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SeashoreEngineering

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Contract

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This report describes work commissioned by the City of Rockingham, on behalf of (state if the Client acted on a third-party), by an instruction dated 16 April 2024. The Client’s representative for the contract was Manoj Barua of the City of Rockingham. Alexandra Maskell and Paul Lee of JB Pacific and Glenn McCormack of Seashore Engineering carried out this work.

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Abbreviations

ADCP	Acoustic Doppler current profiler
AHD	Australian Height Datum
AWAC	Acoustic waves and currents
AWS	Automatic Weather Station
BoM	Bureau of Meteorology
Cor	City of Rockingham
DEM	Digital Elevation Model
Dm	Mean wave direction
H_{max}	Maximum Wave Height
H_s	Significant Wave Height
LiDAR	Light Detection and Ranging
LST	Longshore Transport
mAHD	metres above Australian Height Datum
MAD	Median Average Difference
MAE	Mean Absolute Error
RMSE	Root Mean Square Error
STDerror	Standard Error
SWAN	Simulating Waves Nearshore (wave model)
T_p	Wave Period
WRB	Wave Rider Buoy

Executive Summary

Warnbro Sound is a coastal area in the City of Rockingham, Western Australia, stretching from Mersey Point in the north to Becher Point in the south. The northern coastline is dynamic and has been evolving for a long time, changing through periods of erosion and accretion into the system we see today. The area is important in terms of its recreational activities, environmental ecosystems, and the build assets and infrastructure located along the foreshore. This study provides a robust scientific and numerical modelling assessment on the underlying coastal processes to support future coastal management decisions.

Tern Bank's development is significantly influenced by offshore sediment sources and seasonal wave activity, leading to alternating periods of rapid growth and stabilisation. Current estimates suggest that Tern Bank has about 20-30 years of sediment supply remaining. Interestingly, Tern Bank is following a nearly identical evolution pattern of eastward expansion and attachment to the shoreline as what occurred in the 1800s. However, unlike historical patterns, human interventions, including dredging practices, are now materially affecting its evolution. It is anticipated that over the long term (several decades), irrespective of management strategies employed, Tern Bank will undergo degradation, resulting in the filling of the Pond and redistribution of sand along the northern Warnbro Sound shoreline, smothering Bent Street boat ramp.

Mersey Point has been experiencing a low sediment supply phase since 1995, with the primary sand source—the sand bar between Penguin Island and Mersey Point—exhibiting signs of further depletion. Although a sand mass is forming in the lee of Penguin Island, it is expected to take at least a decade to reach Mersey Point. Until then Mersey Point will continue to be under erosion pressure. Given the dynamic nature of the coastline here, it is crucial to recognise that intervention structures (i.e. offshore breakwater) may become obsolete if sand bar configurations change as it has done in the past, hence highlighting the need for a flexible management approach.

Recommendations for Tern Bank:

- Permit natural coastal processes to continue and consider removing and repurposing the Bent Street boat ramp facility.
- Monitor the Pond for potential closure and proactively develop a response plan for any water quality issues, especially during low spring tides. This approach will ensure that the community can continue to enjoy the Pond while it gradually fills in, maximising its usage during the transition period.

Recommendations for Mersey Point:

- Continue nourishment of Mersey Point Vehicle Beach Access Point through back-passing from the south side of the Mersey Point Jetty, with an estimated rate of 1,000 to 2,000 m³ per year.

- Supplement back-passing efforts with sand from the Point Peron sand trap, requiring a balanced sediment supply of approximately 3,000 to 4,000 m³ per year on average.
- Periodically, reassess nourishment volumes based on changing environmental conditions.
- Restore the beach fronting the revetment through sand nourishment of approximately 13,700 m³ to mitigate erosion pressures on Arcadia Drive and the Carlisle Street boat ramp.
- Incorporate bathymetric surveys every 5 to 10 years within the Coastal Management Plan to enable informed coastal protection strategies and accurate predictions of sediment supply variations.

1 Introduction

The coastline of northern Warnbro Sound is dynamic and has been changing for a long time, with areas shifting between periods of erosion and accretion (i.e., the loss and build-up of sand) shaping the coastline that we see today. These coastal changes have necessitated ongoing interventions to protect public facilities and maintain coastal amenities, particularly along Arcadia Drive and at the Bent Street Boat Ramp.

Today, the coastline continues to change, presenting several challenges:

- **Erosion:** Since around 1992, parts of the shoreline near Mersey Point have been eroding, moving closer to Arcadia Drive and nearby public spaces. In some areas, the shoreline has retreated by as much as 10 meters per year, with a total loss of about 150 meters over time.
- **Movement of Tern Bank:** Tern Bank has been shifting over the years, requiring yearly dredging to keep the Bent Street Boat Ramp accessible for boats. The sandbank first connected to the shore in 1995, moved and built up in different areas between 1995 and 2005, and has been shifting eastward since 2006. Since 2020, its shape has changed more rapidly, rotating towards the land.
- **Changes to the Pond:** A popular kite surfing area behind Tern Bank, known as the Pond, may be affected by these shifts. If the sandbank moves too far inland, it could reduce water flow and impact water quality. Since 2021, the head of Tern Bank has been moving closer to the Bent Street Boat Ramp, raising concerns about accessibility and environmental changes.

Over time, the strategies used to manage these changes have become more difficult to maintain, either because the coastal changes are too significant for current solutions, or because the cost of managing them has increased. This study is part of a larger effort to explore new ways to protect and manage the northern Warnbro Sound coastline for the future.



Figure 1-1: Map of study area.

1.1 Objectives of the study

The objectives of the Warnbro Sound Modelling project are to enhance the understanding of coastal processes and develop sustainable solutions for shoreline protection and maintaining of amenities.

Key objectives include:

- Coastal Processes Assessment (Seashore Engineering):
 - Understand historic trends in sediment movement in the local area and key metocean drivers.
 - Understand recent sediment accumulation trends at Tern Bank.
 - Assess future evolution of The Pond.
 - Understand recent erosion/accretion trends at Mersey Point
 - Assess future evolution of Mersey Point
- Coastal Stabilisation (JB Pacific):
 - Evaluate feasibility of maintaining Bent Street Boat ramp access.
 - Assess sustainable protection options along Arcadia Drive and Mersey Point.

1.2 Scope and Limitations

This study has been undertaken by JB Pacific and Seashore Engineering. It aims to assess the coastal dynamics of northern Warnbro Sound and evaluate potential engineering solutions to address ongoing challenges such as erosion, sediment transport, and infrastructure protection. The scope of the study includes:

1. Assessment of Coastal Processes:
 - a. Analysis of historical and recent coastal changes, with a focus on shoreline evolution, sediment movement, and erosion trends at key locations such as Tern Bank and Mersey Point.
 - b. Identification of key metocean drivers influencing sediment transport, including wave climate, tides, and seasonal variations.
2. Numerical Modelling:
 - a. Development and application of a suite of numerical models to simulate sediment dynamics with the view to assess coastal protection options.
 - b. Calibration and validation of models using available historical data, aerial imagery, and recent bathymetric surveys.
3. Evaluation of Engineering Solutions:
 - a. Assessment of potential coastal management options, including nourishment, revetments, dredging, and alternative non-structural interventions.
 - b. Consideration of environmental, social, and economic factors in selecting the most feasible options.

Despite the comprehensive approach, it is important to highlight that the study is subject to several limitations. These include:

Table 1-1: Study limitations.

Category	Limitation	Description
Data Constraints	Limited Historical Records	Incomplete or inconsistent data on past shoreline changes and sediment transport may introduce uncertainties in model predictions.
	Spatial and Temporal Gaps	The availability of high-resolution datasets is limited, which can affect the calibration and validation of numerical models.
Numerical Modelling Limitations	Simplifications and Assumptions	Models rely on assumptions regarding sediment properties, hydrodynamic conditions, and boundary conditions, which may not fully capture real-world complexities.
	Computational Limitations	High-fidelity simulations require significant computational resources, which may limit the resolution and scope of modelling scenarios.
	Extreme Event Prediction	Models may struggle to accurately capture the impact of extreme storm events or climate change-driven processes such as sea-level rise.
Engineering Challenges	Dynamic Coastal Environment	The highly variable and evolving coastal system makes it difficult to implement long-term static solutions without adaptive management strategies.
	Effectiveness of Structural Solutions	Hard engineering solutions such as revetments and seawalls may lead to unintended consequences, such as increased erosion in adjacent areas.
Regulatory and Financial Constraints	Environmental Restrictions	Proposed interventions must align with regulatory frameworks, which may limit available engineering options.
	Budgetary Constraints	The cost of implementing and maintaining engineering solutions may be prohibitive, necessitating prioritization of options within available funding.
Stakeholder Expectations and Public Perception	Differing stakeholder interests and community expectations	Differing stakeholder interests and community expectations may influence decision-making, potentially leading to compromises that impact the effectiveness of proposed solutions.

1.3 Common datums and terms used in the report

Datums and naming conventions remain a significant source of uncertainty in any coastal study. The definitions used throughout this report are listed below.

- All vertical elevations have been measured from the Australian Height Datum (AHD), which normally approximates mean sea level within a range of several centimetres.
- Winds and waves are designated by the direction they come from. Both a south-easterly wind and wave originates from the southeast.
- Currents are designated by the direction in which they are going. A northerly current is flowing from south to north.
- Longshore sediment transport is the movement of sand parallel to a beach. When standing on a beach facing the ocean, the convention is typically that 'rightward' directed transport is considered positive and 'leftward' directed transport is considered negative. This can cause confusion, so within this report the main direction is typically stated.
- When referencing changes to a beach profile, a negative shoreline change indicates landward movements (erosion, recession or a general loss of sediment) and positive shoreline change indicates a seaward movement or accretion.

There are many coastal parameters referenced throughout the report, which include:

- Significant Wave Height (H_s)
- Maximum Wave Height (H_{max})
- Wave Period (T_p)
- Mean wave direction (D_m)

2 Background

2.1 Study Area

Warnbro Sound is a coastal area in the City of Rockingham, Western Australia, stretching from Mersey Point in the north to Safety Bay in the south. It features key natural landmarks such as Tern Bank and Penguin Island, which play an important role in shaping the coastline. The area is influenced by several nearshore sand bars that contribute to the ongoing coastal changes. These features, combined with prevailing oceanographic conditions, make Warnbro Sound a dynamic coastal system requiring careful management to balance erosion control, recreational use, and environmental conservation.

2.2 Current Environmental Conditions

2.2.1 Shoreline characteristics

The shoreline of Warnbro Sound is made up of sandy beaches and dunes that help protect the coast from erosion. The beaches are shaped by dynamic processes influenced by tides, waves, and wind patterns. During the summer months, prevailing south-westerly winds contribute to the widening of beaches, while winter storms lead to erosion, causing the shoreline to retreat.

Several prominent coastal features shape the shoreline dynamics of Warnbro Sound (Figure 2-1). Cuspate forelands, such as those at Mersey Point, and offshore sand bars contribute to the redistribution of sediments along the coast. Tern Bank, a dynamic sand spit, has been gradually migrating eastward, influencing local beach profiles and posing challenges for navigation and beach access. These features, coupled with tidal and wave-driven forces, create a constantly changing coastal landscape, which can affect how people use the beach and how local wildlife habitats develop.



Figure 2-1: Local sedimentary features (Aerial image captured in October 2014).

2.2.2 Ecosystem and Habitat Overview

Warnbro Sound is home to a diverse range of coastal and marine habitats that support rich biodiversity and provide important ecological services. Seagrass meadows are one of the most significant features of the area, playing a crucial role in stabilising sediments, improving water quality, and offering habitat for fish and other marine species. However, recent observations have shown a decline in seagrass coverage due to increased sediment deposition from Tern Bank.

The marine ecosystem in Warnbro Sound supports a variety of fish species, seabirds, and other marine organisms, making it an important part of the Shoalwater Islands Marine Park. Changes in water circulation and sediment dynamics could have long-term effects on these ecosystems, potentially impacting recreational and commercial fishing activities. The lagoon area known as "The Pond," a popular spot for water sports, is at risk of decreased water quality due to shifting sandbanks that may restrict water flow and lead to stagnation. These environmental changes highlight the need for continued ecological monitoring and adaptive management strategies to ensure the protection of the area's unique habitats.

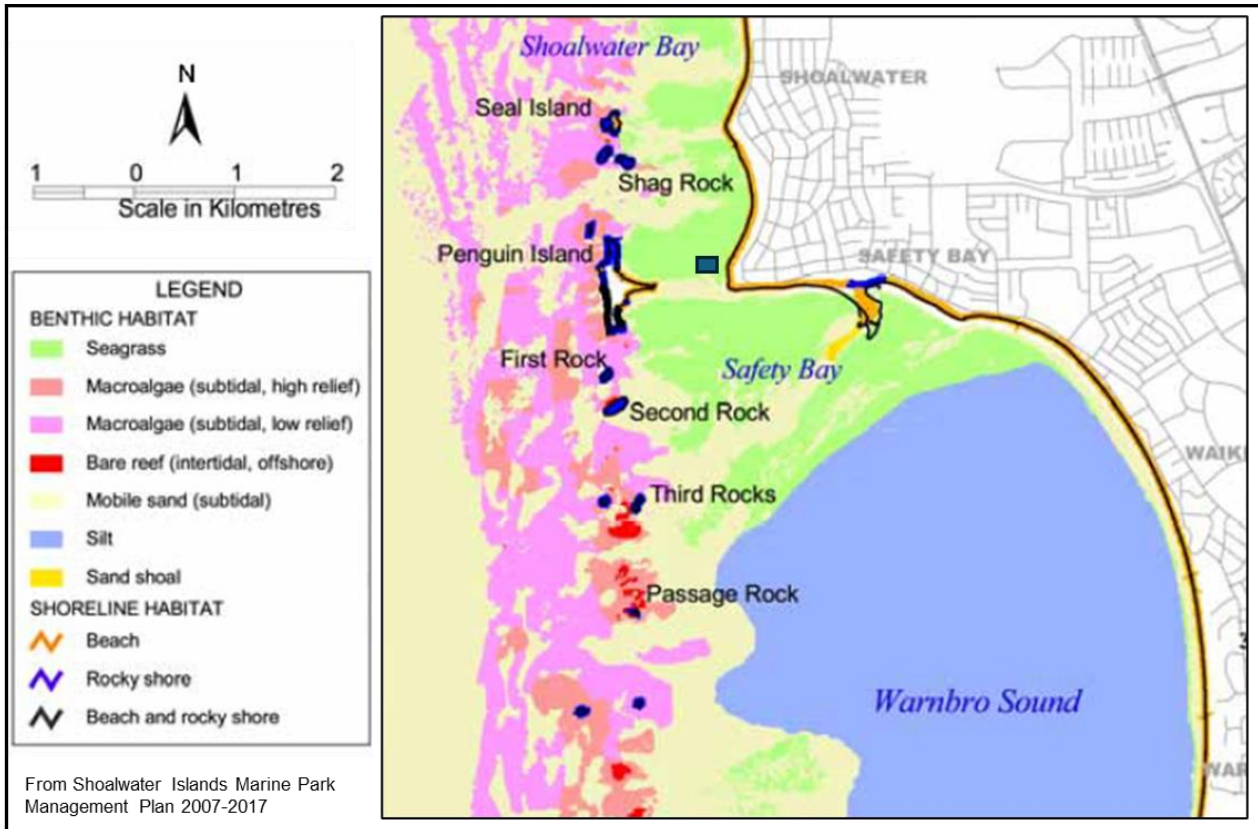


Figure 2-2: Map showing key environmental habitats within northern Warnbro Sound (from Shoalwater Islands Marine Park management plan 2007-2017¹).

2.3 Coastal Dynamics

The coastal areas of Mersey Point and Tern Bank in Warnbro Sound have been undergoing significant natural changes driven by sediment transport, wave action, and seasonal weather patterns. These changes have led to challenges such as erosion at Mersey Point and sand buildup (accretion) at Tern Bank, affecting local infrastructure and recreational areas. Seashore Engineering undertook a comprehensive Coastal Processes Assessment as part of the wider project. Key findings are discussed throughout this report. Their detailed report is provided in Appendix A.

2.3.1 Coastal Processes Driving Change

The coastal changes at Warnbro Sound are primarily influenced by a combination of natural and human-driven factors. Seasonal wave and wind patterns play a crucial role, with higher wave energy during the winter months (May–September) driving increased sediment transport and shoreline adjustments. During the summer months, calmer conditions allow for sediment stabilization and temporary beach widening.

¹ Western Australia Department of Environment and Conservation. (2007). Shoalwater Islands Marine Park management plan 2007–2017. <https://www.dbca.wa.gov.au/media/1367/download>

Offshore reefs, such as those near Penguin Island, provide partial protection from wave energy but also influence where sediment is deposited or eroded. These natural barriers contribute to the dynamic nature of the coastline, creating localized erosion and deposition patterns. Additionally, rising sea levels and climate variability may be accelerating the processes of erosion and accretion, presenting new challenges for long-term coastal management.

2.4 Key Stakeholder Concerns

The ongoing coastal changes in Warnbro Sound have raised several concerns among local residents, businesses, and environmental groups. One of the primary concerns is the erosion along Arcadia Drive, which poses a threat to the Penguin Island Visitor Centre and Carlisle St Boat Ramp. The encroaching shoreline requires costly maintenance and potential future interventions to ensure public safety and asset protection.

Another major concern is the accumulation of sand at the Bent Street boat ramp, which impacts boating access and has necessitated frequent dredging operations. The recurring need for dredging to maintain this asset places a financial burden on local authorities and raises questions about long-term solutions to the issue. In addition, Recreational Users, including Boat Users, Swimmers and Kite Surfers have reported changes in water depth and beach configurations that affect their activities.

Environmental conservation is also a significant stakeholder concern, with the community emphasising the importance of preserving the ecological integrity of the Shoalwater Islands Marine Park. Any coastal management efforts must carefully balance development needs with environmental protection goals to ensure the long-term health and sustainability of the region. Balancing environmental protection with coastal development and recreational usage remains a key challenge for the City of Rockingham and other stakeholders involved in the management of Warnbro Sound.

3 Methodology

This study provides a robust scientific and modelling assessment to support future coastal management decisions. This includes:

Data Collection and Analysis:

- **Coastal processes review:** Regional to local-scale review of coastal processes, analysed by Seashore Engineering in their report “Northern Warnbro Coastal Processes Assessment” (see Appendix A). This included analysis of historical and recent datasets, including aerial photos, bathymetric surveys, ocean conditions, such as wave heights, wind patterns, and tide levels. This data helps us understand how the coastline has evolved over time, allowing us to identify long-term trends and patterns in shoreline movement and erosion, as well as what factors influence how sand moves along the coast and the overall shoreline shape.

Modelling Coastal Processes:

- **Wave and Current Modelling:** To simulate how waves and tides behave as they move toward the shore.
- **Sediment Transport Modelling:** The movement of sand and sediment is a crucial part of shoreline change. We model how waves and currents move sediment in the nearshore.
- **Shoreline Evolution Modelling:** By integrating wave, current, and sediment transport models, we model how the shoreline will change over time.

Evaluating Coastal Management options:

- **Hard Engineering Solutions:** where erosion is threatening infrastructure, we have built protective structures like seawalls, revetments and breakwaters. These are designed to shield the coast from wave impacts and slow down the erosion process. We assess how well these structures perform and whether they may have unintended consequences, such as transferring erosion to other areas.
- **Soft Engineering Solutions:** Where erosion is occurring, soft options such as sand/beach renourishment can help maintain healthy large beaches. We assess the viability of sand nourishment to protect Mersey Point, Arcadia Drive and Carlisle St Boat Ramp. Where accretion is reducing the functionality of assets, options such as dredging can maintain their use. We assess the feasibility of maintaining access to Bent St boat ramp and possible impacts.

4 Tern Bank

4.1 Coastal Dynamics

4.1.1 Historic

Records from the 19th century show a large-scale episode of coastal accretion occurred along Safety Bay foreshore (Figure 4-1), with rapid landward movement of a large sand spit, very similar to today's configuration of Tern Bank. The 1832 survey is coarse but suggests a large sand mass was present south of Mersey Point. By the 1838 and 1839 surveys, this sand mass had rotated and extended eastward connecting to the shore near today's location of the Bent Street boat ramp. It subsequently entered a second phase of eastward extension and by 1859 a second connection to the shore had occurred between Berry Street and June Road creating two partially connected water bodies. These water bodies disappeared over time and were not recorded in the 1876 survey. The shoreline was significantly advanced by this accretion event, with topographic maps suggesting the relict 1800s frontal dune is located ~250 m landward of the current shoreline. A simple estimate from elevation data by Seashore Engineering suggests that approximately 1.2 to 1.8 million cubic metres of sand likely came onshore during this event (Figure 4-2).

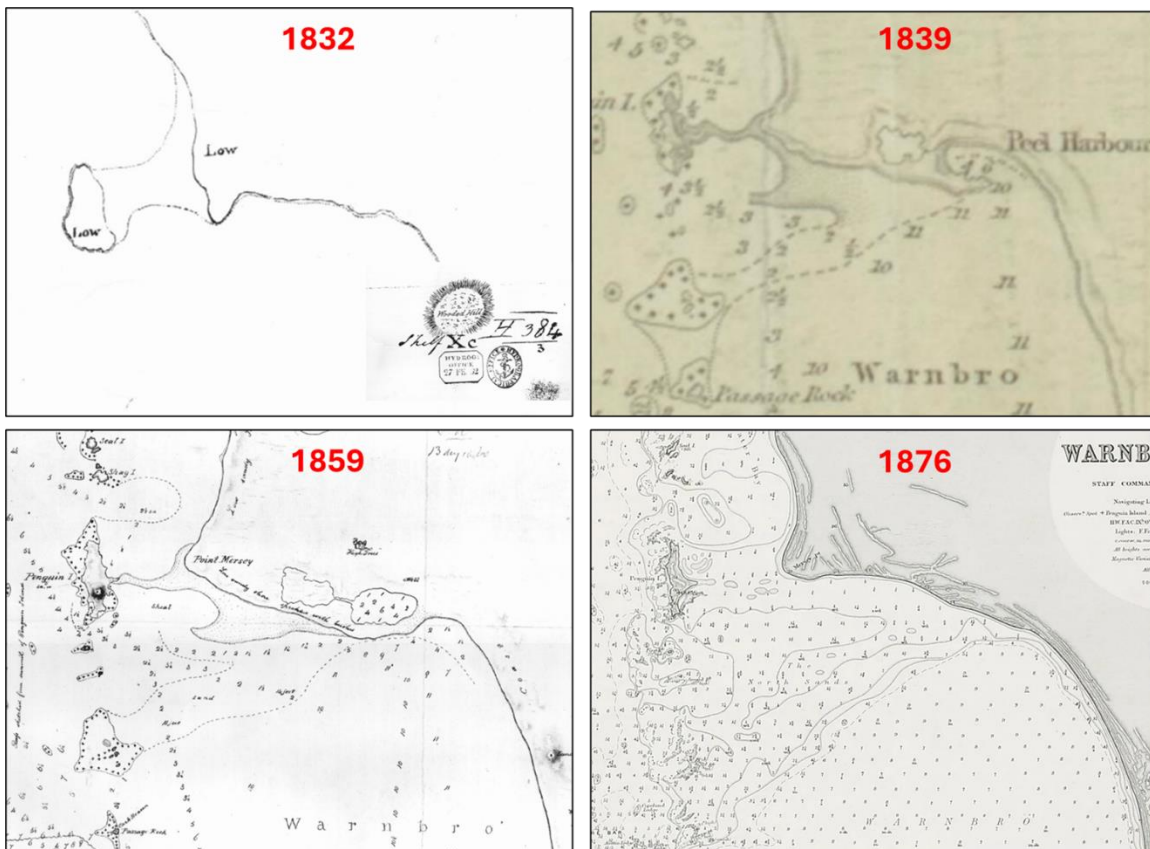


Figure 4-1: Historical Surveys from 1800s. Sources: 1832 Survey of Mangles Bay by Hydrographic Office; 1839 Survey by J. S. Roe; 1859 Survey of Warnbro Sound (Historical Plan No. 302); 1876 (1923) Admiralty Chart – Western Australia.

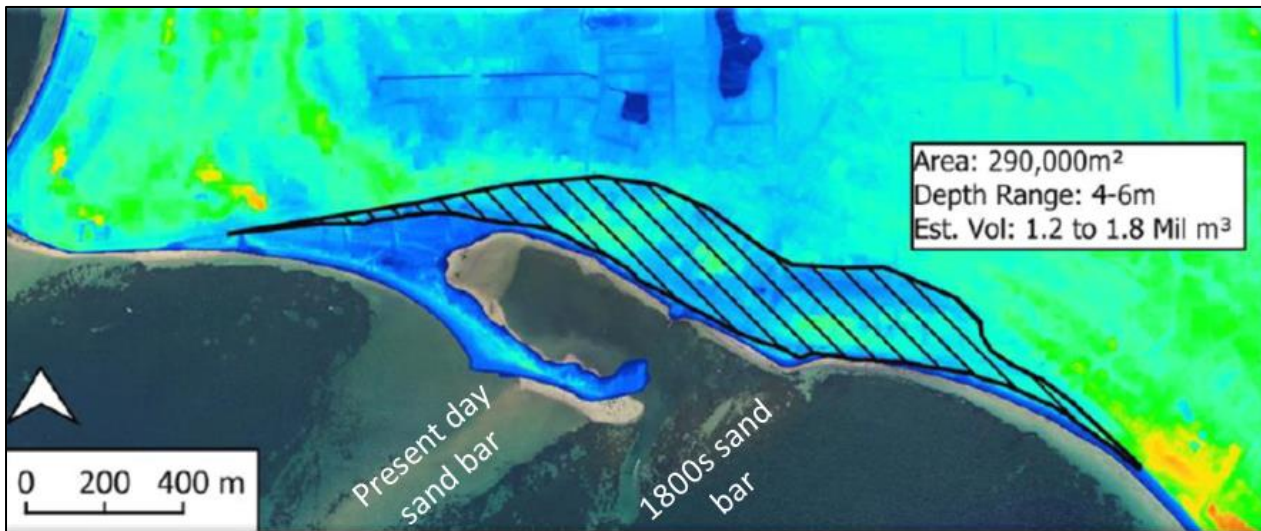


Figure 4-2: Elevation map (blue - lower elevation, yellow - higher elevation) with hashed zone showing approximate location of relict frontal dune from 1800s accretion event (Seashore Engineering, 2024).

