonal and annual anomalies of wave conditions and longshore transport rates are compared to climate indices. These studies could be extended to understand in more detail the cause of these relationships and nuances such as lags, impacts to extreme conditions or the exploration into other climatic indices which describe the climate drivers.

6.2.2 Probabilistic assessment of change

The numerical modelling performed in this thesis has a significant amount of uncertainty in parametrisation, representation of physical processes, and in the measured data used for calibration and validation. Uncertainty has been discussed throughout this thesis and qualitatively appreciated through sensitivity analysis; however, the quantification of uncertainty would considerably improve the strength of the conclusions in this study. A common method adopted to quantify this uncertainty is to assign a probability distribution to the variables used in the numerical modelling and run a number of stochastic simulations to find the probability of various outcomes

(Ding et al., 2018). Though it is theoretically possible to achieve this in ShorelineS, computational constraints limit the capacity to perform this type of analysis. As the model becomes more efficient and computational abilities improve, this methodology should be considered.

6.2.3 Additional physical processes in numerical modelling

The shoreline model utilised in this thesis and shoreline models generally are under continual improvement. Having been released recently in 2020, ShorelineS has added a number of capabilities since this analysis and will continue to do so in the coming years. Processes such as dune interactions with shoreline dynamics have been added to the model's capability but not currently represented in the Adelaide Managed Beaches shoreline model. Further processes which would make the Adelaide model more robust are the consideration of cross shore processes, tidal currents, overfill dynamics of varying sediment size, and consideration for offshore sediment sources and exchanges.

6.2.4 Consideration of storms

The focus of this thesis is on the timescales of months to decades assessing trends and drivers of anomalies. To achieve this, coarse timesteps are required (e.g. 9 hours for the ShorelineS model) in which it is difficult to represent storm conditions. In addition, cross shore processes become much more significant at this shorter-term storm scenario, and these are currently not represented in the model. A possible methodology to achieve this would be to couple a model more suited to storm conditions, for example, coupling XBeach with ShorelineS. When storm conditions are identified, the storm model could be triggered and output results back to the shoreline model when more mild conditions return. Such methodologies have been adopted for the adaption of other models (Vitousek et al., 2017, Robinet et al., 2018), however this has largely been performed in a simplified manor.

6.2.5 Application of methods to additional locations

The methods used in this thesis are widely applicable to sandy coastlines around the world. There is often a focus on the short term time frame of defence against storms and the consideration of long term timeframes to combat the negative effects of sea level rise, however there is often less consideration to the medium term fluctuations of wave conditions and shoreline change which can also have significant impacts. This thesis highlights methodologies to assess the drivers of these medium-term fluctuations and quantifies the management approaches necessary to mitigate their negative impact. This understanding of medium term drivers should be considered for other coastlines worldwide, particularly those with beach nourishment schemes susceptible to the pressures posed by wave climate anomalies driven by large scale climate modes.

6.3 Concluding remarks

The impact of a changing climate on sandy beaches around the world is likely to be a key area of research in the coming decades. This thesis contributes to this body of knowledge with a focus on the climate drivers which contribute to medium term fluctuations of change as well as the longer-term pressures of sea level rise. Key to the success of this study has been the development of numerical modelling techniques which utilise the ever-improving computational resources in which researchers can access and the availability of satellite derived data which can be utilised around the world. In addition to developing novel numerical modelling techniques, this study has been able to apply wave and shoreline models to Adelaide’s coastline which are products capable of providing future insight to coastal managers and act as inputs to future studies in the region. It’s likely that computational and satellite derived resources will continue to rapidly improve in the coming decades, so it is critical that the efficient and considered application of these resources continues to improve in parallel. This will not only allow for the improved understanding of coasts in which we have existing knowledge, but also for coastlines vulnerable to the impacts of climate change that do not have a rich history of data collection.

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