4.1.2 Current

Today, Tern Bank is following a nearly identical pattern of eastward expansion and attachment to the shoreline as that in the 1800s (Figure 4-3).

Volume estimates from elevation data suggest that approximately 0.7 million cubic metres of sand have already come onshore forming the bulk of what we see as Tern Bank, with approximately the same volume stored in the Safety Bay sand bar, waiting to come ashore. Year-on-year growth rates of Tern Bank have varied significantly, ranging between 4,000 and 36,000 m³/yr between high and low supply phases, with an average growth rate of ~16,000 m³/yr over the last decade. High supply phases are driven by the steepening of the bar forming a distinctive ridge, followed by low supply after ridge collapse/deflation. Since 2018, there has been high onshore supply attributed to high long period swell events in 2018 and subsequently supported by periods of high wave energy (e.g. strong summer sea breeze seasons from 2020-2024)

Over a year, there are distinct seasonal patterns of change. During winter, high energy storm waves converge along the sand bar leading to the formation of a well-defined elevated ridge, this is followed by increased onshore sediment transfer and subsequent extension and rotation of the head of Tern Bank spit. During the summer, water levels and wave energy are lower, leading to reduced onshore sediment supply and smoothing out of shoreline features. However, strong summer sea breeze seasons can generate sufficient energy waves to maintain increased onshore sediment transfer.

As shown in Figure 4-4, the sediment budget of this Tern Bank is primarily controlled by the sand bar sediment source, which supplies the majority of material (16,000m³/yr) to the spit

through wave action. Alongshore transport from Mersey Point contributes additional sediment (~3,000m³/yr), but in relatively small volumes compared to the sand bar supply. Further east, sediment transport is limited due to reduced wave energy, effectively making a semi-contained sediment cell. As a result, Tern Bank has continued to accrete, with limited redistribution beyond the immediate area (see Appendix A; Section 5 for derived sediment budget from Cape Peron to east of Tern Bank).

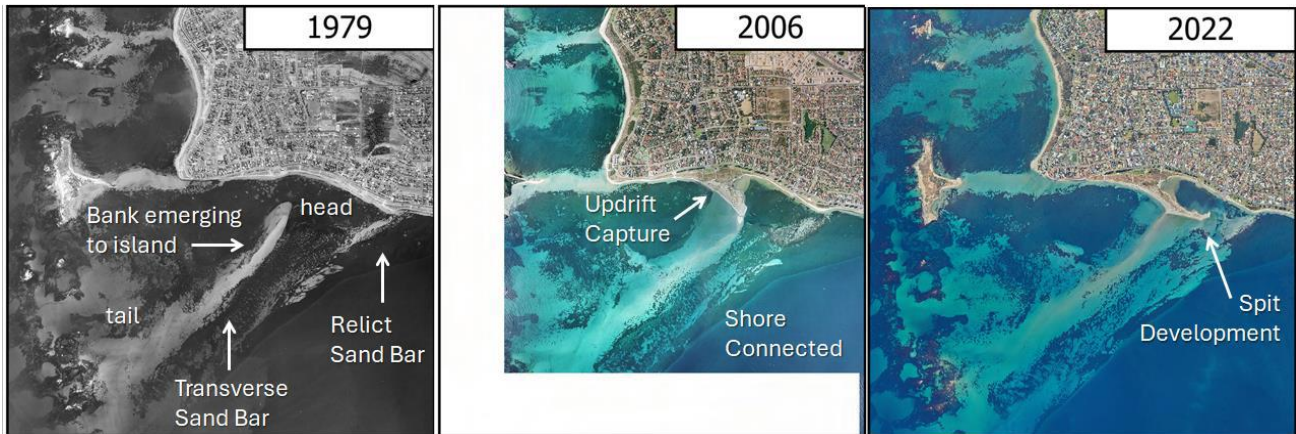


Figure 4-3: Tern Bank evolution

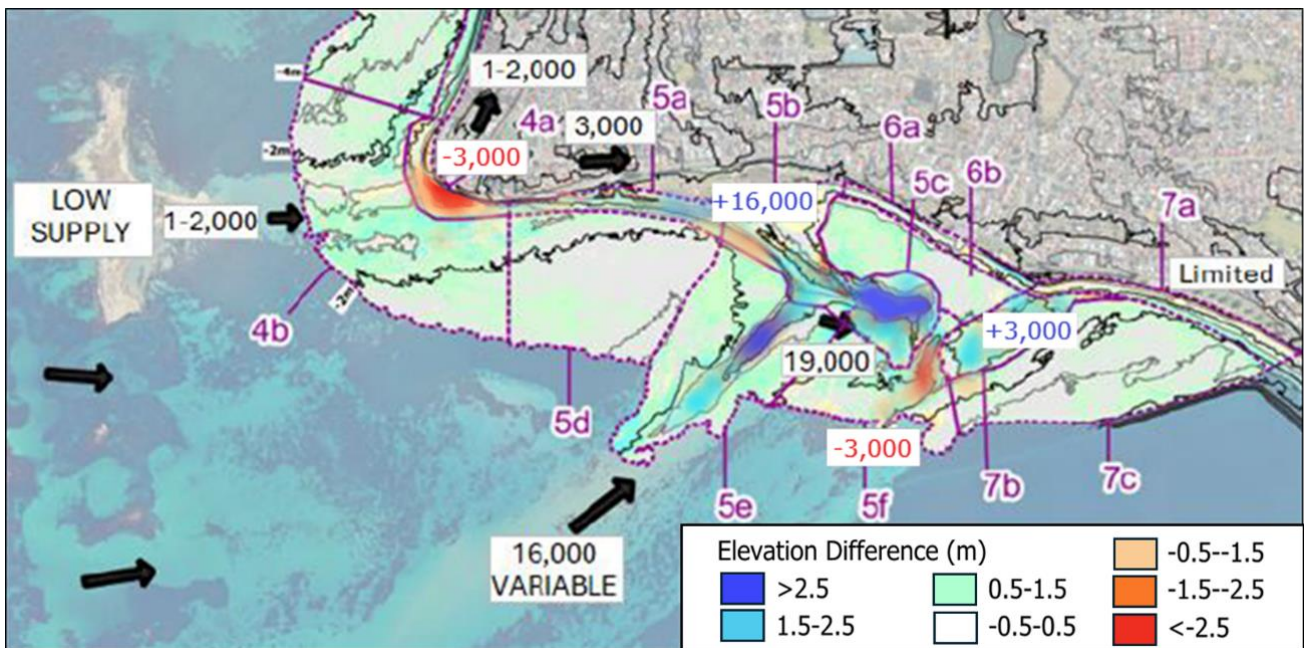


Figure 4-4: Sediment Budget Derived for 2008/09 to 2021/23 based on elevation differences. Values in m³/year. Zoom in of Figure 5-1; Appendix A.

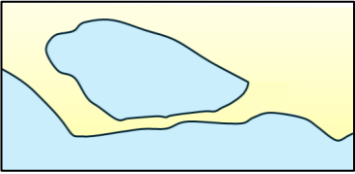
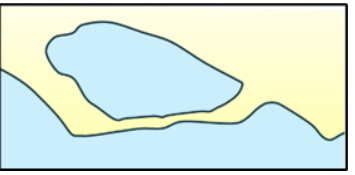
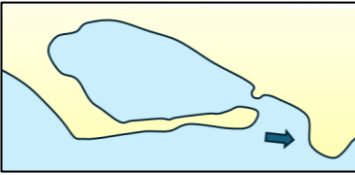
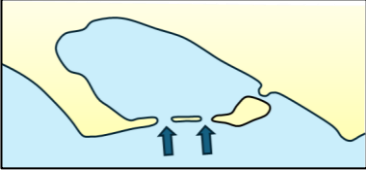
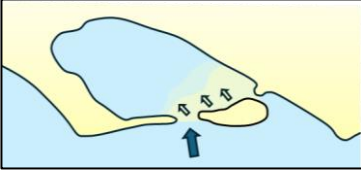
4.1.3 Future

The ongoing coastal changes at Tern Bank are remarkably similar to patterns observed in the past, particularly during the 1800s and early 1900s. The cyclical nature of sediment transport, erosion, and accretion shows that these processes are ongoing and to some extent predictable. Based on these observations, several potential future changes are expected:

- Tern Bank is expected to remain highly dynamic over the next few decades, influenced by ongoing sediment supply from the Safety Bay sand bar. The spit's evolution will continue to be shaped by variable sediment availability, prevailing weather conditions, and management interventions such as dredging.
- Safety Bay sand bar will continue to supply sediment for at least the next 20-30 years. Since 2013, the removal of approximately 180,000m³ of sediment has significantly altered the spit's growth, reducing its overall volume by nearly 40% and slowing eastward expansion. For this reason, it is unlikely that another phase of eastward extension with formation of a second pond will occur as what happened during the 1800s accretion event.
- In the short term (1-5 years), Tern Bank is likely to experience several changes based on current trends and management actions, plausible changes are outlined in Table 4-1.
- Generally, the spit is most likely to continue rotating shoreward each winter, progressively infilling the Pond from the eastern end as it folds inward.

In the longer term, as sediment supply diminishes; the spit will collapse, the Pond will be infilled, and accumulated sediments will redistribute along the northern margin of Warnbro Basin, with a small quantity potentially transferring towards Mersey Point. The future shoreline will be positioned well landward of the position prior to the development of Tern Bank (i.e. pre-1995), which will bury Bent Street boat ramp.

Table 4-1: Possible Changes to Tern Bank spit in the Shorter-Term (1-5 years)

#	Possible change	Description	Variability
A 	Spit connection to the mainland	If the spit connects to the mainland, substantial sediment delivery will occur at or near the boat ramp and redistribute eastward. The spit head was already encroaching on the Bent by the end of 2024.	More likely without management (sediment removal)
B 	Closure of the Pond	Lack of flushing over extended periods could result in degraded water quality within the Pond, especially if this coincides with high temperatures during the summer months.	Likely requires low water levels (e.g. around October) and no management.
C 	Accretion east of Bent Street boat ramp	Increased sediment delivery to shore east of the Bent Street boat ramp may occur due to the release of sediments previously stored in the remnant 1800s bar, as seagrass has been smothered since 2018.	Greater during high swells.
D 	Elongation and narrowing of the spit	Driven by increasing eastward transport potential under winter wave conditions and supported by the shoreward rotation. This creates a local sediment transport imbalance, increasing the likelihood of breaches and subsequent formation of new entrance channels.	Enhanced during low supply phase.
E 	'New' channel to Pond established further from shore	If formed, the channel is likely to remain relatively small and shallow due to the limited tidal prism of the Pond. Sedimentary features left on its east/landward side will degrade, infilling the Pond through over washing and supplying sediment to the shore.	Enhanced during low supply phase.

4.2 Shifting benefits

When considering coastal protection strategies or any coastal management it is important to consider the benefits and perceived values a site has, how they have changed over time and how they might be impacted in the future.



Tern Bank coastline is constantly evolving, often rapidly and in dynamic ways. Its unique configuration currently provides significant public value, supporting a range of recreational and environmental activities—notably kite surfing, swimming, and boating. We have identified several key attributes that support activities at the site, benefiting various stakeholders and user groups. These include the esplanade, shallow and protected waters, shorebird habitat, boat ramp, and ocean access (Table 4-2).


Table 4-2: Summary of attributes of Tern Bank and "The Pond" and the associated benefits.

Attribute	Benefits	Uses
Esplanade	Safe space for recreation promoting physical health and social interaction	Walking, cycling, running, accessibility for all users
	Green spaces and seating areas for relaxation	Picnicking, social gatherings, unwinding
	Provides scenic views	Boosts mental well-being
	Space for community and cultural events	Markets, performances, festivals
Shallow Waters	Calm and safe for all ages	Swimming, wading, paddling
	Accessible environment for families	Family-friendly recreation, play areas
	Favourable conditions for wind-based sports (easy to launch)	Kite surfing, windsurfing
Protected Waters	Smooth conditions for skill development	Kite surfing, windsurfing (safer learning environment)
	Reduced wave energy makes swimming safer	Swimming, stand-up paddleboarding, kayaking
Shorebird Habitat	Supports biodiversity and ecological balance	Habitat conservation, bird watching
	Provides opportunities for eco-tourism	Nature appreciation, photography, guided wildlife tours
	Enhances public understanding of ecological importance	Educational signage, conservation awareness programs
Boat Ramp	Enhances access for recreational and commercial activities	Boating, fishing, powered recreational craft
	Marine safety	Emergency access, marine rescue operations
Access to Ocean	Facilitates offshore access for various activities	Boating, offshore fishing, diving, spearfishing
	Supports scientific studies and environmental monitoring	Marine research, conservation studies

The benefits derived from these attributes is expected to continue changing overtime. We explain how current uses may be affected under the different future scenarios in Table 4-3. Notably, the potential changes are not expected to have any influence on esplanade related activities and will primarily impact water, and shorebird habitat related activities.

Table 4-3: Illustration of potential future changes and how they may impact users of "The Pond" at Tern Bank.

Scenarios	Description	Impacts
	<p>A: Sand build up creates unsafe conditions for boating; or obstructs access altogether</p> <p>B: Reduced flushing of the system creates poorer water quality; unlikely to become hazardous</p>	<p>A: Boat users are required to use substitute sites</p> <p>B: Minor impact to direct water uses such as swimming, and water/wind sports (kiting and windsurfing)</p>
	<p>C: New sandy point creates additional beach area</p> <p>D: Potential for increased wave overtopping, which may impact the depth and area of water of 'The Pond'.</p>	<p>C: Covers seagrass environment</p> <p>D: Less area for kite surfing and other protected water activities; Reduced shorebird habitat</p>

Scenarios	Description	Impacts
	<p>E: May impact the level of protection in the 'The Pond' (i.e., how calm the water is).</p>	<p>E: Impact swimming and other protected water activities; Reduced shorebird habitat</p>

It is worth illustrating how future scenarios may lead to reduced values for activities in protected and shallow waters, shorebird habitats, and the boat ramp, while also highlighting the relatively recent emergence of some of these benefits (Figure 4-5). For example, the Bent Street boat ramp, built in the 1990s, is now becoming obstructed by sand, diminishing its usefulness. Similarly, Tern Island joined the mainland in 1995, but it wasn't until 2005 that it began migrating east, creating the protected waters that now benefit kite surfers and other users. These benefits are expected to diminish over time as Tern Bank degrades and the Pond fills in (Table 4-3).

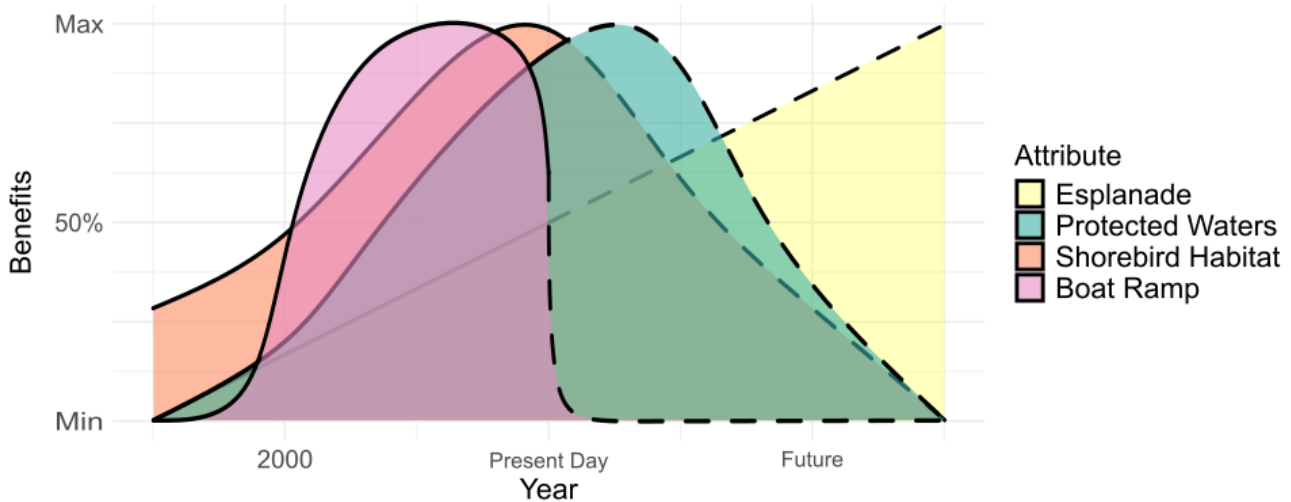


Figure 4-5: Illustration of shifting benefits over time at Tern Bank.

4.3 Options

The appraised design life for coastal management options at Tern Bank is 20-30 years, which is how long sediment will likely continue to supply Tern Bank.

Two options were appraised:

- Dredging & channel relocation
- Repurpose boat ramp facility

4.3.1 Dredging & channel relocation

Since 2013, the City has undertaken dredging to maintain a navigable channel for boat access to/from Bent Street boat ramp. Campaigns have occurred every year since 2021, with a substantially greater volume removed over three campaigns in 2022 which required additional approvals. Despite this, dredging was still required in 2023. In November 2024 the City of Rockingham ceased dredging.

To maintain boat ramp access, removal at an average excavation rate of 20,000m³ a year is required to keep pace with ongoing growth. Continued sediment removal is necessary, most likely for at least another 20-30 years - this is based on the volume of sediments within the sand bar feeding Tern Bank.

If dredging were to recommence a larger-scale initial excavation may want to be considered to reduce the immediate threat of direct smothering from the spit connecting to the shore at the boat ramp site. It is important to note that any significant reduction in spit volume will accelerate Tern Bank's degradation, likely increasing the rate of loss of the sheltered area within the Pond used for recreation.

Upon review, there is little value in relocating the navigation channel, as the current evolutionary pattern, with the spit folding inwards towards the shore, mean sedimentation at the boat ramp will continue to be an issue for the foreseeable future.

4.3.2 Remove and repurpose boat ramp facility

Ongoing excavation of sand from Tern Bank spit has a high cost, and removes sediment from the littoral system, that would otherwise naturally act to build resilience of the Rockingham coast. An alternative to excavation is allow the natural coastal processes to continue. This would likely mean that Bent Street boat ramp would no longer be operational and therefore the City may wish to remove and repurpose of the boat ramp facility.

Ceasing of dredging will likely prolong the lifespan of the Pond. Potentially giving another decade or so of recreational use. However, ultimately, regardless of management choice, long-term the spit will degrade, and the Pond will fill in progressively from the east.

During spring, when tidal ranges are low, there will be a risk of the Pond closing. The City should monitor the Pond for potential closures and determine an appropriate response to mitigate impact on water quality if required (e.g. channel excavation).

5 Mersey Point

5.1 Coastal Dynamics

5.1.1 Historic

Historical comparisons suggest that Mersey Point has undergone multiple phases of erosion and accretion as follows (illustrated in Figure 5-2):

- **1942 - 1995:** Mersey Point experienced significant sand buildup due to onshore sediment transport from the Penguin Island sand bar. Sand was able to build up in the lee (sheltered sides) of Penguin Island due to waves bending and spreading around Penguin Island (refraction and diffraction), which concentrated sand and created a pathway transporting sand toward Mersey Point. Between 1980 and 1995, the trend continued, however, Penguin Island was becoming smaller.
- **1995 - 2018:** From 1995, Mersey Point saw a reversal of the previously accretionary phase, this shift was driven by diminishing sand supply from Penguin Island.
- **2018- Present:** Since around 2018 to the present, this erosional trend has persisted, characterised by substantial deflation of the Penguin Island sand bar, further increasing the northward migration of Mersey Point and exacerbating erosion on the south side. As a result, this has resulted in the need to implement infrastructure such as the Arcadia Drive revetment wall and renourishment efforts in order to maintain the shoreline stability.



Figure 5-1: Penguin Island-Mersey Point sand bar evolution (Seashore Engineering, 2024).

5.1.2 Current

The sand bar connecting Penguin Island and Mersey Point has acted as the primary source of sediment for Mersey Point. The sand bar has been in a low supply phase since 1995, and has experienced significant deflation (reduction in volume and height) in the past couple of years. With the reduced size of the bar, less sediment is available to replenish Mersey Point, contributing to significant shoreline retreat, particularly on the southern side along with northward migration of the tip of Mersey Point.

Over the past decade, the average deficit of sediment at Mersey Point has been ~3,000 m³/yr. This has increased erosion pressure on key assets, such as Arcadia Drive, and reduced the ability of the coastline to weather storms - resulting in the need to construct the rock revetment along Arcadia Drive in 2021. Because the Mersey Point is in a low supply phase, the construction of the Arcadia Drive revetment has caused flanking erosion at its edges, requiring renourishment works to protect the foreshore fronting the Penguin Island Visitor Centre.

Seasonal changes continue to shape sediment movement, with the tip of Mersey Point tending to migrate northward under summer sea breezes and shift southward in winter due to changing wave patterns.

5.1.3 Future

Erosion at Mersey Point is projected to persist in the short to medium term due to decreased sediment supply from offshore sources, including the depletion of the Penguin Island sand bar and the northward migration of Seal Island's cusped foreland. The movement of the Mersey Point cusped foreland has increased exposure to coastal infrastructure, particularly the Arcadia Drive revetment, which may exacerbate erosion through flanking effects.

Potential future changes for Mersey Point include:

- **Continued Focal Erosion on the South Side:** If the Penguin Island bar remains in its current deflated state and connected to the shore, erosion will intensify, further threatening public assets.
- **Temporary Erosion Reduction:** A shift in the bar's crest further south could temporarily reduce erosion pressures on the southern shoreline while increasing stress on the northern sections.
- **Long-Term Sediment Supply:** Recent growth of the leeside sand mass on Penguin Island suggests a potential increase in sediment availability, but significant shoreline accretion from this source is likely to take decades.

As Tern Bank degrades, a portion of its sediment may migrate northwest, contributing to potential changes in sediment distribution at Mersey Point.

5.2 Options Assessment

Management at Mersey Point requires a strategic approach to address ongoing erosion and the protection of vulnerable infrastructure. We have developed a suite of calibrated/validated numerical models to support evaluation (See Appendix B). Several managements options have been assessed, particularly looking at how existing and proposed management options such as groynes, revetment walls, and beach nourishment, will be influencing sediment transport patterns. Illustrated below in Figure 5-2, we have explored five management options intended to assess their effectiveness in managing the ongoing issues at Mersey Point.



Figure 5-2: Schematic of management options assessed for Mersey Point.

Summarised in Table 5-1, the modelling process involved the simulation of six seasonal environmental conditions which have significant potential to move sand. Selected periods are characterised by times in which there was high energy (i.e. from strong swells and wind) and lower energy (i.e. from calmer swell and winds) during Winter and Summer months.

Table 5-1: Summary of modelling scenarios.

	Winter Season	Long-period swell	Summer sea breezes
High	2020	25/05/2018 event	2022/23
Model	2022	-	-
Low	2015	-	2018/19

5.2.1 "Do Nothing"

"Do nothing" assumes no future management. It is used as a baseline scenario to support options appraisal. Modelling suggests that should no interventions occur, there will be continued erosion pressure at the flanks of the Arcadia Drive Revetment, exasperated by the continued low supply of sediment from the sand bar to Mersey Point and scouring along the toe of the revetment. The modelling uses average yearly conditions therefore short-term erosion due to storm events will be larger. The Unibest-CL model underestimates erosion due to model limitations associated with the simulation of wave reflection and increased turbulence-induced erosion at structure. The model suggests erosion rates at the western flank of the Arcadia Drive revetment wall approaching 25m, and at the eastern flank around 37m. Satellite images shows that the shoreline has retreated ~30 m since construction of the revetment. The prolonged low supply of sediment to Mersey Point is highlighted by the rate of shoreline retreat following the October 2024 beach nourishment works (Figure 5-4).



Figure 5-3: Coastline modelling results, adopting a 'Do Nothing' approach, modelled with average yearly conditions. NB: average conditions underestimating rate of erosion at west tip of revetment.



Figure 5-4: Aerial images from recent October 2024 back-passing campaign (Nearmap imagery) showing extent of focal erosion following nourishment.

5.2.2 Beach and Sand nourishment

At present there is a net sediment deficit of ~3,000 m³/yr at Mersey Point. This is expected to continue for at least the next decade. The low supply of sediment has exacerbated scouring along Arcadia Drive Revetment and flanking erosion. For the present phase of behaviour, mitigating focal erosion stress on the south side of Mersey Point and east side of Arcadia Drive revetment will be necessary to prevent the early loss of vehicle and pedestrian beach access points and to restrict encroachment toward parkland and buildings within the foreshore reserve. In the short term, this may involve continued beach renourishment, either through:

- **Beach nourishment** (on land) as has been conducted previously (e.g October 2024), this would involve the back-passing of ~1,000-2,000 m³/yr from the tip of Mersey Point (as undertaken in 2024) with an additional ~1,000-2,000 m³/yr trucked in from the Point Peron sand trap.
- **Sand bar nourishment** (nearshore). A second option alongside back-passing from the tip of Mersey Point is to deposit ~2,000 m³/yr on the sand bar, 100 m or so offshore. By placing in water on the sand bar it allows waves to naturally rework the sand, breaking down wrack before it reaches shore. This strategy would require approval from the DBCA.
- **Sand nourishment along Arcadia Drive revetment wall toe**. This option would place an approximate volume of ~13,700 m³ along the toe of the existing Arcadia Drive revetment wall, see Section 5.2.2.1. This added material will act as a buffer zone to absorb wave energy and reduce erosion along the revetment. Wave action and tidal currents will naturally redistribute the sand, helping to limit erosion.

Key modelling results:

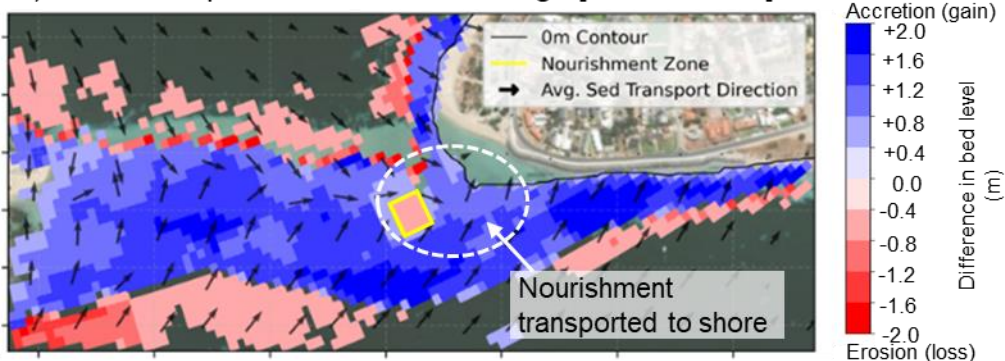
- Beach nourishment maintains buffer to key assets, renourishment of ~4,000 m³/yr currently required to maintain sediment balance. An initial large renourishment may want to be considered to alleviate immediate erosion pressures.
- Sand bar nourishment maintains buffer to key assets. Importantly no sea grass is predicted to be smothered. The deposited sand moves from the sand bar to Mersey Point with limited transverse movement. Combined with beach nourishment at Mersey Point this is predicted to reduce erosion pressures at the western flank of the revetment wall by up to 19m compared to the implementation of no management strategies (e.g. Do Nothing).
- Sand nourishment at the Revetment wall toe is expected to act as a buffer zone for scouring along the wall and is estimated to relieve erosion pressures at the eastern flank by up to 33m compared to the implementation of no management strategies (e.g. Do Nothing).

Required volumes of sediment will change year-on-year, depending on the wind and wave conditions and as such more or less may be needed in any given year. This should be considered in any permitting.



Figure 5-5: Coastline modelling results, beach nourishment.

a) Difference plot: seabed level change [WINTER '20]



b) Difference plot: seabed level change [SUMMER '22/'23]

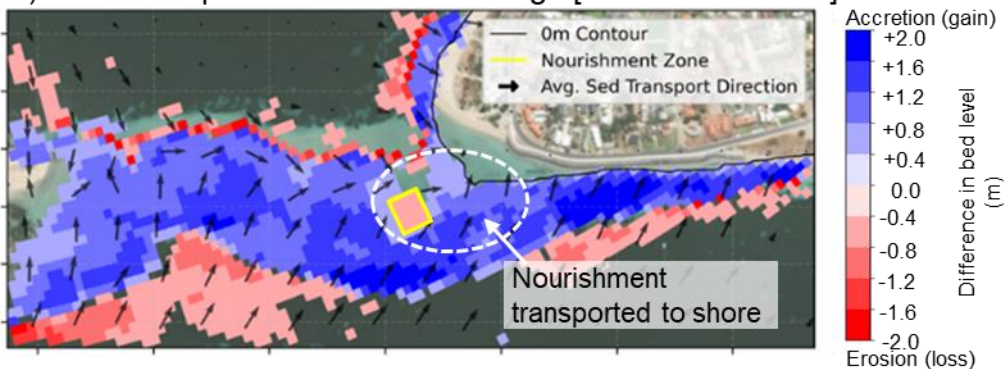


Figure 5-6: Key morphological modelling results for nourishment on the sand bar; a) stormy winter conditions, b) strong summer sea breeze conditions.

5.2.2.1 Revetment wall toe nourishment

The extended low sediment supply phase at Mersey Point has resulted in scour and lowering of the beach in front of the Arcadia Drive revetment. It is recommended that an initial nourishment campaign be undertaken along the toe of the revetment alleviate flanking erosion pressures.

Satellite images from when the revetment was upgraded in suggest that the beach used to be ~10 m wide. We have used this width to calculate a nourishment volume, however, if no beach front is desired then about half the volume can be used.

The volume of sediment required to restore the beach fronting the revetment to a width of 10 m was calculated based on a final profile under equilibrium condition (i.e. plan form equilibrium and profile equilibrium). Figure 5-7 shows an equilibrium profile that would need to be filled for a 10 m-wide beach at 1m AHD in front of the revetment wall. The equilibrium profile has been calculated using the Dean equation², $h(y) = Ay^{2/3}$, where water depth, h , is considered a function of distance from the shoreline, y , and a profile parameter, A , based on the sediment grain size. The volume of sediment required has been calculated based on the assumption that the recharge sediment will have the same properties as existing sediment. The baseline profile has been based on surveys undertaken by the City of Rockingham in June 2024. Taking this profile, approximately 13,700 m³ of sediment is required over the length of the Arcadia Drive revetment wall to reconstruct a ~10-m wide beach.

When undertaking toe nourishment, it is not feasible for contractors to construct the equilibrium profile, instead a construction profile is used.

A construction profile has been designed based on the target cross-sectional profile that the contractor is expected to build to ensure that correct volume of sediment is placed along the toe of the Arcadia Drive revetment wall. The profile has been based on the overbuild approach, where sediment is placed on the upper beach profile by stacking the fill material adjacent to the revetment wall. This approach minimises the construction work required to place and shape the recharge sediment at the discharge point, providing the most economic construction technique.

The construction width incorporates the entire sediment volume required to meet the equilibrium profile at 33 m, therefore is much greater than the design beach width. The profile would be built with a trapezoidal cross section, with a gentle slope (e.g. 1:100) built into the beach width falling towards the sea, and the seaward slope placed at a constant grade of 1:2 to 1:4 from the crest into the nearshore zone.

Following construction, the first storms and high waters will act to change the shape of the profile towards the equilibrium profile shown in Figure 5-5. Sand will be removed (eroded) from the beach and moved towards the nearshore zone as it fills the deep channel. During

² Dean, R. G. (1977), "Equilibrium Beach profiles: U.S. Atlantic and Gulf Coasts", Ocean Engineering Technical Report No. 12

this time scarping (near vertical sections of profile) may be apparent, which can be modified using earth-moving equipment if desired by the City of Rockingham.

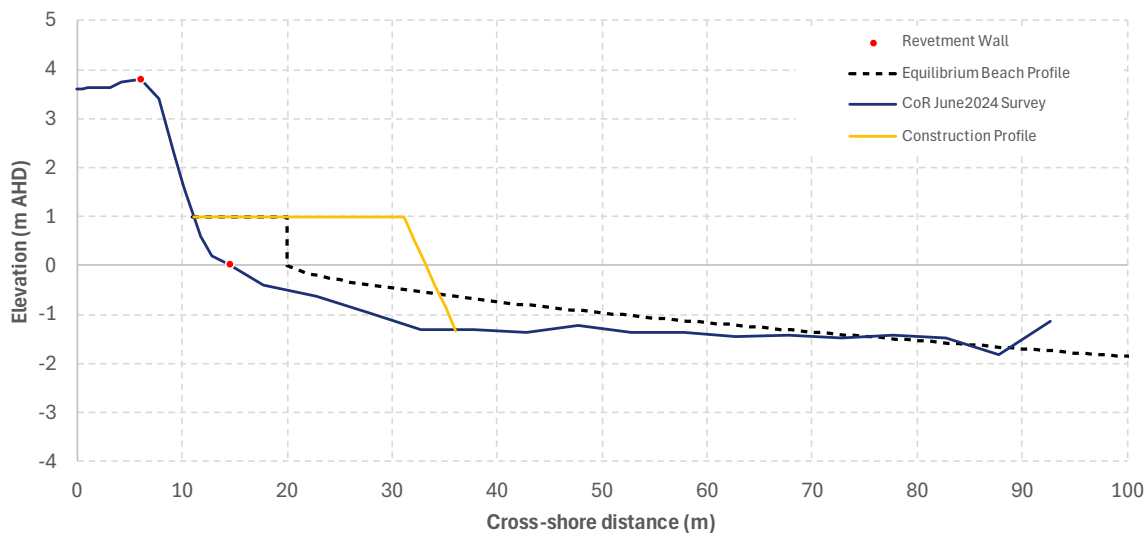


Figure 5-7: Equilibrium profile required to stabilise beach fronting Arcadia Drive.

5.2.3 Revetment extension

Revetments provide essential protection for critical coastal assets by shielding them from wave energy and erosion; however, they also disrupt natural sediment transport processes, often leading to beach loss in front of the structure and increased erosion at its flanks. This is because the revetment reflects wave energy rather than dissipating it, which can result in the scouring of sand at its base, reducing beach width over time (as has been observed along Arcadia Drive). Additionally, by fixing the shoreline position in an already low supply phase, it reduces alongshore sediment supply, thus adjacent areas experience flanking erosion.

If critical assets require protection, a more sustainable approach is to pair revetment extension with beach/sand renourishment, replenishing lost sediment to maintain beach width and recreational value. This combination helps balance asset protection with the preservation of beach amenity, ensuring long-term coastal resilience while mitigating the negative impacts of hard engineering solutions.

Key modelling results:

- Revetment extension to the west and east **without** nourishment will see key assets protected (i.e Penguin Island Visitor Centre and Arcadia Drive). However, erosion pressure shift to the flanks of the new revetment - with Carlisle Street boat ramp coming under threat within ~5 years. To the west, the revetment will need to extend past the current beach access that the City used for beach works, thus the City will lose its access point for the beach. The beach fronting the revetment will also be lost.

- Revetment extension **with** nourishment, alleviates key erosion pressures while maintaining beach amenity. The revetment would be the "second line of defence", there to protect key assets should the beach buffer be lost during an extreme storm. Renourishment will be required periodically (modelling suggests ~3 years) while the sand bar is in a low supply phase.

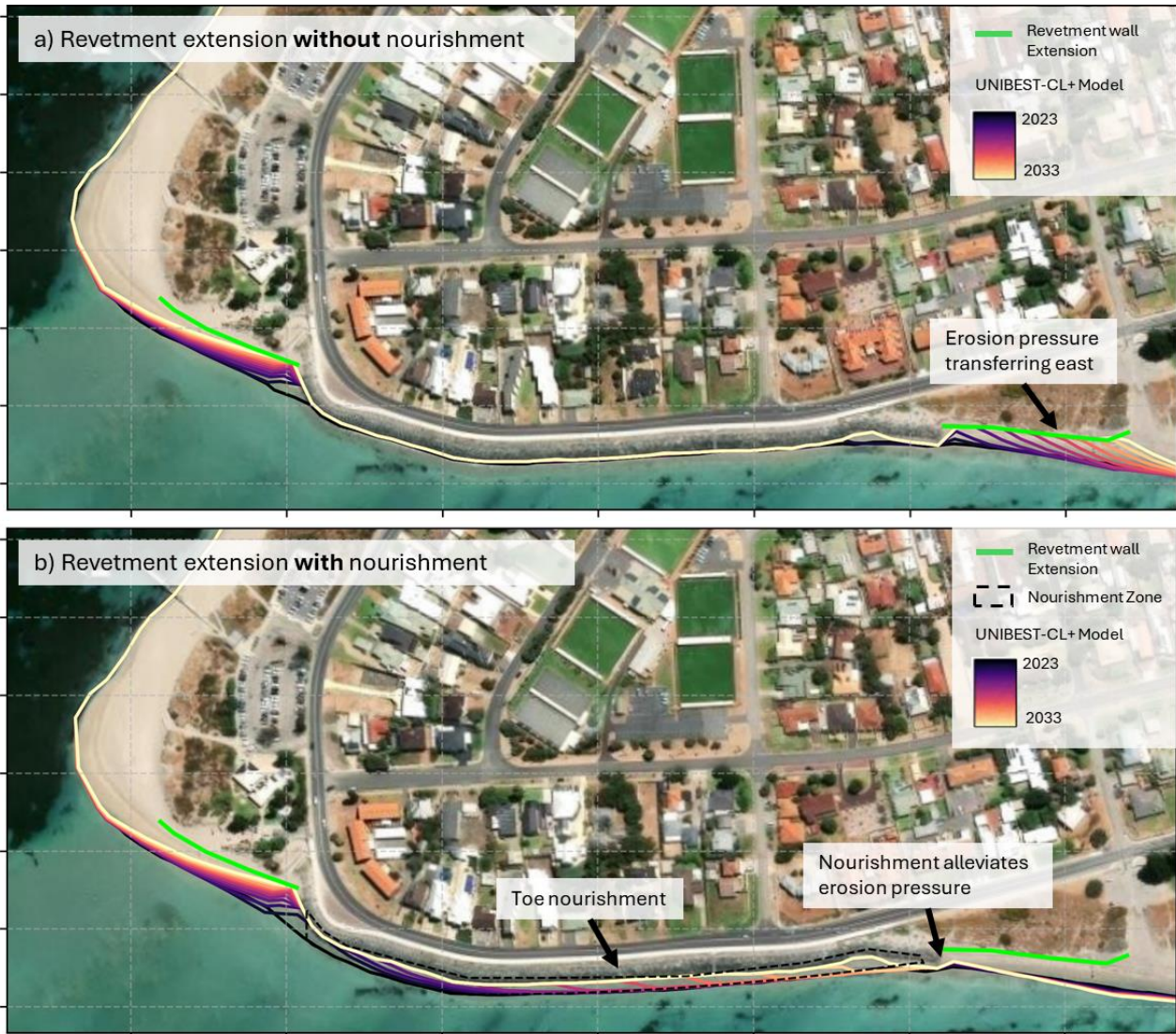


Figure 5-8: Coastline modelling results for revetment extension (green line) scenario; a) no nourishment, b) with sand nourishment along revetment toe.

5.2.4 Groynes

Groynes are effective at trapping sediment and reducing erosion on the updrift side, stabilising the immediate beach. However, groynes also interrupt natural alongshore sediment transport, leading to sediment accumulation on one side while causing erosion on the downdrift side due to reduced sediment supply. This can result in progressive beach narrowing and retreat in areas where sediment cannot bypass the structure. Over time this erosion may require additional interventions, such as beach nourishment or extension of the groyne field to maintain shoreline stability.

Key modelling results:

- Two groynes placed along the Mersey Point foreshore add shoreline stability, reducing localised erosion immediately adjacent to the western side of the Arcadia Drive revetment.
- The eastern groyne disrupts the natural northward sediment transport direction, leading to accelerated erosion at the tip of Mersey Point.
- The western groyne disrupts the natural eastward sediment transport direction, increasing erosion pressures at the eastern flank of the Arcadia Drive revetment.

Groynes are not a viable alternative for Mersy Point as they will exasperate erosion pressures at Carlisle Street boat ramp in addition to shifting erosion pressure to the tip of Mersey Point.

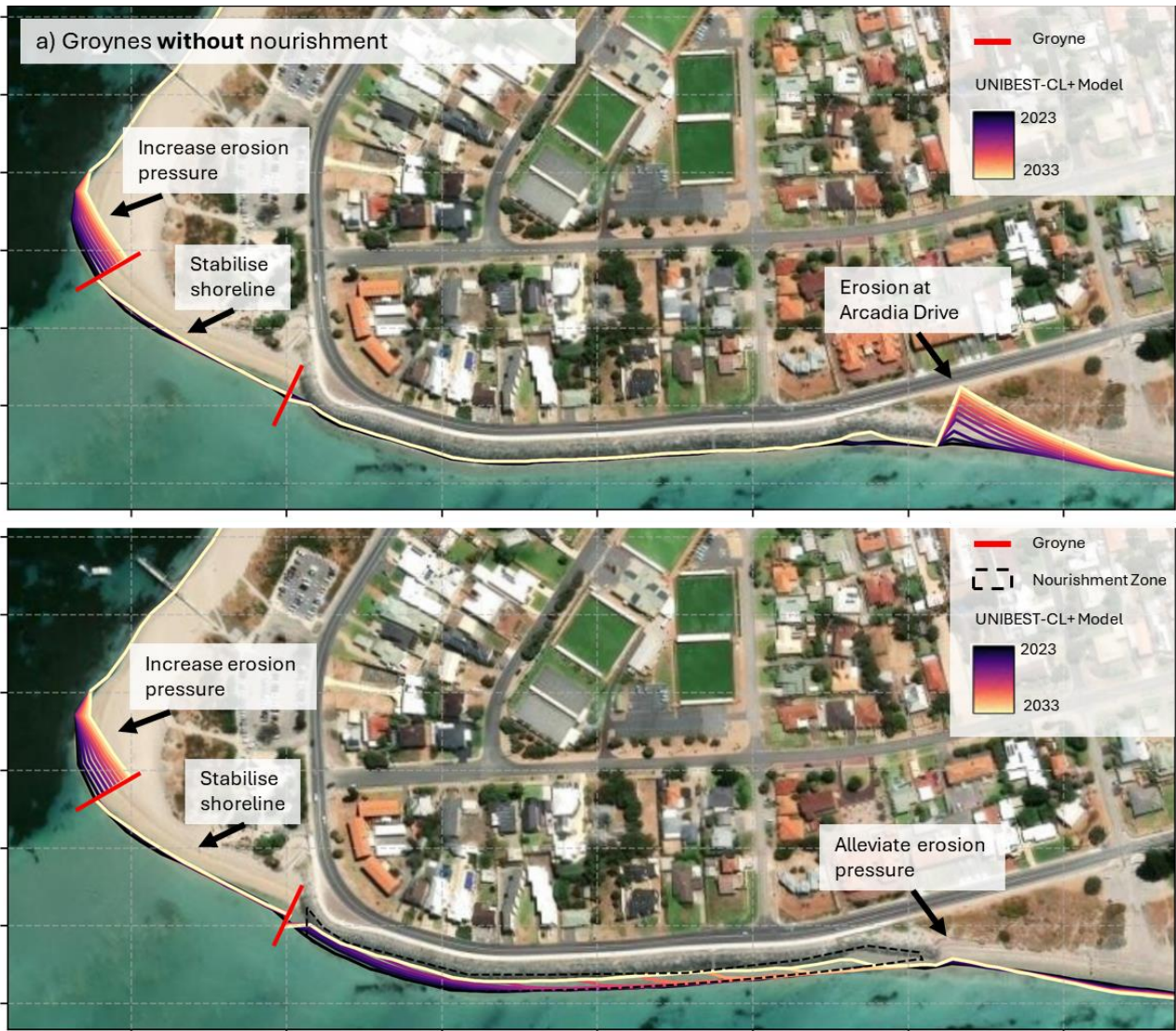


Figure 5-9: Coastline modelling results, incorporating the construction of groynes; a) no nourishment, b) with sand nourishment along revetment toe.

5.2.5 Offshore breakwater

Offshore breakwaters provide coastal protection by reducing wave energy before it reaches the shore, helping to alleviate erosion pressures. By creating a low-energy zone in the lee of the structure, they encourage sediment deposition, often leading to the formation of a wider beach in the sheltered area.

To limit impacts on seagrass, the offshore breakwater is placed on the sand bar.

Key modelling results:

- Offshore breakwater dissipates wave energy with sediment deposition occurring in the lee of the breakwater during summer conditions
- Strong winter storms (north and north westerly conditions) shift the sand bar south

The rapid coastal changes that have been observed along this part of the coast over the past century are indicative of a **very** dynamic system. The active nature of the feature may result in stabilisation structures, such as an offshore breakwater, becoming 'redundant' over extended periods. Should the sand bar shift back to the south, as it has done in the past, this would alleviate the present phase of focal erosion naturally.

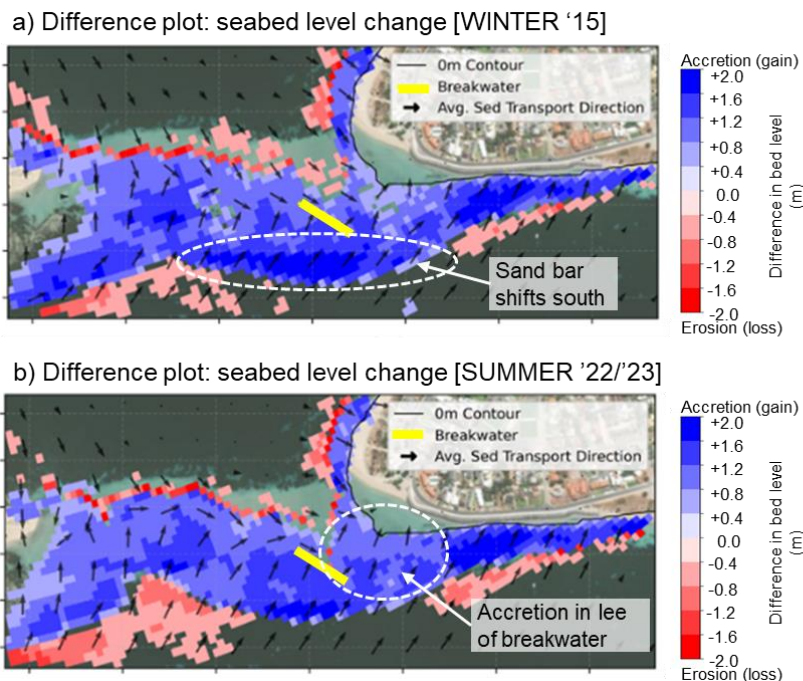


Figure 5-10: Key morphological modelling results for offshore breakwater; a) stormy winter conditions, b) strong summer sea breeze conditions.

6 Conclusions and Recommendations

6.1 Tern Bank

Offshore sediment sources and seasonal wave activity will continue to drive the expansion of Tern Bank, with alternating periods of rapid growth and stabilisation linked to storminess each winter. Volume and rate estimates suggest there is another 20-30 years of sediment supply to Tern Bank. However, unlike the past, human interventions such as dredging are significantly influencing its evolution.

Long-term, regardless of management option, the spit will degrade, the Pond will fill in and the sand from Tern Bank will redistribute along the shoreline of northern Warnbro Sound smothering Bent Street boat ramp. It is difficult to put a time on this process, but based on the 1800s episode and estimated volumes in Safety Bay sand bar waiting to come ashore, there may be 10 years of use of the Pond before it fills in. This will greatly depend on what the environmental conditions are over the coming years. Strong storm seasons will enhance delivery of sediment to the spit and thus speed up evolution. Additionally, any dredging is expected to speed up degradation of the spit and loss of the Pond.

Recommendations

Given the evolution trajectory of Tern Bank, it is recommended that the City allows natural coastal processes to continue and remove/repurpose Bent Street boat ramp. The Pond should be monitored for potential closures and an appropriate response agreed to mitigate impact on water quality if required (e.g. channel excavation). Closure is most likely to happen during the spring when tidal ranges are low. This approach will ensure that the community can continue to enjoy the Pond while it gradually fills in, maximising its usage during the transition period.

6.2 Mersey Point

Mersey Point has been in a low supply phase since 1995. The main sand source, the sand bar connecting Penguin Island and Mersey Point, has been deflating and widening indicating the low supply of sediment will continue within the coming decade. There is a sand mass forming in the lee of Penguin Island, which will make its way to Mersey Point, but this is likely at least a decade off.

Human interventions such as Arcadia Drive revetment and foreshore development are significantly influencing the evolution of Mersey Point, requiring careful management to balance natural processes with human needs. The current low supply phase has naturally enhanced erosion flanking the revetment, placing pressure on Arcadia Drive, Carlisle Street boat ramp and Mersey Point beach access.

Due to the dynamic nature of the coastline, there is the potential for intervention structures to become obsolete, e.g. if the sand bar shifts back south, erosion pressure would naturally be alleviated and infrastructure such as an offshore breakwater would become "redundant".

For this reason, it is recommended that a flexible approach be implemented.

Recommendations

It is recommended that the City:

- Continue nourishment of Mersey Point beach through back-passing from northern sections, with an estimated need for 1,000 to 2,000 m³ per year.
- Augment back-passing efforts with sand from the Point Peron sand trap, requiring a balanced sediment supply of approximately 3,000 to 4,000 m³ per year.
- Periodically, reassess nourishment volumes based on changing environmental conditions—either calm summers or stormy winters.
- Restore the beach fronting the revetment, with a large initial nourishment campaign (to create a 10-m wide beach approximately 13,700 m³ is required). Renourishment along the revetment toe will mitigate erosion pressures on Arcadia Drive and the Carlisle Street boat ramp.
- Incorporate bathymetric surveys every 5 to 10 years within the Coastal Management Plan to enable informed coastal protection strategies and accurate predictions of sediment supply variations.

In light of the potential development of a new Discovery Centre at Mersey Point, the City may wish to evaluate the feasibility of extending the revetment as a secondary line of defence. This should be combined with ongoing beach nourishment initiatives to maintain beach amenities. Additionally, it will provide essential protection against extreme storm events, especially in scenarios where the beach buffer may prove insufficient. Incorporating sand nourishment is crucial; without it, the beach area in front of the revetment faces the risk of degradation, as evidenced by the situation along the Arcadia Drive revetment wall.

A Appendix: Coastal Processes Assessment

B Appendix: Numerical Modelling

To accurately simulate the local wave and tidal climate within Warnbro Sound, a regional coupled hydrodynamic and wave model has been developed to capture the key physical processes governing coastal dynamics within the region. This model incorporates metocean conditions including winds, tides and offshore waves. Modelling outputs have been used for the following:

- **Local scale morphological modelling:** Results from large scale modelling have been used as boundary conditions for finer scale morphological modelling at Warnbro Sound and has been used to model the effects of management strategies including an offshore breakwater and surf-zone nourishment.
- **Coastline Modelling:** Modelled nearshore conditions have been used to estimate coastline changes in the shoreline modelling suite UNIBEST-CL+ under several management options including, beach nourishment, the extension of the Arcadia Drive revetment wall, and groynes at the frontage of Mersey Point.

B.1 Regional Modelling

Regional to local representation of forcing conditions has been developed using the Delft3D-Flexible Mesh modelling suite, configured as a coupled wave and tide model. The Delft3D modelling suite is capable of dynamically linking the tide, wave, sediment transport and morphology models together.

The primary models utilised in this setup include:

- **D-FLOW:** This hydrodynamic component manages calculations related to tidal currents and water levels across a model domain. By simulating the flow and circulation patterns, D-FLOW provides a detailed representation of the tidal forces that drive sediment transport on a large scale.
- **D-WAVE:** Incorporating the SWAN (Simulating Waves Nearshore) model, D-WAVE simulates wave generation, propagation, and transformation, accounting for complex wave-current interactions. The module integrates wind conditions and offshore wave parameters.
- **D-MORPH:** D-MORPH evaluates sediment transport rates and bed morphology changes over time. It simulates the combined effects of hydrodynamic and wave forces, supporting the prediction of long-term morphological changes in the region.

As schematised in Fig. B.1.1-1, these processes are linked together within the Delft3D modelling suite which undertakes hydrodynamic calculations within the D-Flow module, wave transformation in D-Wave, sediment transport and the resulting changes in bed level changes calculated within the D-Morph module. At each timestep the combined information is then fed back into the D-Flow module at each timestep to repeat this process over the simulation period.

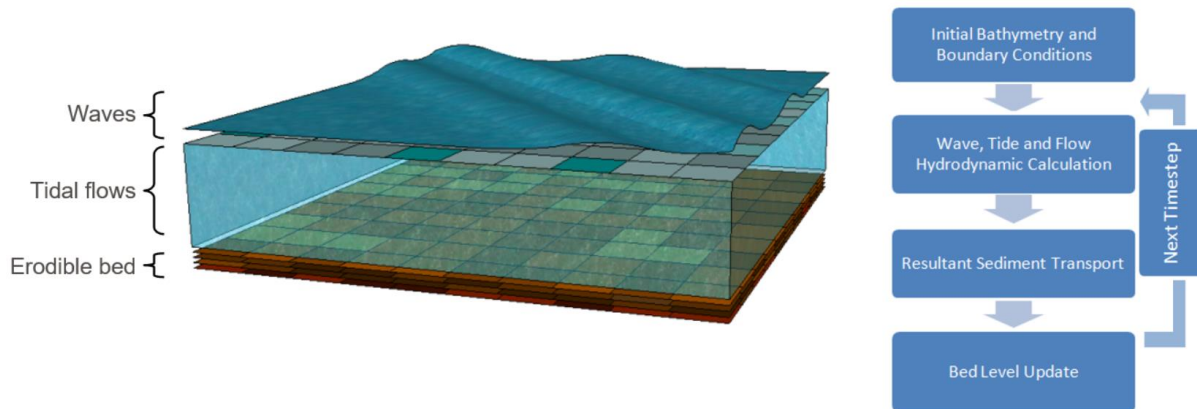


Fig. B.1.1-1: Schematic of the Delft3D model, showing the available functionalities that can be coupled within the numerical calculations.

B.1.1 Model setup

Two regional modelling domains have been developed for the use in the D-FLOW and D-WAVE modelling suite, extending from approximately Two Rocks to Clifton in the south. These models provide boundary conditions for hydrodynamic (i.e. water levels, tides and current speeds) and hydraulic (i.e. wave height, direction and period) data for a high-resolution morphological model at Warnbro Sound (See Appendix B.2).

Local grid refinement has been incorporated to balance computational efficiency and accuracy, with finer resolution incorporated in key areas such as Northern Warnbro Sound to capture the local variation in flow, wave action and sediment movement. Tab. B.1.1-1: summarises the grid resolution used in regional tide and wave modelling.

Numerical modelling has utilised a combination of elevation datasets. The model uses the AusBathyTopo 250m 2023 grid and 2009 10m LiDAR (WA Department of Transport) in the model build. The higher resolution LiDAR was merged with the 250m Australia-wide depth grid to account for higher spatial resolution and increased vertical elevation accuracy in the nearshore. Prior to merging the datasets, the vertical datum of each was checked. The vertical datum for this modelling is Australian Height Datum (AHD)

Tab. B.1.1-1: Regional D-FLOW and D-WAVE grid resolution.

Grid	Grid Size	Resolution
D-FLOW		
Overall	56 x 150 km	1000 - 1500m
Local Refinement	Variable	100 - 500m
D-WAVE		
Overall	~ 65 x 165 km	2000m
Local Refinement		500m

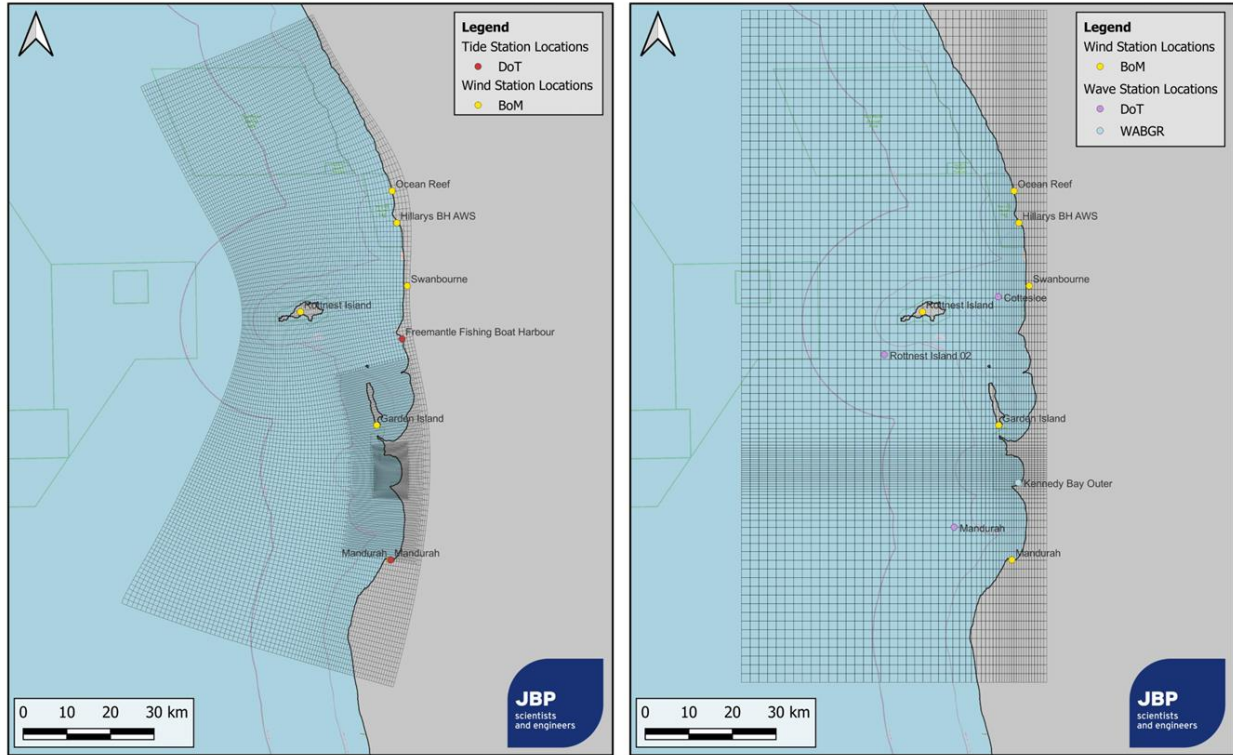


Fig. B.1.1-1: Regional Delft3D-Flow domain (left) and regional Delft3D-Wave domain (right).

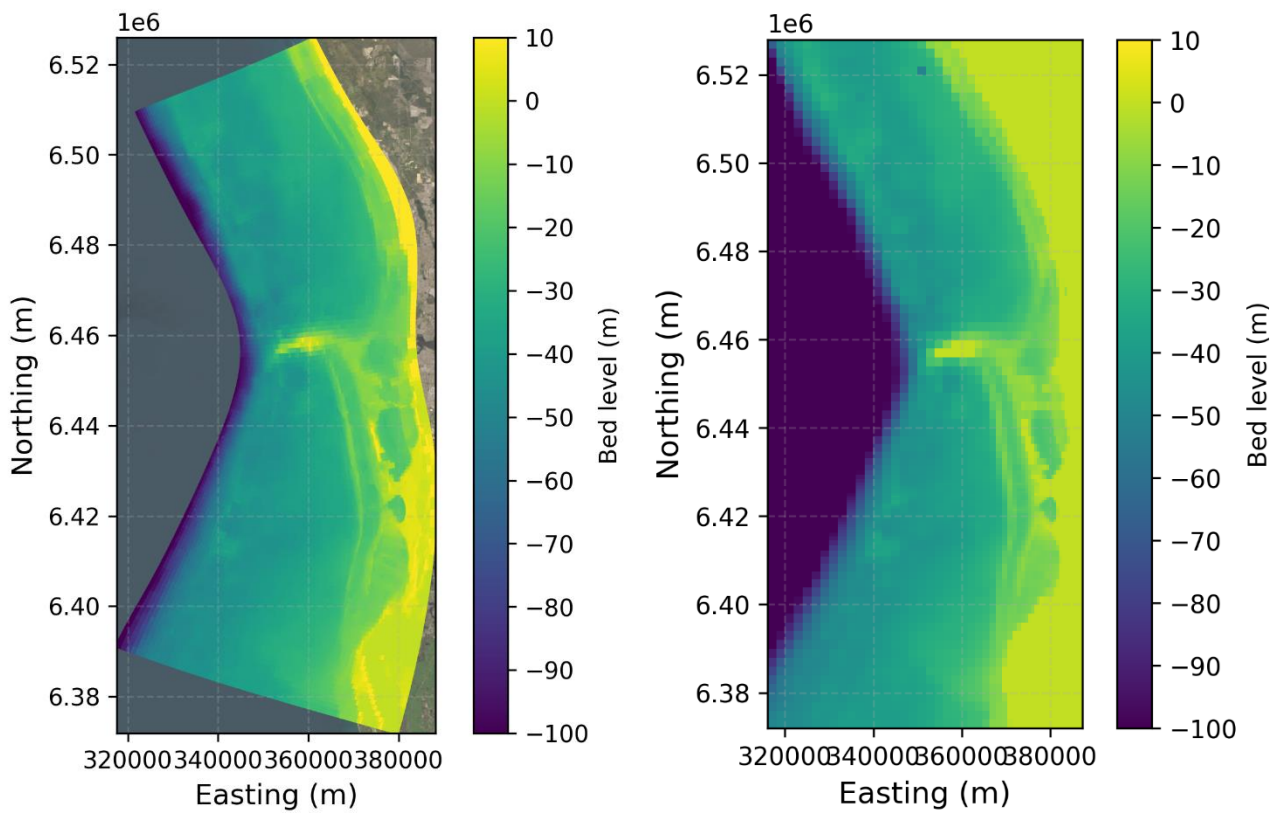


Fig. B.1.1-2: Regional Delft3D-Flow bathymetry (left) and regional Delft3D-Wave bathymetry (right).

B.1.2 Planned MetOcean Data Capture

A planned MetOcean data collection was undertaken in Warnbro Sound during the period between June and August 2024 as part of the Northern Warnbro Sound numerical modelling.

An Acoustic Wave and Current device (AWAC) was deployed to collect metocean measurements. In addition, a pressure transducer was deployed to log water level data near Third Rock. This was intended as a safety blanket should something happen to the AWAC device.

On recovery, the pressure transducer could not be located. Over a period of one month, including contact with the DBCA, local sailing and fishing groups, the conclusion was that it was likely stolen. The device was weighted such that it would be difficult to move by natural means. The AWAC was collected but no data was retrievable by the contractor.

The contractor completed a diagnosis of the cause of the 'no data' from the AWAC deployment. The cause was a faulty power connection. The sub-sea connector used to supply power to the AWAC had a loose connection, when used with conductive silicone gel, resulted in intermittent power supply. During pre-deployment QA power was being supplied and no issue identified. The likely cause for the data loss was losing the power connection once the equipment was deployed.

As such no MetOcean data was recoverable from the Winter 2024 deployment.

B.1.3 Available data

No new site-specific metocean dataset was available to use for the validation/calibration of the new numerical model within Northern Warnbro Sound. In the absence of site-specific field data, historic metocean datasets was used to complete the modelling deliverables. Data sources such as from the Department of Transport (DoT) which provide historic wave and water level records were selected based on their relevance to the local wave and tide climate, and spatial proximity to Warnbro Sound. These observation records are available from various monitoring stations throughout the region.

Recorded water levels are available from the Fremantle and Mandurah tide gauges. Recorded wave data is available from the Rottnest Island Wave Rider Buoy (WRB), Cottesloe WRB and Mandurah WRB. Wind data is available from various Bureau of Meteorology (BoM) automatic weather stations (AWS) including, Rottnest Island, Garden Island, Hillarys, Ocean Reef, Mandurah and Swanbourne. Below in Tab. B.1.3-1 the available data for numerical modelling has been summarised.

Tab. B.1.3-1: Available model input data for regional tide and wave modelling

Input	ID	Type	Latitude	Longitude	Depth/Elv	Source
Rottneest Island Wave Buoy	RDW47	Waves	-32.09	115.41	48 m	DoT
Fremantle Fishing Boat Harbour Tide Gauge	FFFBH01	Tide	-32.07	115.75	-	DoT
Mandurah Ocean Marina Tide Gauge	MHMAN02	Tide	-32.52	115.71	-	DoT
Rottneest Island	009193	Wind	-32.01	115.50	43.1 m	BoM
Hillarys Boat Harbour	009265	Wind	-31.83	115.74	0 m	BoM
Swanbourne	009215	Wind	-32.96	115.76	40.96 m	BoM
Rottneest Island	009193	Wind	-32.01	115.50	43.1 m	BoM
Garden Island HSF	009265	Wind	-32.24	115.68	6 m	BoM
Mandurah	009977	Wind	-32.52	115.71	3 m	BoM
Ocean Reef	009214	Wind	-31.76	115.73	10 m	BoM

B.1.4 Bottom friction

Bottom friction plays a significant role in wave transformation processes such as wave energy dissipation as waves propagate from deep waters to the shoreline, with its effect varying based on the seabed composition, roughness and topographic relief. To account for the effects of bottom friction, a spatially varying bottom friction grid has been implemented throughout the modelling domain. Friction coefficient values were determined through model calibration and assigned by the classification of three substrate types which include: high-relief reefs, low-relief reef and sand. The input bottom friction values and their corresponding spatial extents are presented in Fig. B.1.4-1.

Tab. B.1.4-1: Input bottom friction coefficient

Parameter	Bottom Friction Coefficient
Collins Bottom Friction	Sand 0.05 Low Relief Reef 1.1 High Relief Reef 1.2

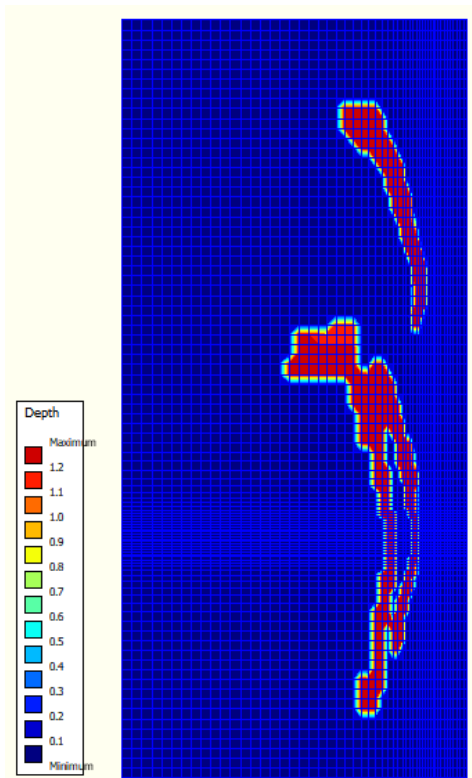


Fig. B.1.4-1: Input Bottom friction.

B.1.5 Model calibration

Although the availability of updated calibration data is no longer available for Winter 2024, calibration data is available for an earlier period during Winter 2022 at Kennedy Bay. Further calibration has been completed using data from the Mandurah and Cottesloe Waverider Buoys further offshore. Using this combination of datasets, Tab. B.1.5-1 summarises the available historic datasets that could be used in the calibration process of the regional model. The chosen calibration periods are shown in Tab. B.1.5-2.

For tidal calibration, a simulation period with minimal storm surge influence was selected to isolate astronomic tidal forcing to ensure the accurate representation of tidal constituents. The modelled water levels were validated against observed data at the Fremantle Boat Harbour tide gauge.

Wave model calibration focused on adjusting bottom friction parameters to improve agreement between simulated and observed wave conditions. Bottom friction values were modified to optimise the calibration process.

Tab. B.1.5-1: Available calibration and validation data

Inputs	Latitude	Longitude	Start date	End date	Bed Elevation	Source
Dataset 1: Spotter 2022	-32.3621	115.7297	14/06/2022	25/08/2022	14 mAHD	WABGR
Dataset 2: Mandurah Waverider	-32.4528	115.5722	3/07/2014	Current	30 mAHD	DoT
Dataset 3: Cottesloe Waverider	-31.9777	115.6867	4/09/1999	Current	17 mAHD	DoT
Dataset 4: Fremantle Boat Harbour	-32.0655	115.7481	19/11/1986	Current	-	DoT
Dataset 5: Mandurah Ocean Marina	-32.5219	115.7141	20/02/2007	31/12/2022	-	DoT

Tab. B.1.5-2: Model calibration periods.

Season	Start date	End date	Calibration data	Peak Hs (m)	Dirswell (°)
Winter	15/05/2022	34/08/2022	Dataset 1	8.53	267
Long Period Swell Event	24/05/2018	29/05/2018	Dataset 2 & 3	8.02	266
Tidal Cycle	08/12/2023	22/12/2023	Dataset 4 & 5	N/a	N/a

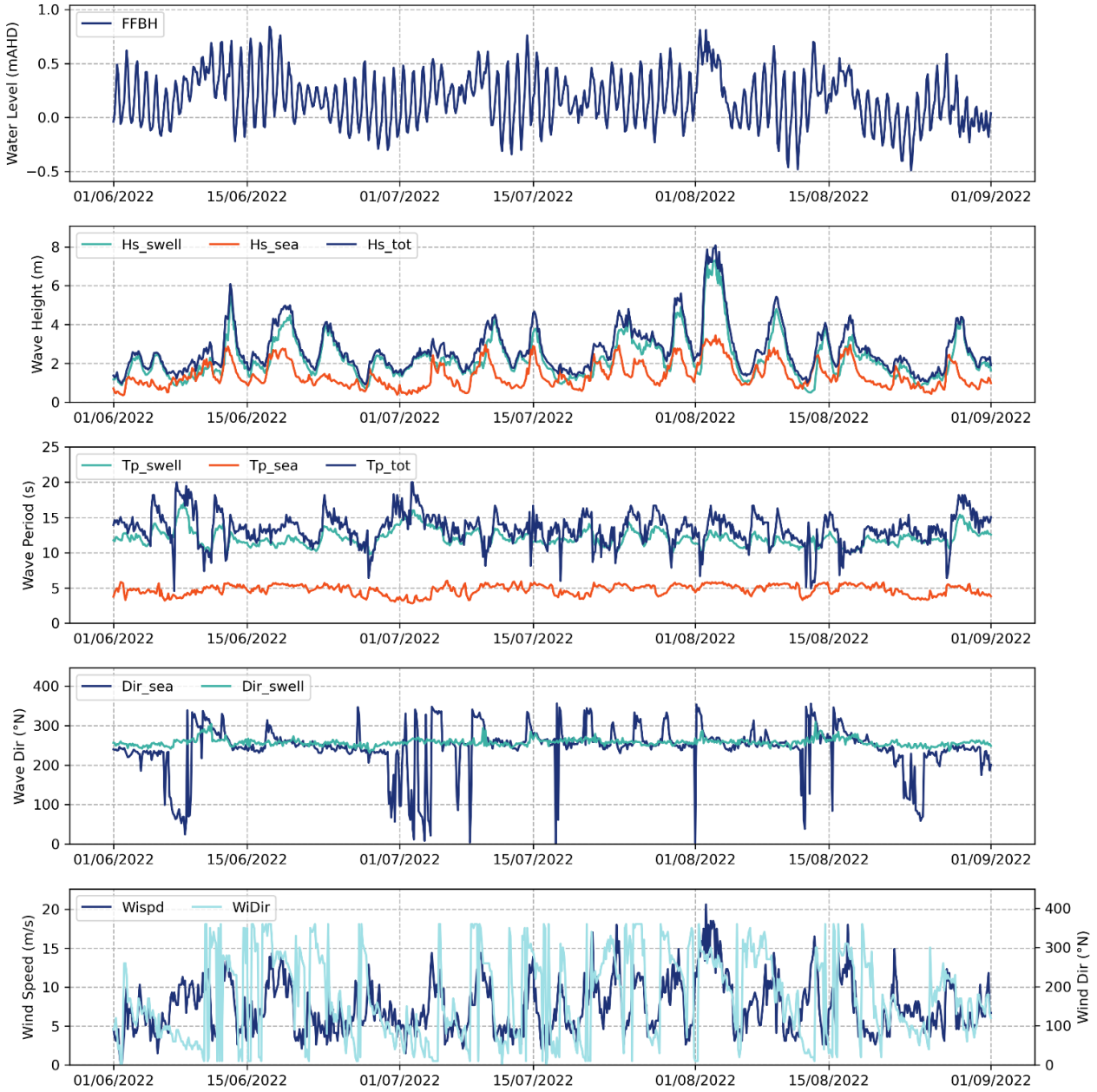


Fig. B.1.5-1: Winter 2022 input calibration data.

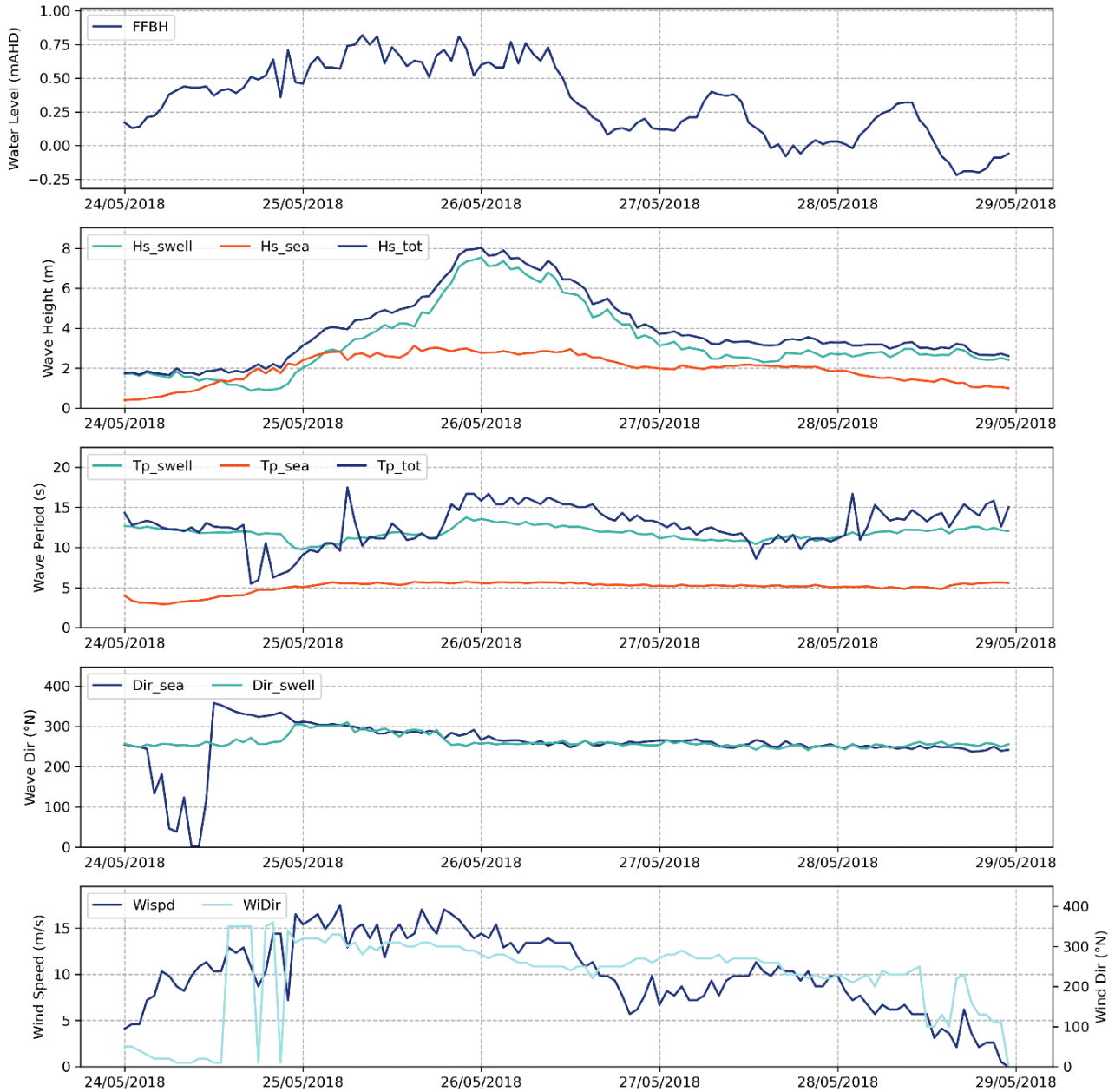


Fig. B.1.5-2: Long Period Swell event (2018) input calibration data.

B.1.6 Calibration results

The accurate representation of local scale wave and tide characteristics has involved the configuration of various modelling parameters including the effects of bottom friction on dissipation of wave energy and wind friction models. Selection of modelling parameters were derived from review of model performance in addition to literature review. The physics parameterisation schemes, and bottom friction coefficients are shown in Tab. B.1.6-1.

Fig. B.1.6-1 and Fig. B.1.6-2 shows a comparison of recorded and modelled wave data for each calibration period during a winter period, at Kennedy Bay and long period swell event at Mandurah WRB, showing good agreement between modelled and recorded data.

Fig. B.1.6-3 shows a comparison of recorded and modelled water level data at the Fremantle Boat Harbour tide gauge, which shows good agreement in simulated astronomic tidal regime.

Tab. B.1.6-1: Delft3D-FM model configuration and parameters.

Description	Model/Value
Offshore boundary	Rottneest Island Waves, Fremantle tide gauge water levels
Generation Mode	GEN3 (Default parameters)
Exponential wind growth	Komen et al., (1984)
Whitecapping	Komen et al., (1984)
Depth-induced wave breaking	Battjes and Janssen (1978)
Bottom friction model	Collins (1972)
Wave-wave interactions	Hasselmann et al. (1985)
Bottom Friction Coefficients:	
Sand	0.05
Low Relief Reef	1.1
High Relief Reef	1.2

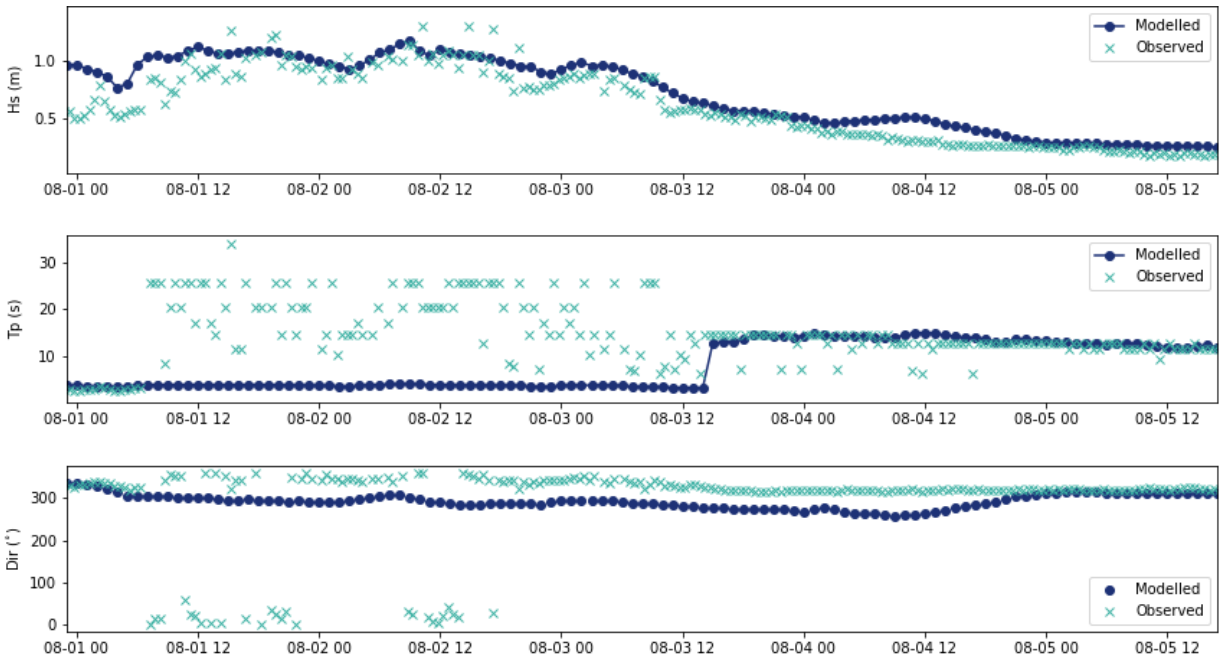


Fig. B.1.6-1: Modelled results vs observed data - Winter 2022 – Kennedy Bay Outer.

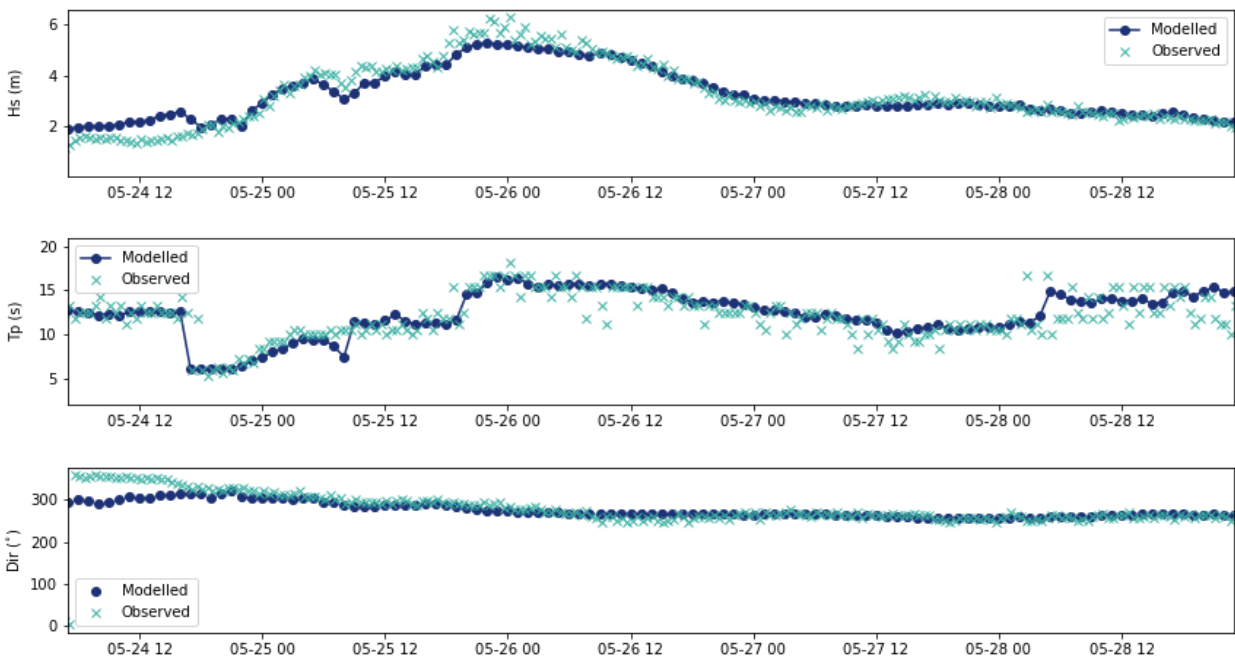


Fig. B.1.6-2: Modelled results vs observed data – Long period swell event 2018 –Mandurah Wave Buoy.

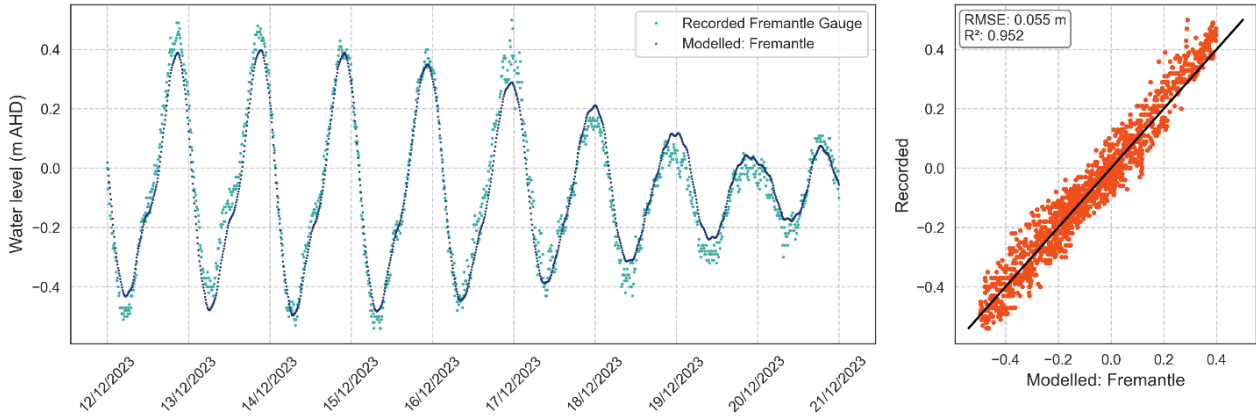


Fig. B.1.6-3: Modelled results vs observed data – tidal cycle –Fremantle Boat Harbour.

B.1.7 Regional hydrodynamic modelling

After the calibration process of the regional model, the numerical model has been utilised to simulate seasonal wave and tidal data, with input conditions derived in accordance with the recommendations outlined in Coastal Processes Study (Appendix A). The selected modelling periods are based on the recommendations outlined in the Coastal Processes Study, which identified the most representative MetOcean conditions influencing sediment transport dynamics within Northern Warnbro Sound.

A total of six modelling scenarios have been selected, as outlined in Tab. B.1.7-1. The primary objective of the regional modelling is to define boundary conditions for a smaller, high-resolution model at Northern Warnbro Sound. In addition, the regional modelling will provide insights into nearshore hydrodynamic processes, including wave patterns, tidal fluctuations and tidal flow dynamics, which will serve as inputs for a high-resolution local scale model. The time series input across each of the modelling scenario is shown between Fig. B.1.7-1 and Fig. B.1.7-6.

Tab. B.1.7-1: Baseline modelling scenarios for morphological modelling at Northern Warnbro Sound.

Season	Start date	End date	Calibration data
Winter	15/05/2022	31/08/2022	Dataset 1
Winter	01/05/2020	31/08/2022	Dataset 2 & 3
Winter	1/05/2015	31/08/2015	Dataset 2 & 3
Summer	1/12/2019	1/03/2020	Dataset 2 & 3
Summer	1/12/2022	1/03/2023	Dataset 2 & 3
Long Period Swell Event	24/08/2018	29/08/2018	Dataset 2 & 3

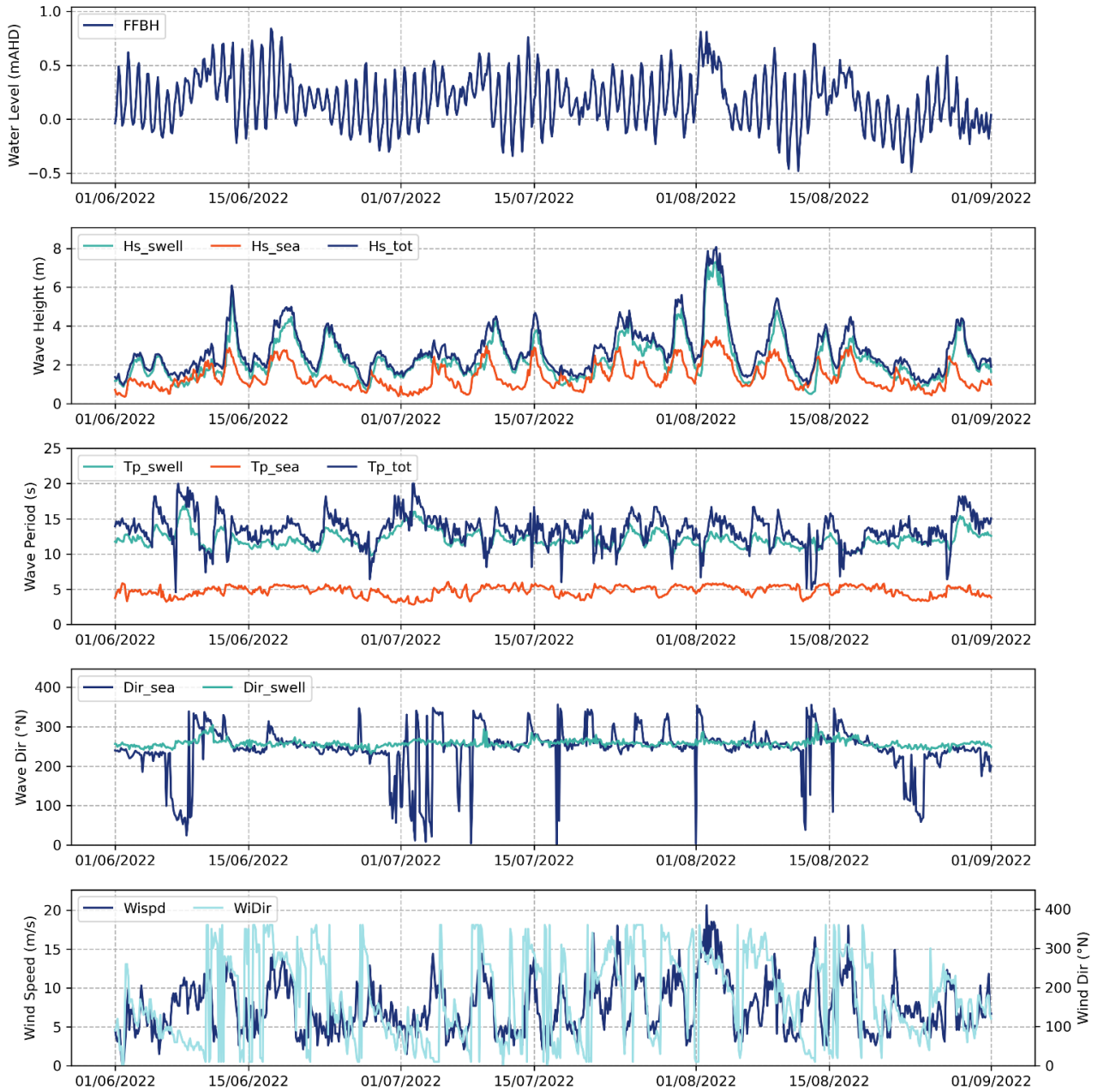


Fig. B.1.7-1: 2022 Winter baseline modelling input data.

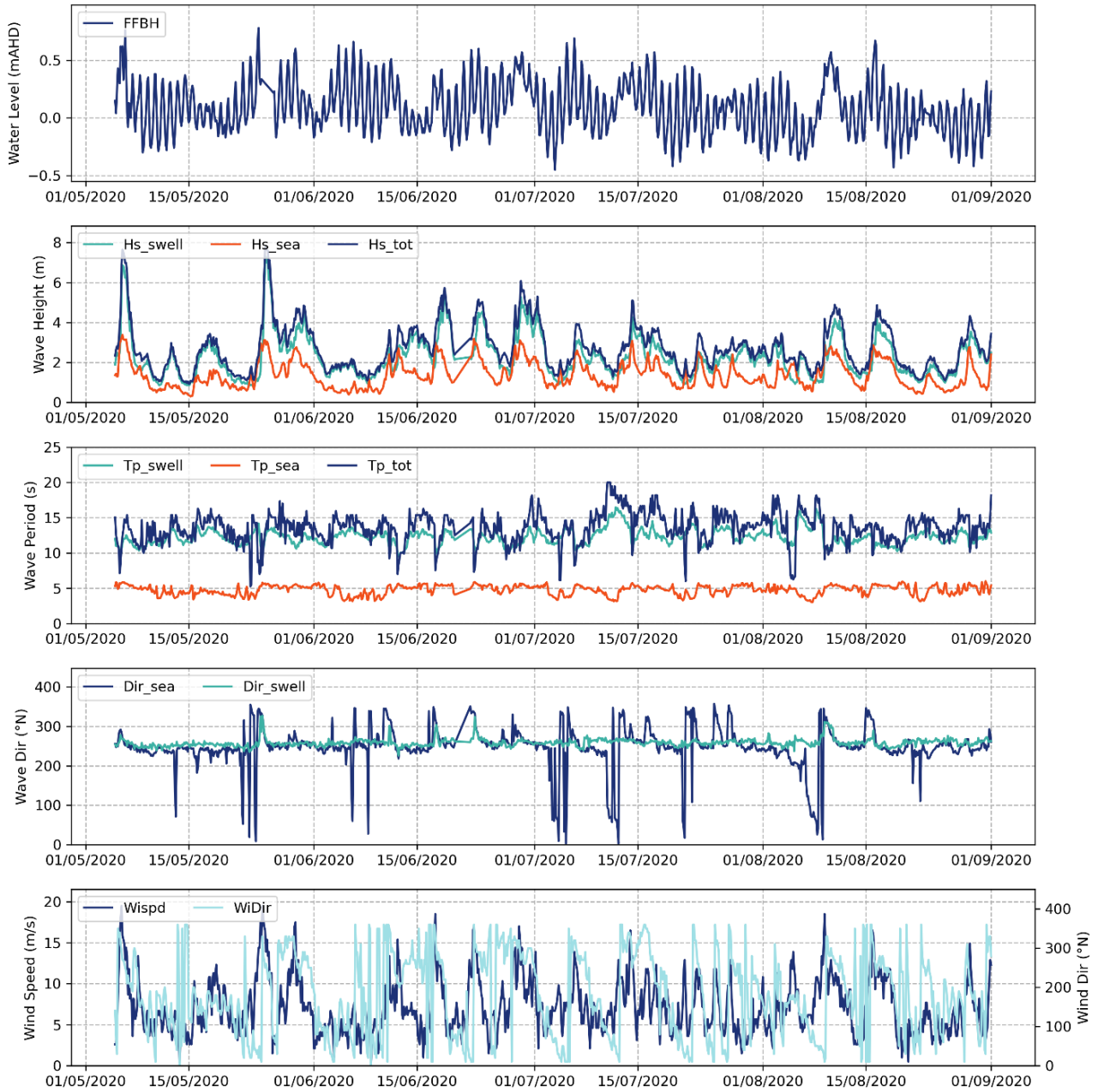


Fig. B.1.7-2: 2020 Winter baseline modelling input data.

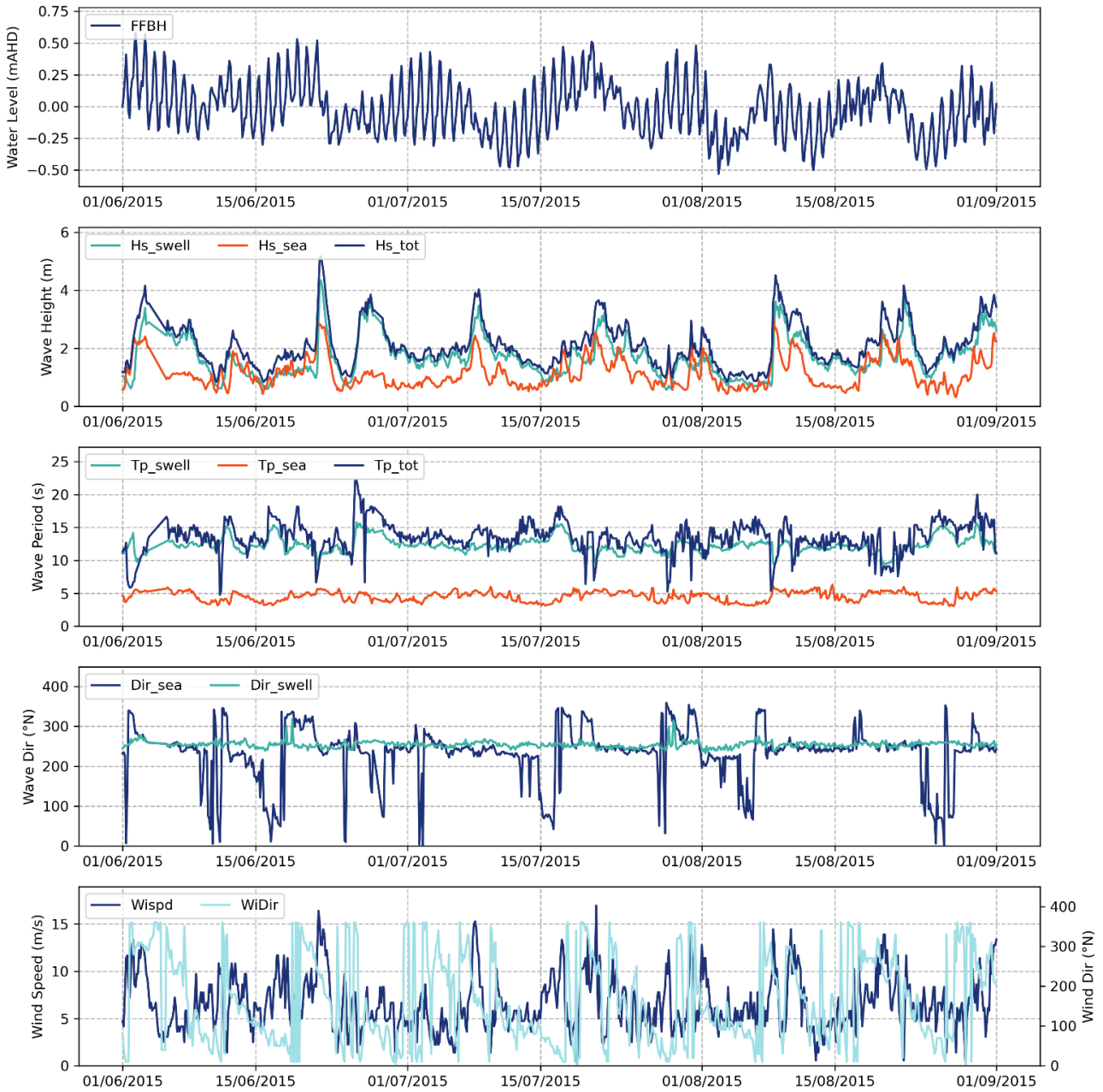


Fig. B.1.7-3: 2015 Winter baseline modelling input data.

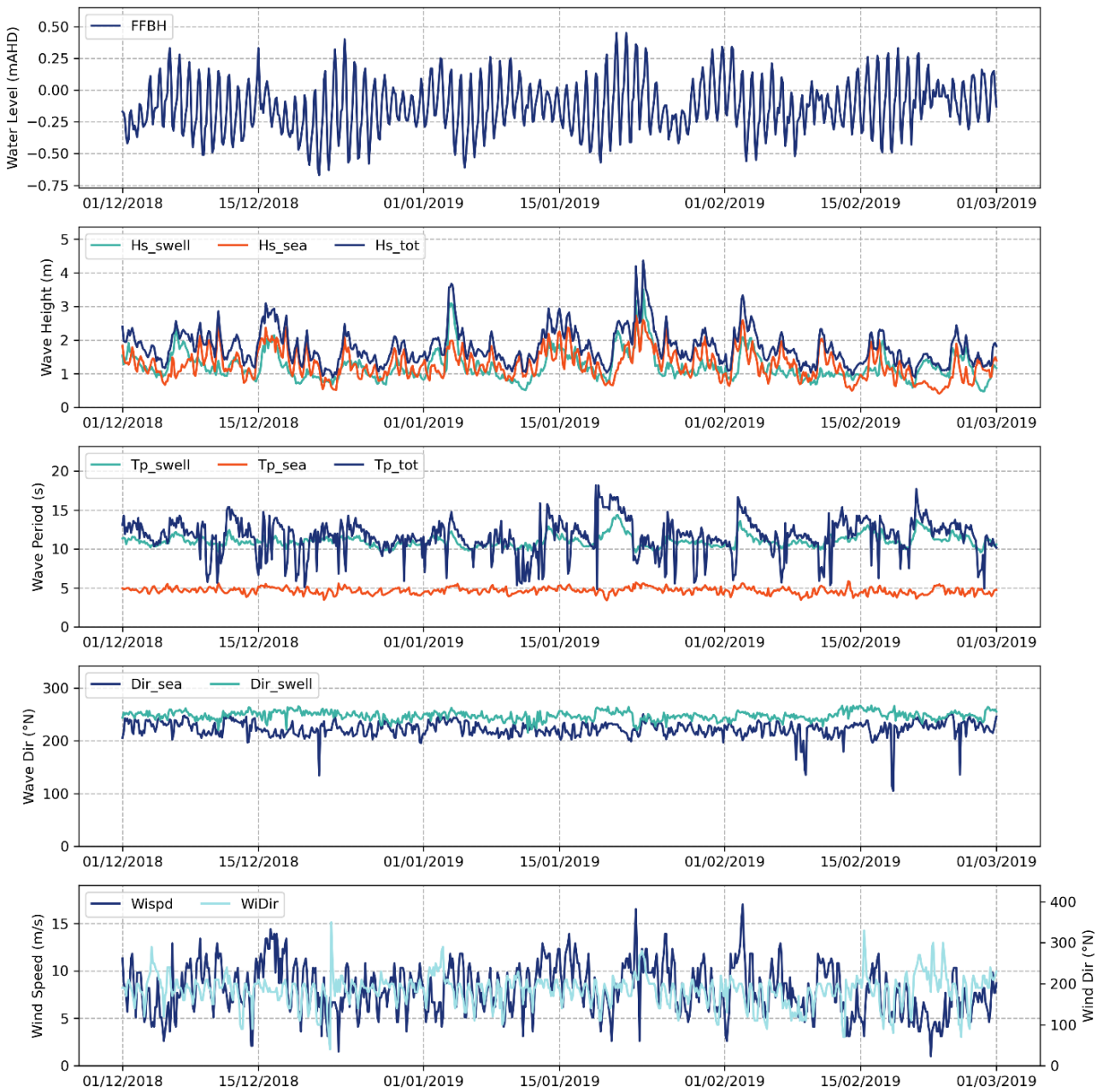


Fig. B.1.7-4: 2018/19 Summer baseline modelling input data.

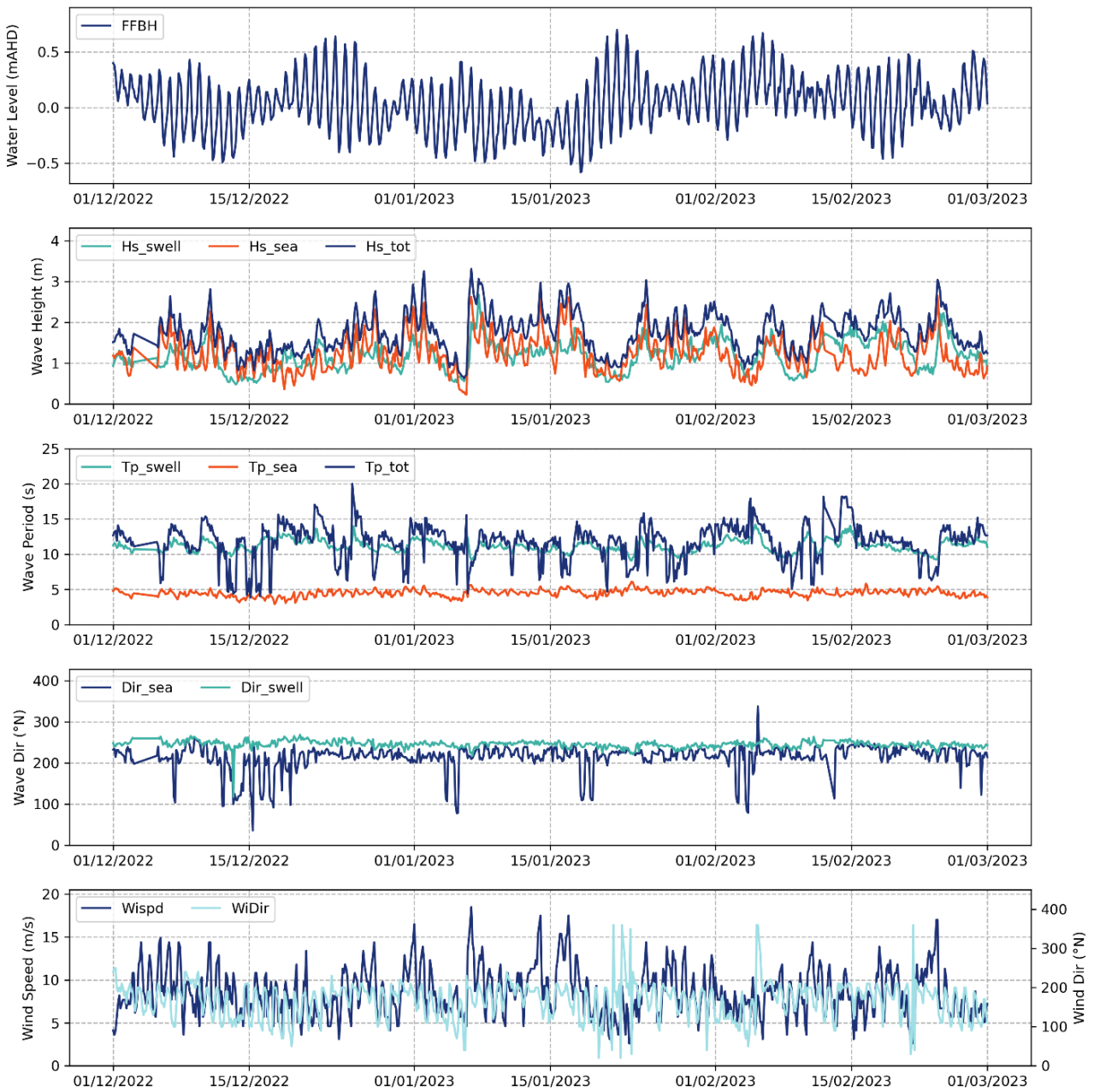


Fig. B.1.7-5: 2022/23 Summer baseline modelling input data.

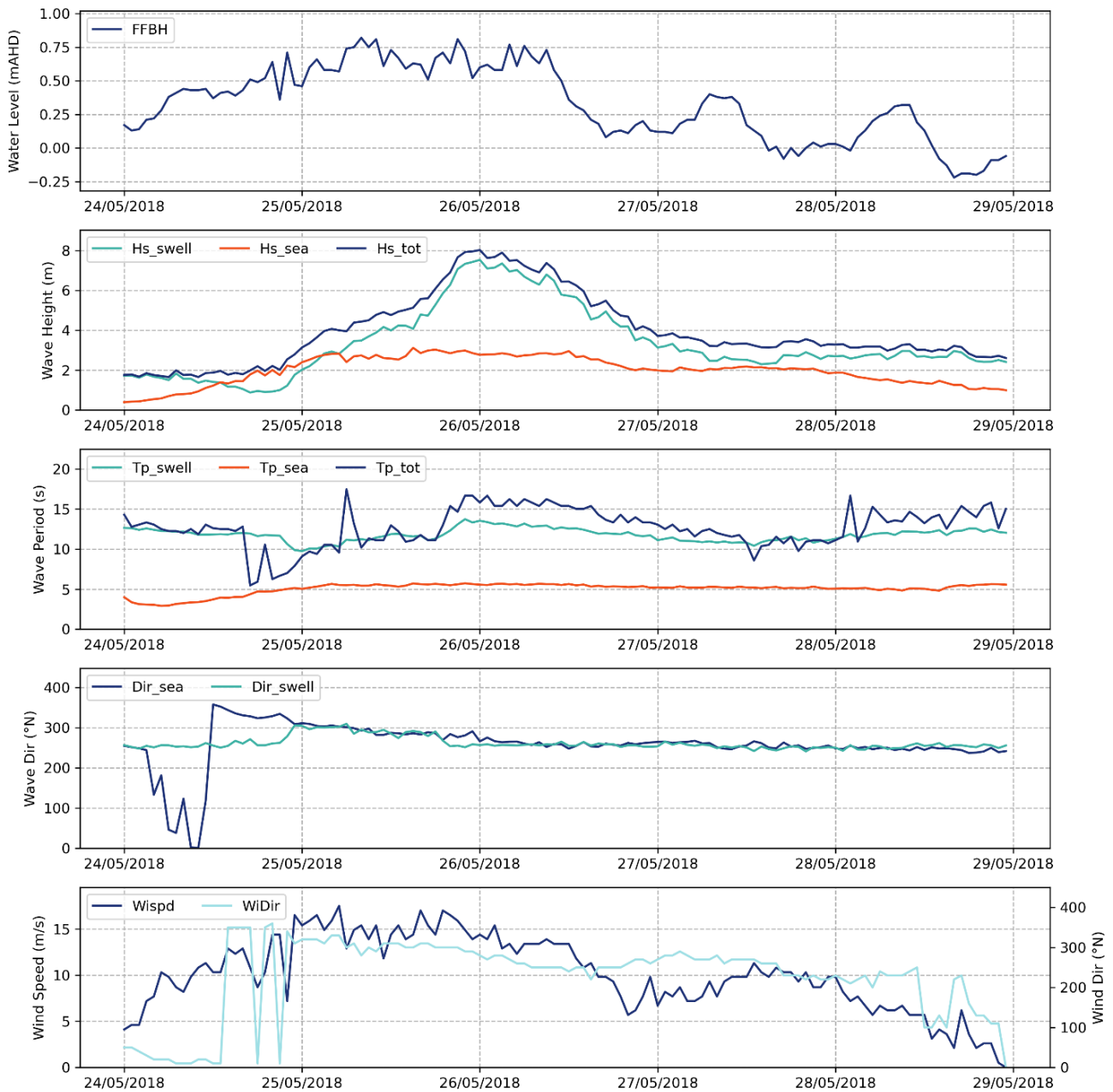


Fig. B.1.7-6: 2018 Long period swell event baseline modelling input data.

B.1.8 Modelling results

The accurate representation of local scale wave and tide characteristics has involved the configuration of various modelling parameters including the effects of bottom friction on dissipation of wave energy and wind friction models. Displayed between Fig. B.1.8-1 and Fig. B.1.8-6 timeseries plots for each baseline modelling period has been compared against available recorded data at the Cottesloe WRB, showing good agreement between modelled and recorded data.

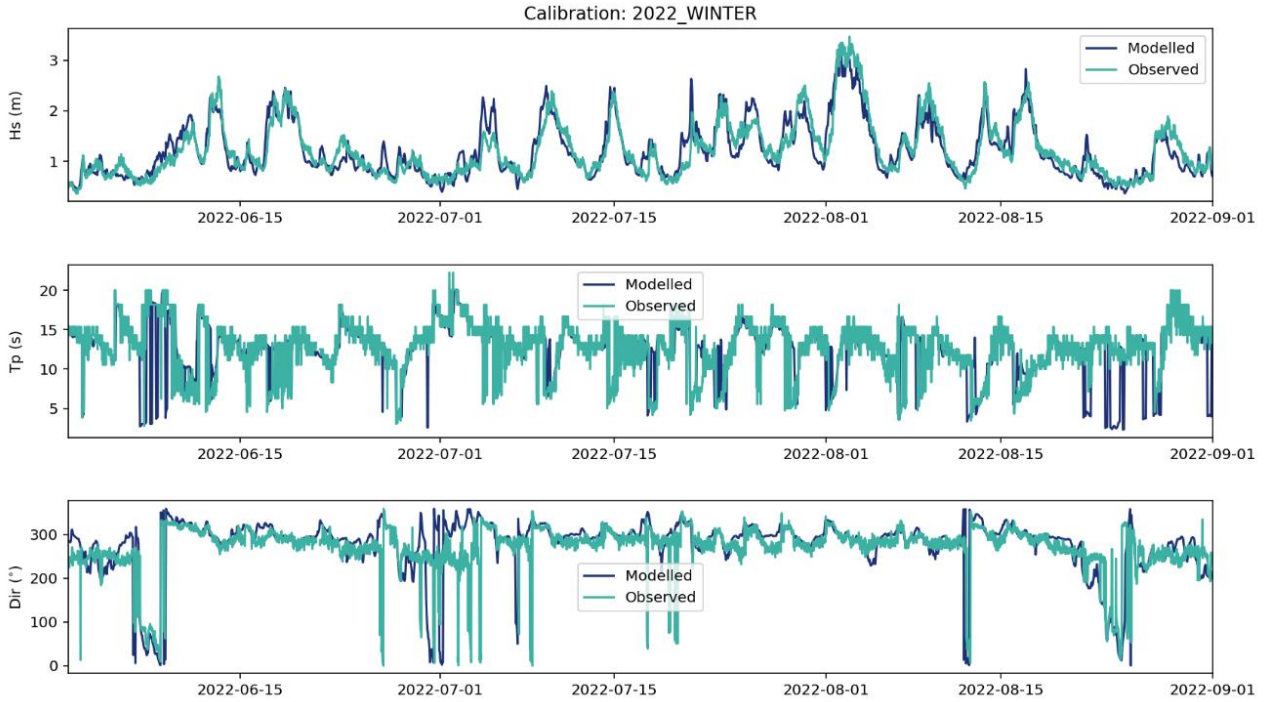


Fig. B.1.8-1: Modelled results vs observed data - Winter 2022, Cottesloe WRB.

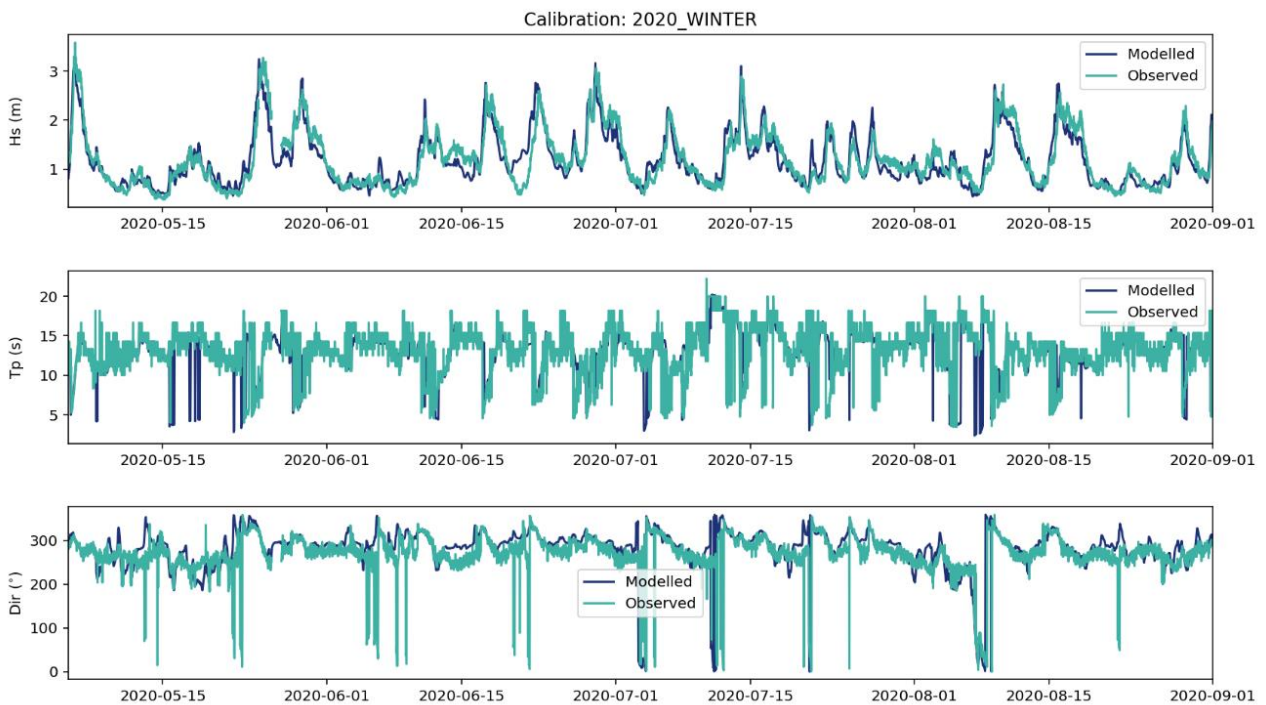


Fig. B.1.8-2: Modelled results vs observed data - Winter 2020, Cottesloe WRB.

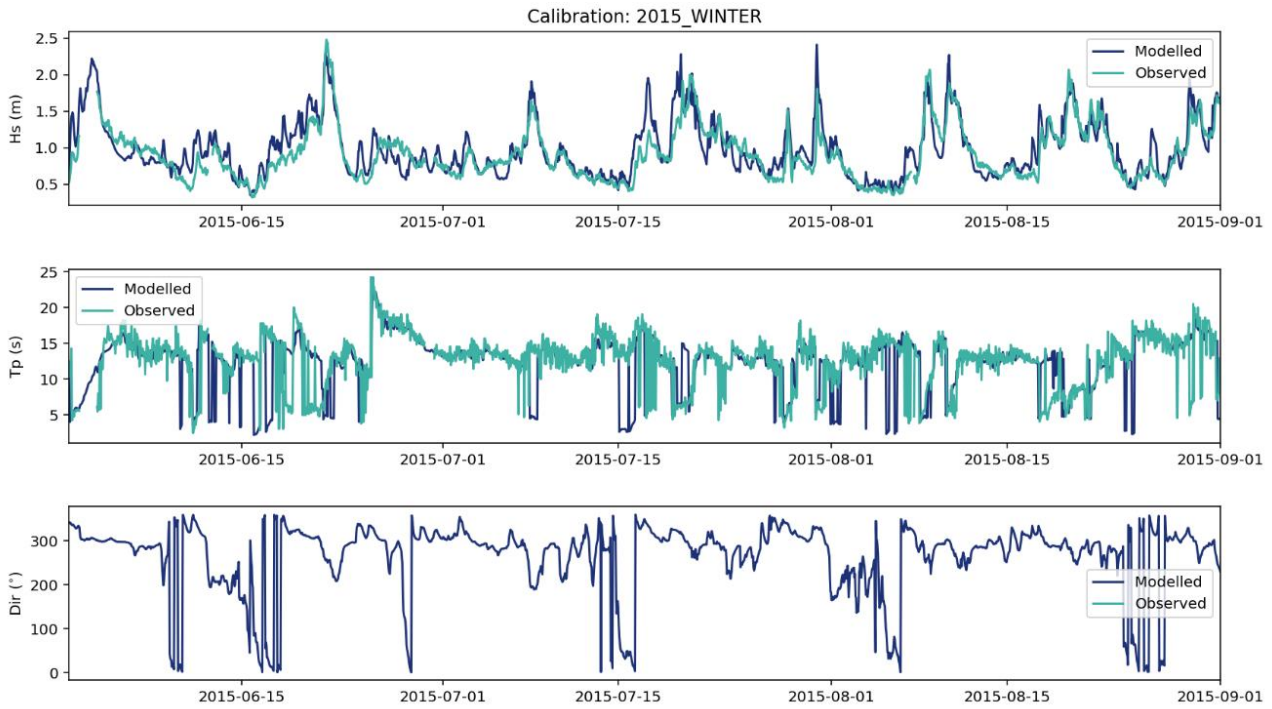


Fig. B.1.8-3: Modelled results vs observed data - Winter 2015, Cottesloe WRB. (Note: Non-Directional observation data during this period).

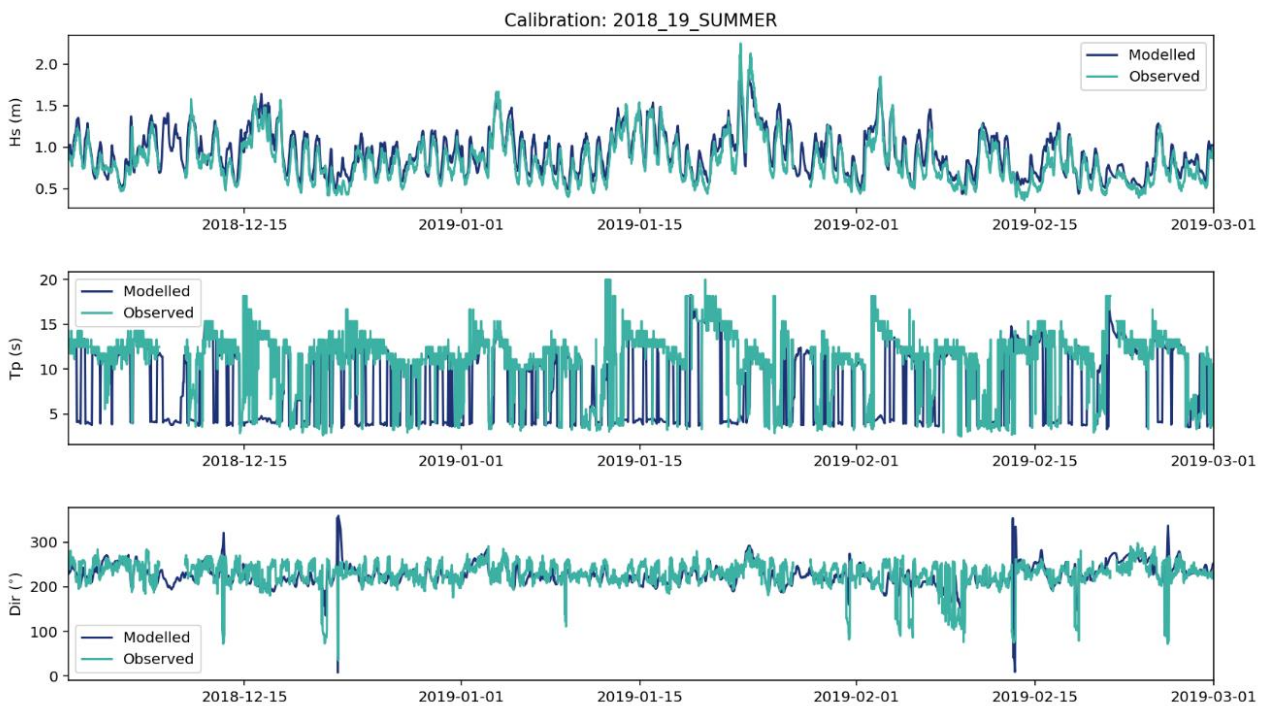


Fig. B.1.8-4: Modelled results vs observed data - Summer 2018/19, Cottesloe WRB.

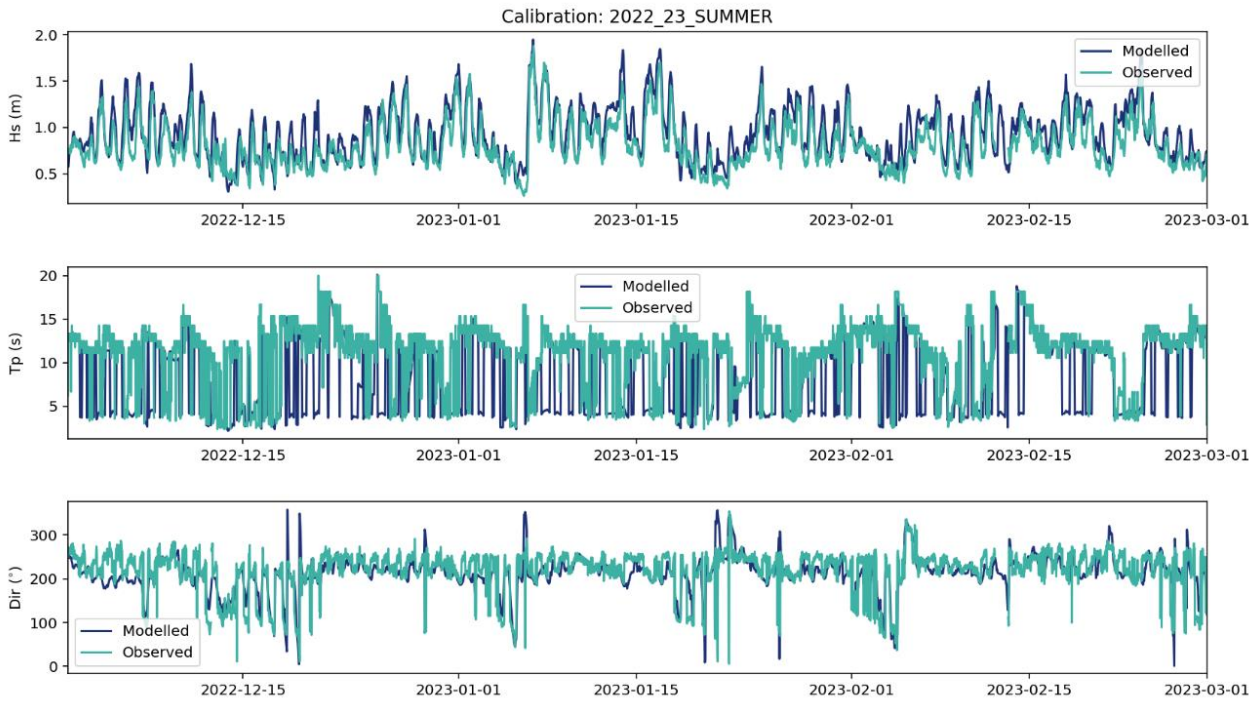


Fig. B.1.8-5: Modelled results vs observed data - Summer 2022/23, Cottesloe WRB.

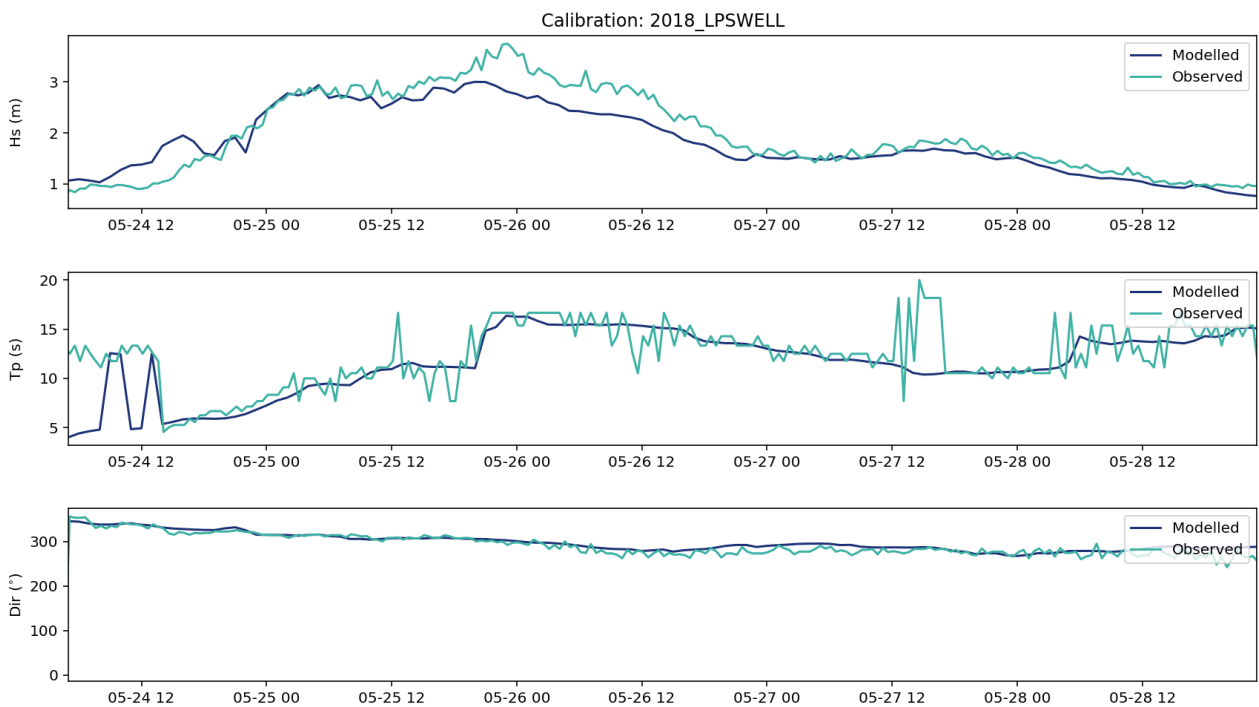


Fig. B.1.8-6: Modelled results vs observed data – 2018 long period swell event, Cottesloe WRB.

B.1.9 Statistical performance

Various error statistics were used to evaluate the accuracy of the model across all baseline scenarios. These errors statistics include the calculation of Bias, Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Standard Error (STDError) and the Median Average Difference (MAD). The calculated error metrics were compared against observed wave data recorded at the Cottesloe and Mandurah Wave Rider Buoys, with error statistics presented in Tab. B.1.9-3 through to Tab. B.1.9-6.

To assess the model performance, the results were benchmarked against threshold values recommended by Evans³ and Bartlett⁴ which provide guidance for acceptable performance metrics in numerical modelling, which are summarised in Tab. B.1.9-2. These references specify RMSE limits of $\pm 10\%$ for significant wave height (H_s), $\pm 20\%$ for wave period (T_p), and $\pm 30\%$ for wave direction (Dir), relative to the observed mean values. Modelled H_s RMSEs ranged from 13% to 30%, and T_p from 17% to 47%, exceeding the thresholds in several cases. These deviations are consistent with known challenges in nearshore wave modeling, where bathymetric complexity, spatial wind variability, and non-linear wave transformations contribute to uncertainty. RMSE values for wave direction remained within the 30% criterion, typically between 5% and 20%, indicating good directional agreement. Overall, the model demonstrates sufficient skill for baseline scenario assessment, though refinement of wave height and period simulation will improve the overall model performance.

Tab. B.1.9-1: Definition of error statistics

Error measure
$Bias = \overline{(m - o)}$
$MAE = \overline{ m - o }$
$RMSE = \sqrt{\overline{(m - o)^2}}$
$Stdererror = \sqrt{\frac{1}{n - 1} \sum (m - o - Bias)^2}$
$MAD = median(m - o)$

3 G. P. Evans, "A framework for marine and estuary model specification in the UK," Tech. Rep. FR0374, p. 58, Foundation for Water Research, 1993.

4 J. M. Bartlett, "Quality control manual for computational estuarine modelling, Binnie, Black & Veatch, R&D," Tech. Rep. W113, p. 80, Environment Agency, 1998.

Tab. B.1.9-2: Statistical guidelines for coastal and estuarine hydrodynamic models, based on recommendations from Evans and Bartlett. Adapted from (Williams and Esteves, 2017)⁵

Model predictions	RMSE	Bias	R	SI
Bathymetry	±2.5% of the mean water depth	<0.10	>0.95	<10%
Water level (coast)	±0.1 m or 10% of the measured level (spring tide); ±15% (neap tide)	<0.10	>0.95	<10%
Water level (estuary)	±0.1 m (mouth); ±0.3 m (head) or 10% of the measured level (spring tide); ±15% (neap tide)	<0.20	>0.95	<15%
Water-level phase (coast)	±15 minutes	<0.20	>0.90	<20%
Water-level phase (estuary)	±15 minutes (mouth); ±25 minutes (head)	<0.25	>0.90	<20%
Average current speed	±0.1 m/s or ±10% to 20% of the measured speed	<0.10	>0.95	<10%
Peak current speed	Within <0.05 m/s (very good), <0.1 m/s (good), <0.2 m/s (moderate), and <0.3 m/s (poor) of the measured peak speed	<0.15	>0.90	<15%
Current direction (coastal)	±10° of the measured direction	<0.25	>0.90	<20%
Current direction (estuary)	±15° of the measured direction	<0.30	>0.90	<20%
Bed shear stress	±10% N/m ² of the measured mean stress	<0.10	>0.95	<10%
Wave height	±10% of the measured mean observed height	<0.15	>0.95	<10%
Wave period	±20% of the measured mean observed period	<0.20	>0.90	<20%
Wave direction	±30% of the measured mean observed direction	<0.25	>0.90	<25%
Mean SPM concentration	±20% of the mean measured SPM concentration	<0.20	>0.90	<20%
Accretion based on dredge volumes	±50% of the measured dredge volume	N/A	N/A	N/A
Temperature	±0.5°	—	—	—
Salinity	±1 psu	—	—	—

Tab. B.1.9-3: Model performance to recorded data (Winter) - Cottesloe.

Error Statistics	Winter 2022			Winter 2020			Winter 2015		
	Hs	Tp	Dm	Hs	Tp	Dm	Hs	Tp	Dm
Bias	-0.004	-0.08	7.74	-0.02	-0.20	14.0	0.06	-0.11	-
MAE	0.005	0.08	7.74	0.02	0.20	14.0	0.06	0.11	-
RMSE	0.24	3.00	55.0	0.25	2.82	53.0	0.21	3.84	-
RMSE (%)	19	24	20	21	21	20	22	30	-
Std Error	0.24	3.00	54.4	0.25	2.82	52.3	0.20	3.84	-
MAD	0.14	0.71	14.2	0.15	0.74	14.6	0.11	0.85	-

Tab. B.1.9-4: Model performance to recorded data (Winter) - Mandurah.

Error Statistics	Winter 2022			Winter 2020			Winter 2015		
	Hs	Tp	Dm	Hs	Tp	Dm	Hs	Tp	Dm
Bias	0.05	-0.19	1.47	0.09	-0.03	2.64	0.07	-0.44	1.12

⁵ Williams, J. J., & Esteves, L. S. (2017). Guidance on setup, calibration, and validation of hydrodynamic, wave, and sediment models for shelf seas and estuaries. *Advances in civil engineering*, 2017(1), 5251902.

MAE	0.05	0.19	1.47	0.09	0.03	2.64	0.07	0.44	1.12
RMSE	0.28	2.64	43.0	0.39	2.23	41.0	0.29	3.04	42.0
RMSE (%)	13.3	20.2	16.6	18.6	16.7	15.8	17.3	22.7	17.0
Std Error	0.28	2.64	43.0	0.38	2.23	41.0	0.28	3.01	42.0
MAD	0.18	0.67	6.80	0.16	0.72	6.58	0.69	7.72	7.72

Tab. B.1.9-5: Model performance to recorded data (Summer) and Long Period Swell Event - Cottesloe.

Error Statistics	Summer 2018/19			Summer 2022/23			Long Period Swell 2018		
	Hs	Tp	Dm	Hs	Tp	Dm	Hs	Tp	Dm
Bias	0.10	-2.70	-2.73	0.12	-3.00	-6.00	-0.14	-0.68	6.50
MAE	0.10	2.70	2.73	0.12	3.00	6.00	0.14	0.68	6.50
RMSE	0.16	4.95	29.0	0.18	5.20	36.0	0.31	2.32	12.28
RMSE (%)	18.7	45.1	12.7	22	47.3	16.4	15.9	19.9	4.2
Std Error	0.11	4.15	29.0	0.13	4.24	35.3	0.28	2.22	10.47
MAD	0.10	1.14	1.14	0.12	1.25	15.4	0.16	0.64	5.81

Tab. B.1.9-6: Model performance to baseline scenarios (Summer) and Long Period Swell Event - Mandurah.

Error Statistics	Summer 2018/19			Summer 2022/23			Long Period Swell 2018		
	Hs	Tp	Dm	Hs	Tp	Dm	Hs	Tp	Dm
Bias	0.22	0.42	3.43	0.32	-0.01	3.79	-0.07	-0.14	3.12
MAE	0.22	0.42	3.43	0.32	0.01	3.79	0.07	0.15	3.12
RMSE	0.30	2.19	12.5	0.41	2.72	27.7	0.29	2.28	29.1
RMSE (%)	20.1	19.5	5.45	29.7	23.6	12.5	9.0	18.9	10.4
Std Error	0.21	2.15	12.1	0.25	2.72	27.4	0.28	2.28	29.0
MAD	0.22	0.58	6.18	0.34	0.62	8.38	0.16	0.71	0.64

B.1.10 Flow pattern validation

The regional model has been validated by comparing the simulated flow direction within Warnbro Sound to earlier numerical modelling completed by Bridgewood⁶. This study showed the variable rotation of surface currents within Warnbro Sound which were shown to be dependent on the seasonal winds experienced during the time. The Surface currents predominantly form an anticlockwise gyre during the winter months and a clockwise gyre during the summer. This seasonal shift is attributed to prevailing wind patterns, strong north-westerly winds during the stormy winter drive the anticlockwise circulation, while south-westerly sea breezes in summer promote clockwise rotation. Flow velocity vectors have been extracted from the regional model best representing similar characteristics of flow redirection within Warnbro Sound. (Fig. B.1.10-1).

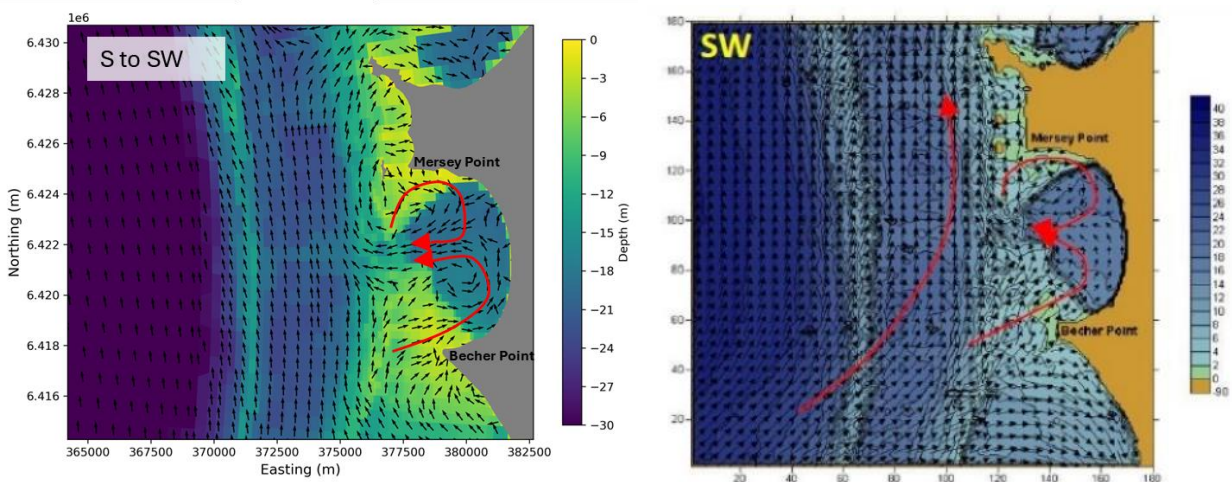


Fig. B.1.10-1: Regional flow patterns arriving from the South-Southwest direction at Warnbro Sound (left), South-westerly flow patterns for a SW wind of 8m/s (Bridgewood, 2006) (right).

⁶ Bridgewood, 2006. Seagrass landscapes along a wave gradient, PhD Thesis, Murdoch University

B.2 Local scale morphological modelling

A coupled local-scale morphological model has been developed to simulate conditions within Northern Warnbro Sound using Delft3D-FM. This model is nested within the regional hydrodynamic and wave model developed in Appendix B.1. The calibrated regional model has been used to simulate larger-scale wave and tidal processes for each of the seasonal baseline scenarios (i.e. 2022-23 Summer Sea Breeze conditions), and the outputs, input at the boundaries of the local model to resolve finer spatial and temporal scales at the local level.

This model has been developed, spanning Northern Warnbro Sound, to enhance the understanding of coastal dynamics and to support informed decision-making for sustainable coastal management. Including:

- Analysing sediment movement patterns within the coastal system under varying conditions (e.g., tides, waves, and wind).
- Identifying sediment sources, transport pathways, and deposition zones to predict changes in coastal morphology.
- Provide a baseline to assess the impact of management strategies including an offshore breakwater and surf-zone nourishment.

Tab. B.1.10-1: Summary of baseline modelling scenarios.

	Winter Season	Long-period swell	Summer sea breezes
High	2020	25/05/2018 event	2022/23
Model	2022	N/A	N/A
Low	2015	N/A	2018/19

B.2.1 Model setup

Two high resolution modelling domains have been developed as an unstructured grid coupled D-WAVE and D-FLOW model. The model extends from approximately from Shoalwater Bay to Southern Warnbro Sound Fig. B.2.1-1. Local grid refinement has been incorporated to balance computational efficiency and accuracy, where finer resolution has been incorporated in key areas such as Mersey Point and Tern Bank to capture the local variation in flows, wave action and sediment movement. Tab. B.1.1-1: summarises the model grid resolution.

The model uses the AusBathyTopo 250m 2023 grid and 2009 10m LiDAR (WA Department of Transport) in the model build. The higher resolution LiDAR was merged with the 250m Australia-wide depth grid to account for higher spatial resolution and increased vertical elevation accuracy in the nearshore. Prior to merging the datasets, the vertical datum of each was checked. The vertical datum for this modelling is Australian Height Datum (AHD).

The morphological model has also been setup under a "Do nothing" scenarios which assumes no future management. It is used as a baseline scenario to support options

appraisal. Additionally, the model incorporates the modelling of structural interventions and nourishment strategies. These include the offshore breakwater structure, designed to attenuate wave energy and reduce erosion, and a surf-zone nourishment zone of approximately 2,000 m³ intended to redistribute sediment along the shore to mitigate erosion in targeted areas (Fig. B.2.1-2).

Tab. B.2.1-1: Regional D-FLOW and D-WAVE grid resolution.

Grid	Grid Size	Resolution
D-FLOW		
Overall	6 x 6 km	15 - 30m
D-WAVE		
Overall	~ 6 x 6 km	20 - 30 m

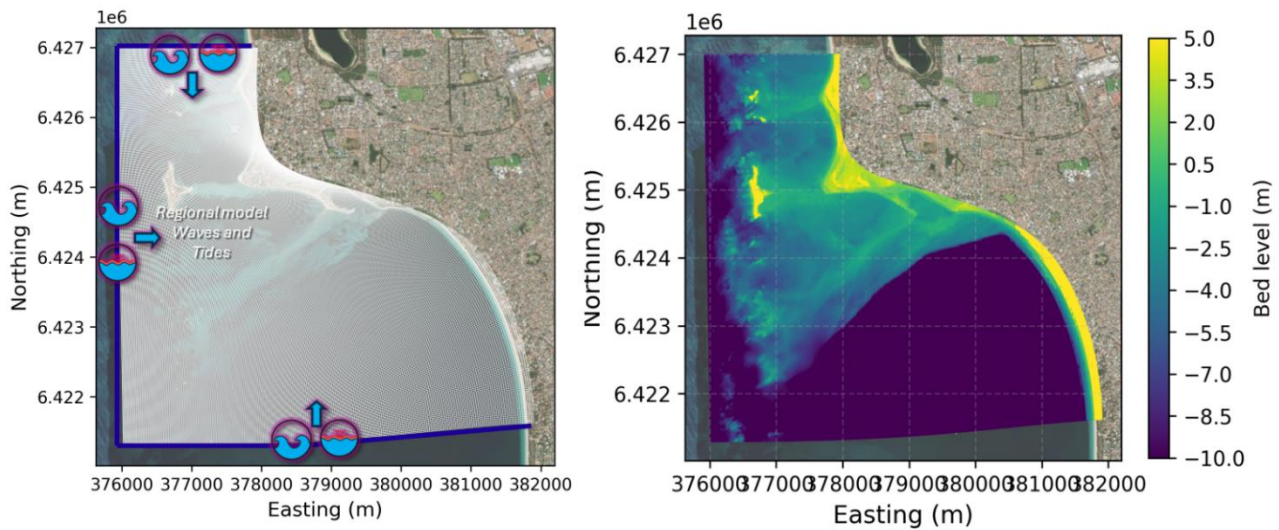


Fig. B.2.1-1: Base case local scale Delft3D-FM morphological model grid (left) and bathymetry (right).

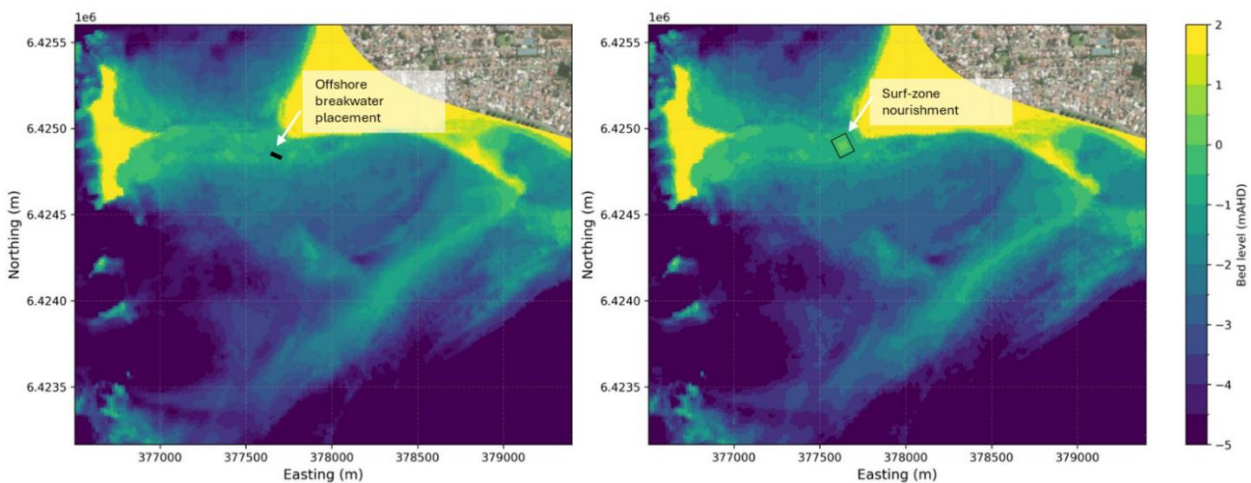


Fig. B.2.1-2: Delft3D-FM morphological modelling of offshore breakwater (left) and surf zone nourishment (right)

B.2.2 Model inputs

Hydrodynamic/Hydraulic input:

The morphological model is forced using boundary conditions derived from the calibrated regional-scale model, as detailed in Appendix B. For each scenario modelled (i.e. Winter, summer sea breeze) modelling results have been extracted at the boundary of the high-resolution model. The key data obtained from the regional model include:

- **Tides:** Water level variations.
- **Currents:** Regional flow patterns that drive sediment transport.
- **Waves:** Wave height, wave direction and wave period.

Morphological input:

The Delft3D morphological model uses the default Van Rijn (2007) formula which was determined to be sufficient for this application. A median grain size (D_{50}) of 0.2 mm was adopted for morphological modelling to represent the seabed sediments across the model domain. This value has been based on previously collected sediment sampling by MDW Environmental Services (2013)⁷ and O2 Marine (2021)⁸, collected from sites along the Bent Street navigation channel. The two-investigation reported similar sampling results indicating that the sediments are predominantly composed of fine sand (62–250 μm) and medium sand (250–500 μm), with combined proportions typically exceeding 60–70% by weight. As shown in the grain size distribution graphic Fig. B.2.2-1, the selected D_{50} of 0.2 mm lies within an acceptable range. In the absence of broader site-specific sediment sampling across the model domain, this combined dataset provided the most reliable basis for defining representative bed material characteristics for morphological modelling.

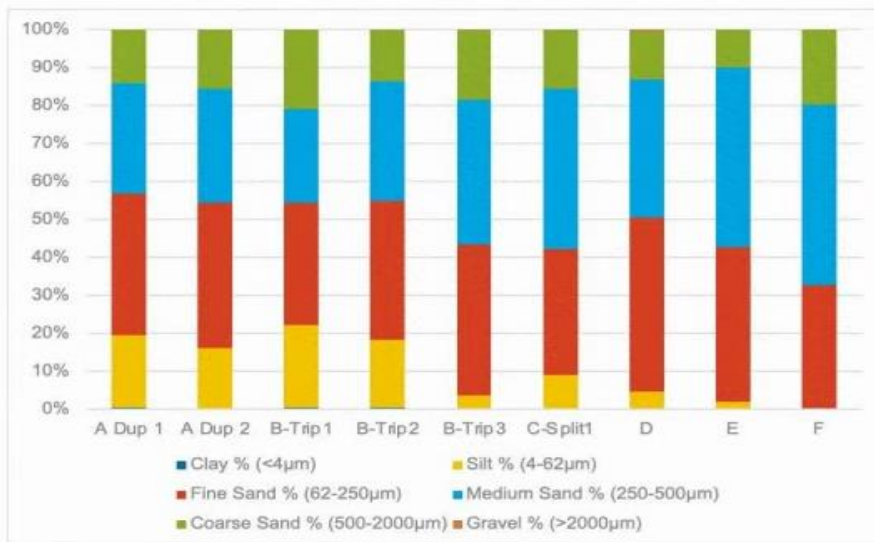


Fig. B.2.2-1: Particle size distribution in Bent Street channel (O2 Marine, 2021).

⁷ MDW Environmental Services (2013). Environmental Investigation for the new navigation Boating Channel, Bent Street Boat Ramp. Prepared for City of Rockingham. MDW Environmental Services. E2013-002.

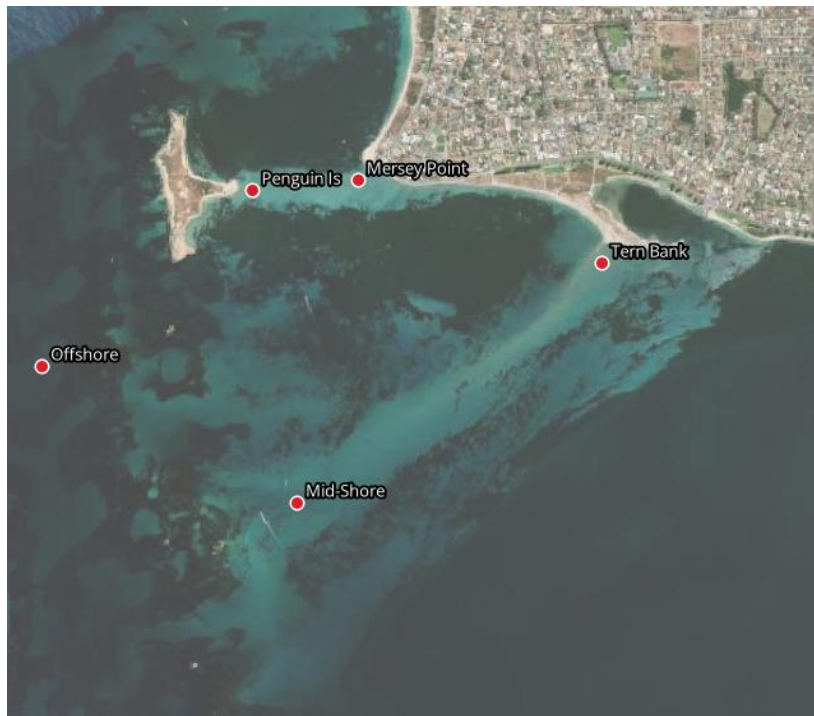
⁸ O2 Marine (2021). Bent Street Boat Ramp Project. Sediment Sampling and analysis Plan Implementation Report. O2 Marine. R210057 Rev. 1 28 July 2021

B.2.3 Hydrodynamic results

The local scale model was used to simulate the six base line scenarios, representing the range of forcing conditions driving sediment transport within Warnbro Sound. Estimates of the depth of closure have been calculated based on the equation by Hallermeier (1978)⁹ using extracted wave results at the mid-shore of the model (shown Fig. B.2.3-1). From Fig. B.2.3-2 through to Fig. B.2.3-7, wave roses displaying the directional distribution of wave heights and wave directions have been plotted at each point, showing the distribution of wave heights in Warnbro Sound.

Fig. B.2.3-8 to Fig. B.2.3-10 displays the spatial distribution of mean wave height and mean current vectors within Warnbro Sound for each of the modelled scenarios (i.e. basecase, offshore breakwater and surf-zone nourishment).

Fig. B.2.3-1: Extracted wave point used for calculation of the approximate depth of closure.



Tab. B.2.3-1: Estimated Closure depth for each modelling period at the Mid-Shore point.

Modelling Scenario	Depth of Closure (m)
2022 Winter	3.3
2020 Winter	3.1
2015 Winter	3.2
2022/23 Summer	2.5
2018/19 Summer	2.9
2018 Long period swell event	3.3

⁹ Hallermeier, R. J. (1978). Uses for a calculated limit depth to beach erosion. In Coastal engineering 1978 (pp. 1493-1512).

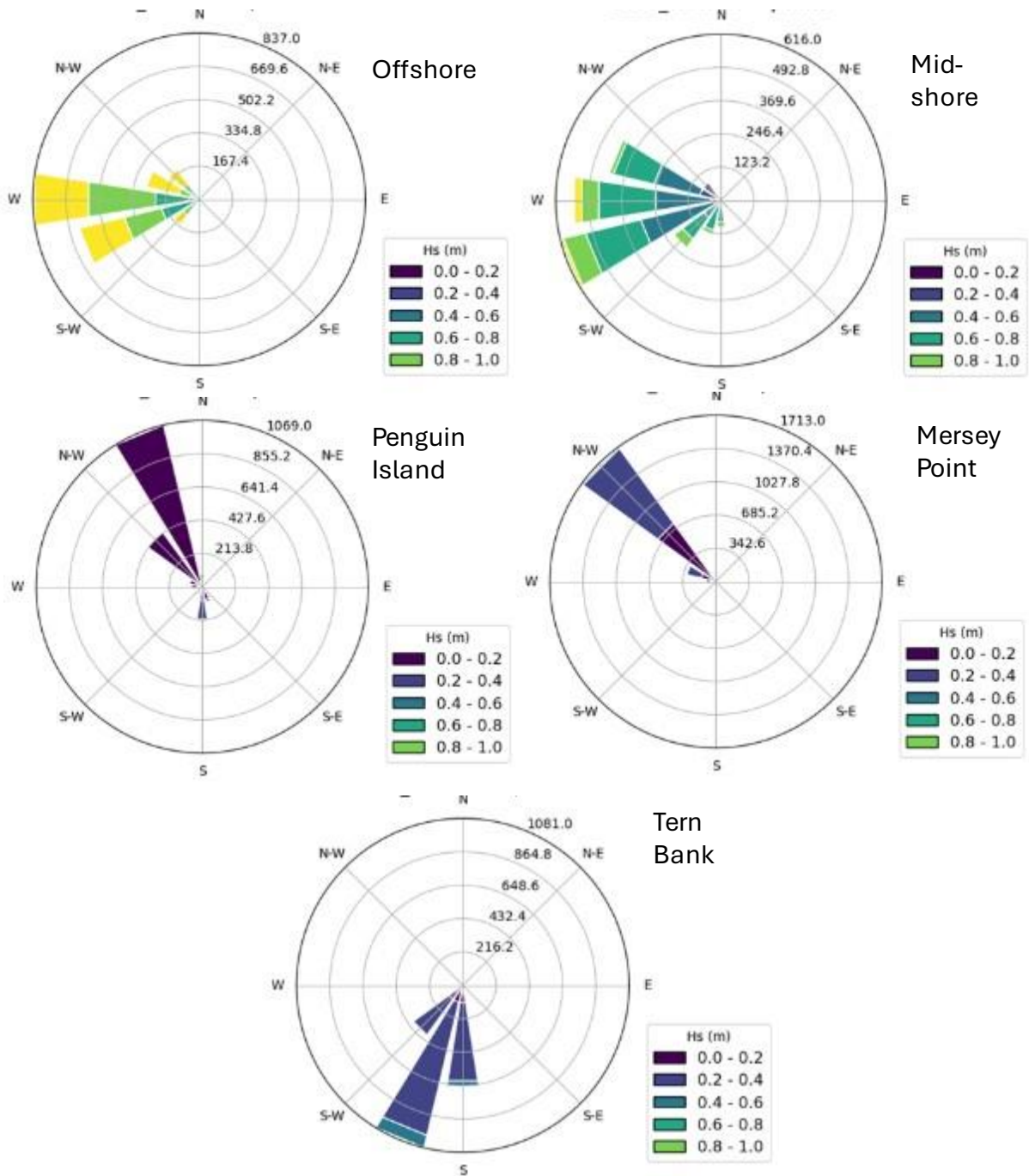


Fig. B.2.3-2: Wave rose plots within Warnbro Sound, Winter 2022.

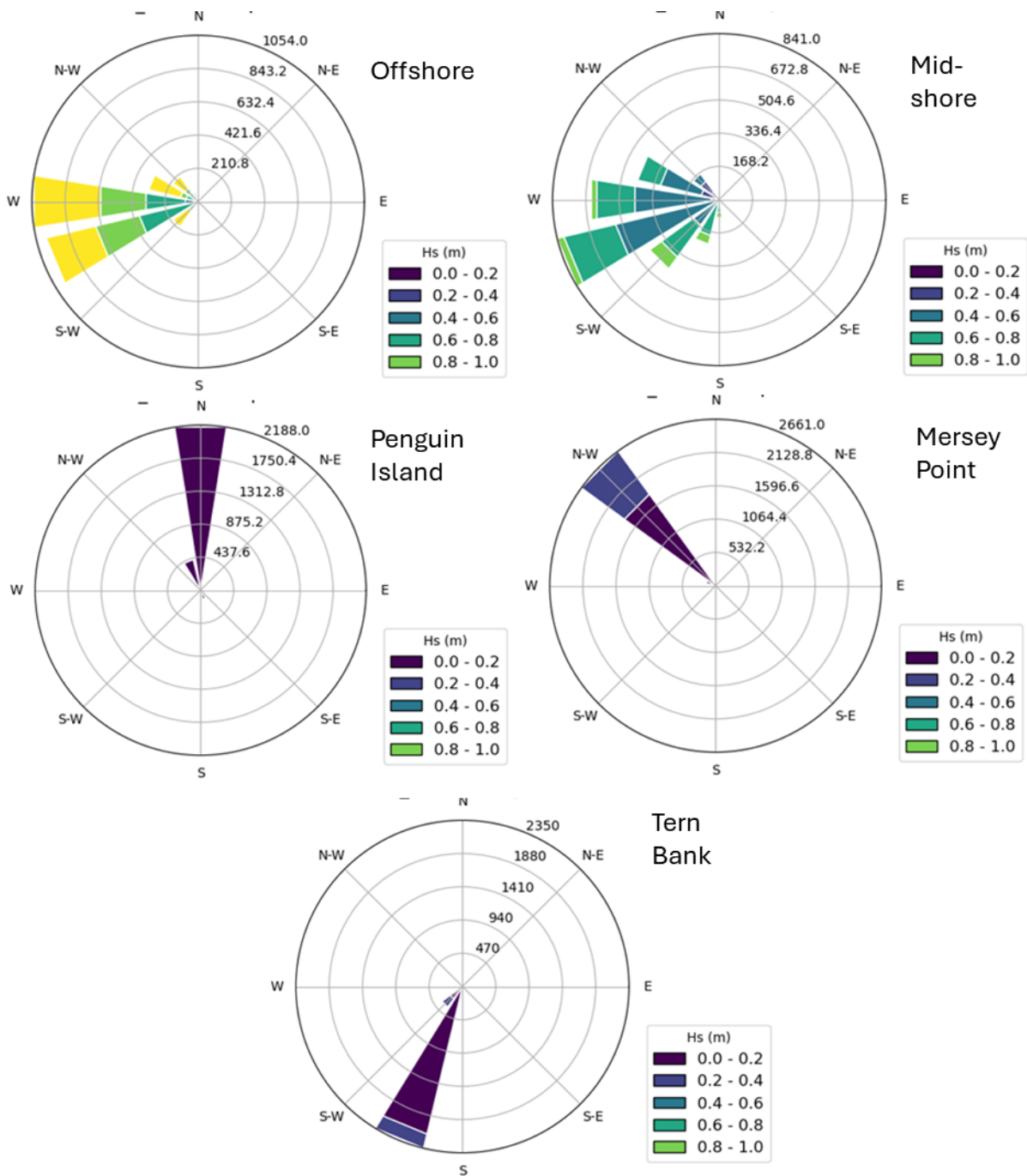


Fig. B.2.3-3: Wave rose plots within Warnbro Sound, Winter 2020.

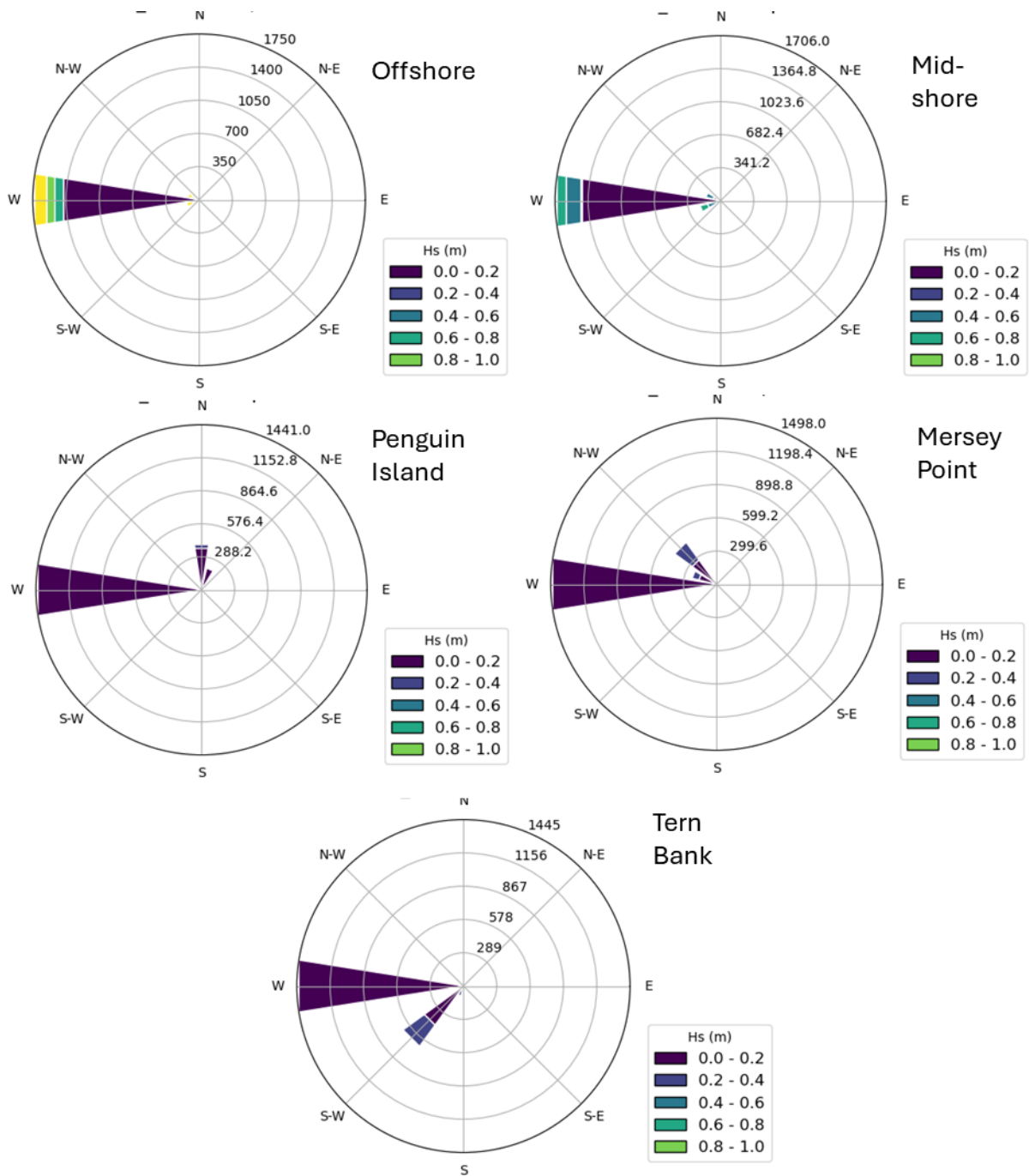


Fig. B.2.3-4: Wave rose plots within Warnbro Sound, Winter 2015.

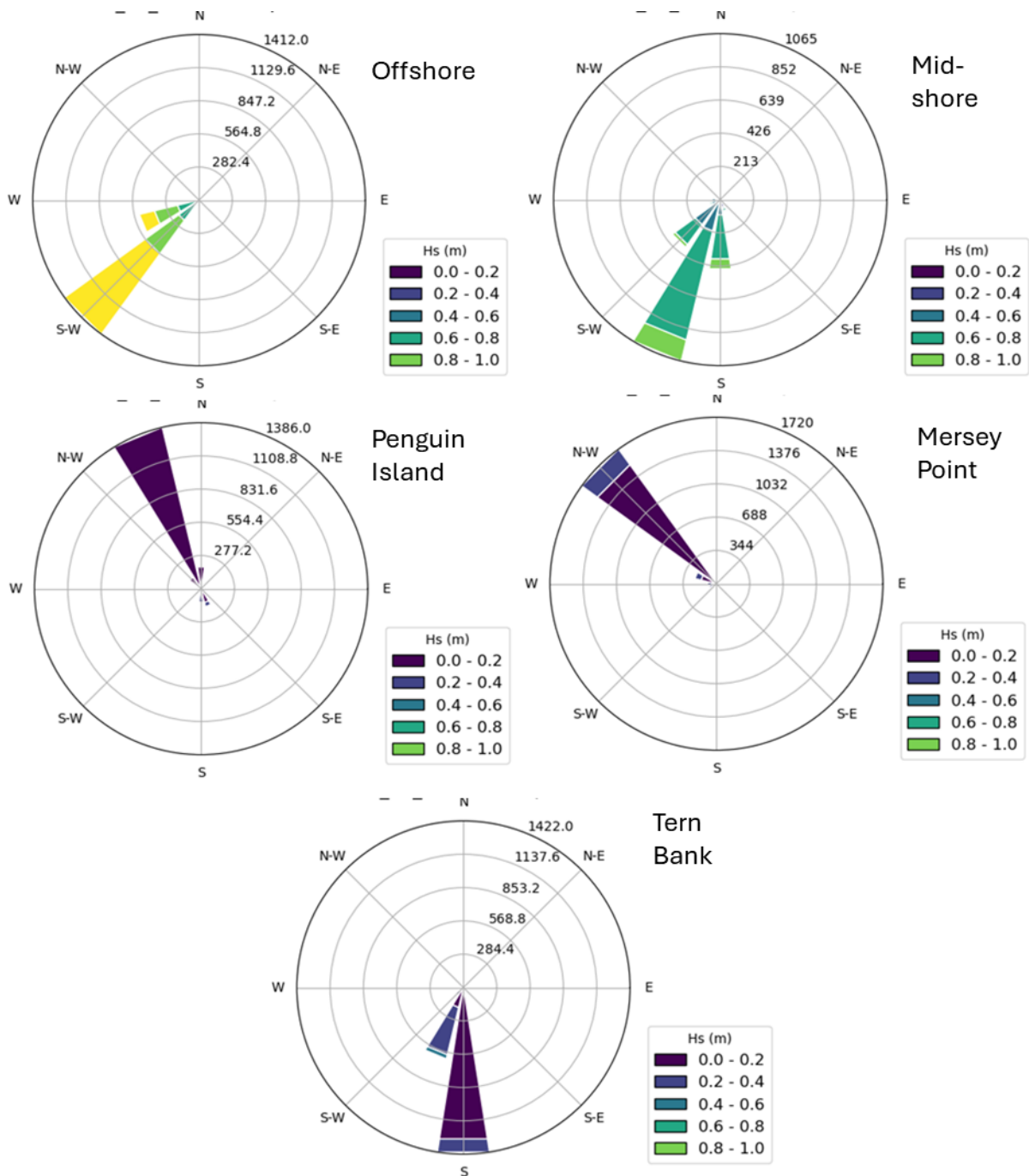


Fig. B.2.3-5: Wave rose plots within Warnbro Sound, Summer 2022/23.

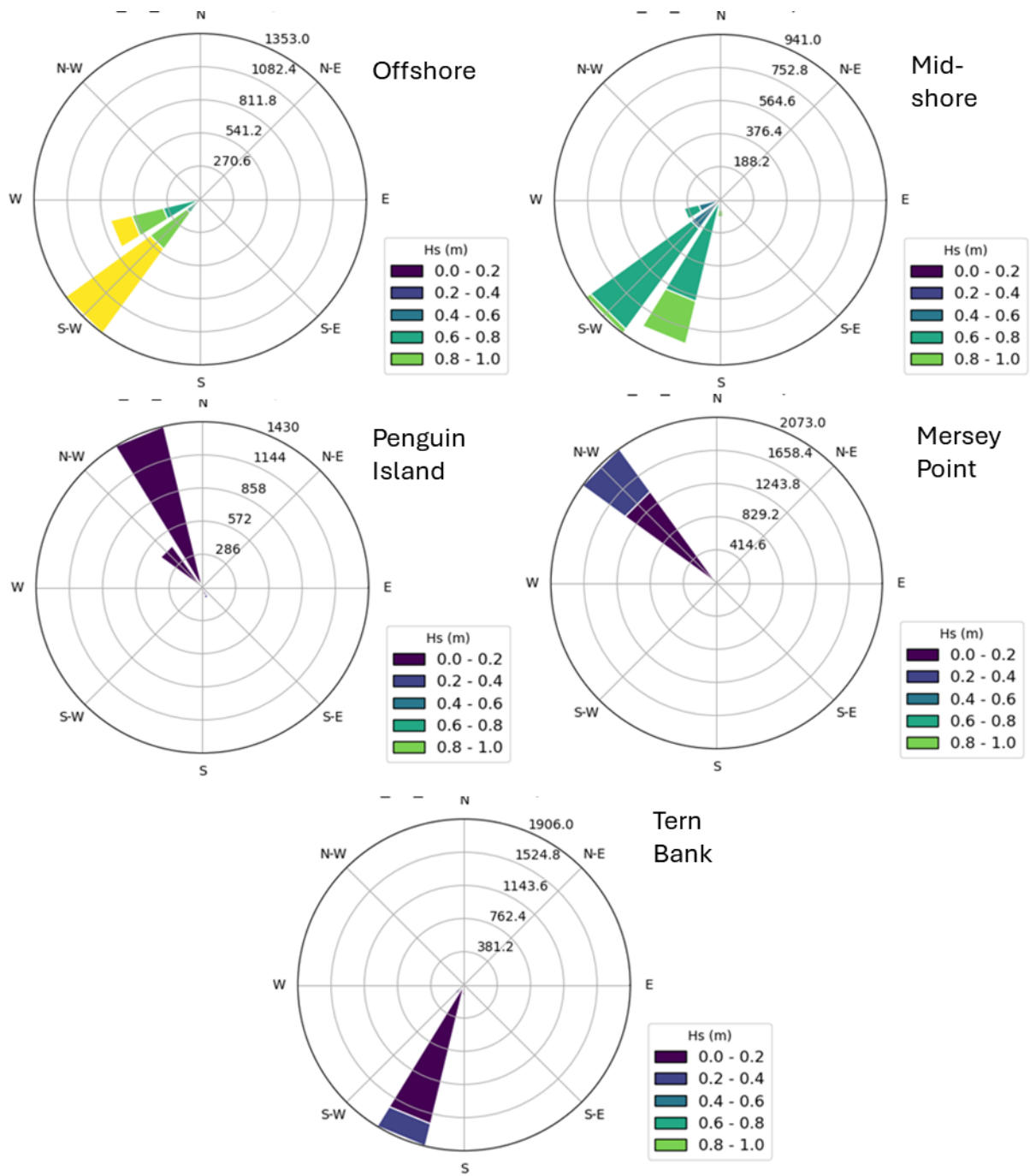


Fig. B.2.3-6: Wave rose plots within Warnbro Sound, Summer 2018/19.

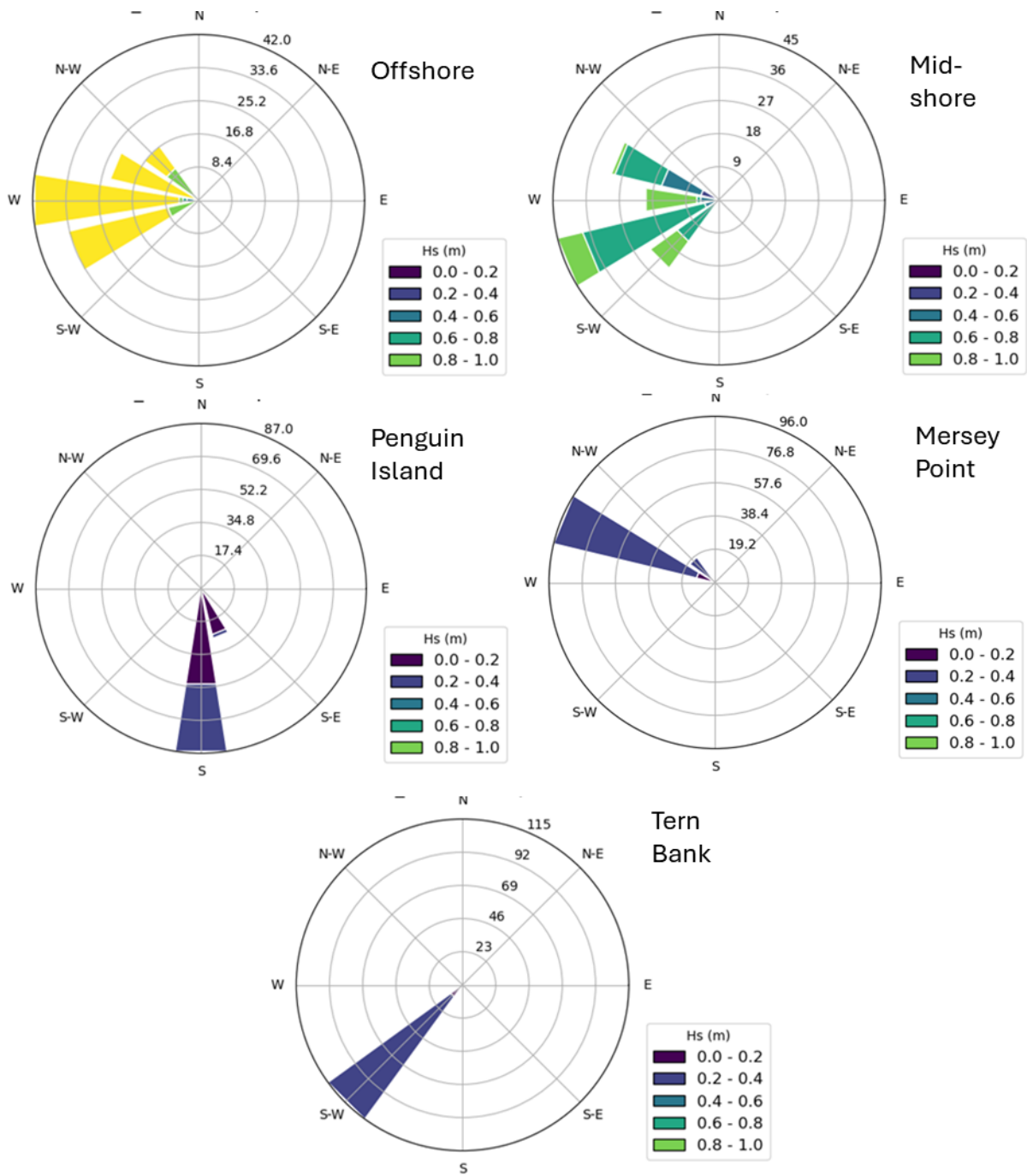


Fig. B.2.3-7: Wave rose plots within Warnbro Sound, 2018 Swell event.

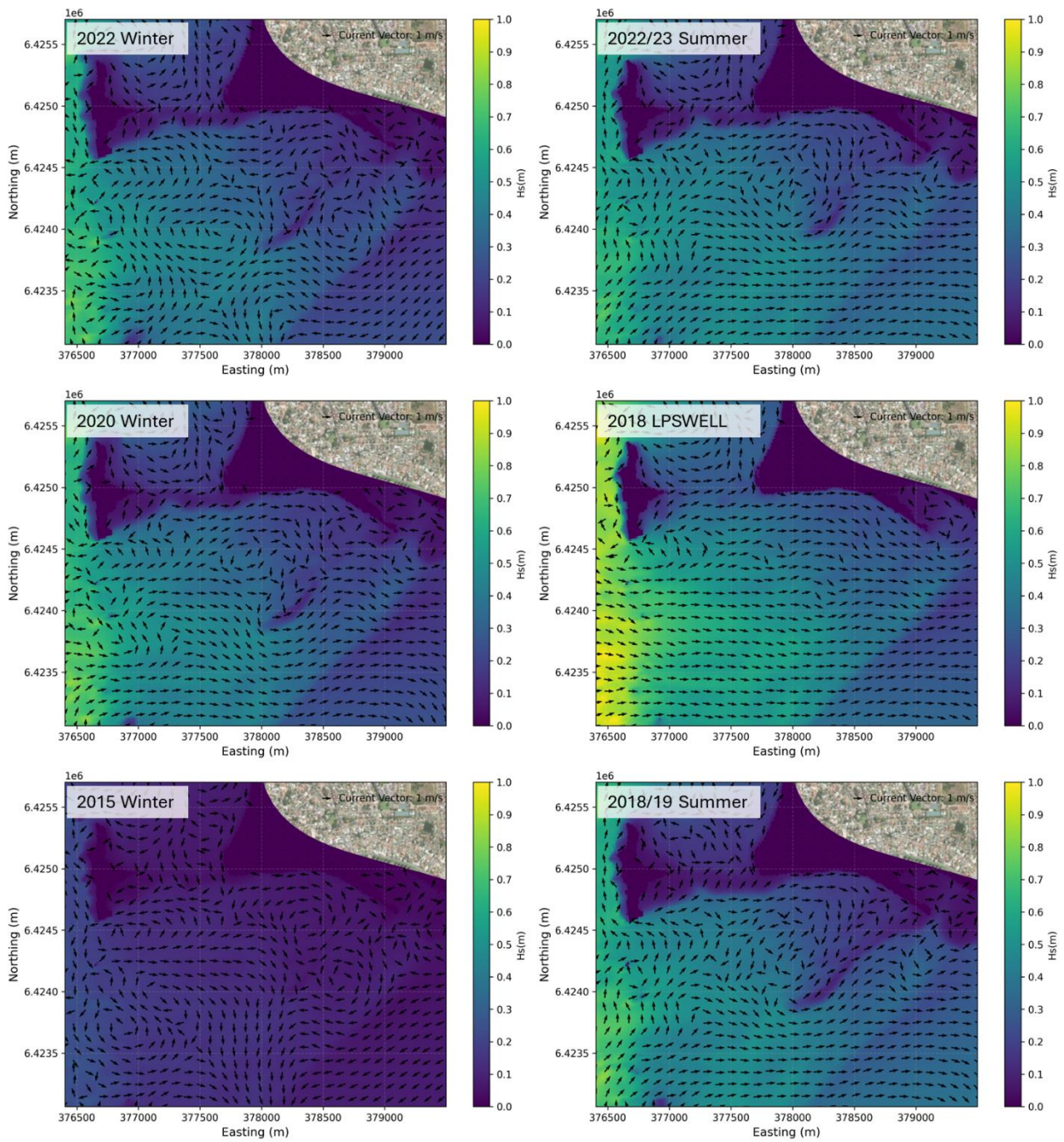


Fig. B.2.3-8: Mean wave heights and current vectors within Warnbro Sound modelled with no intervention strategies.

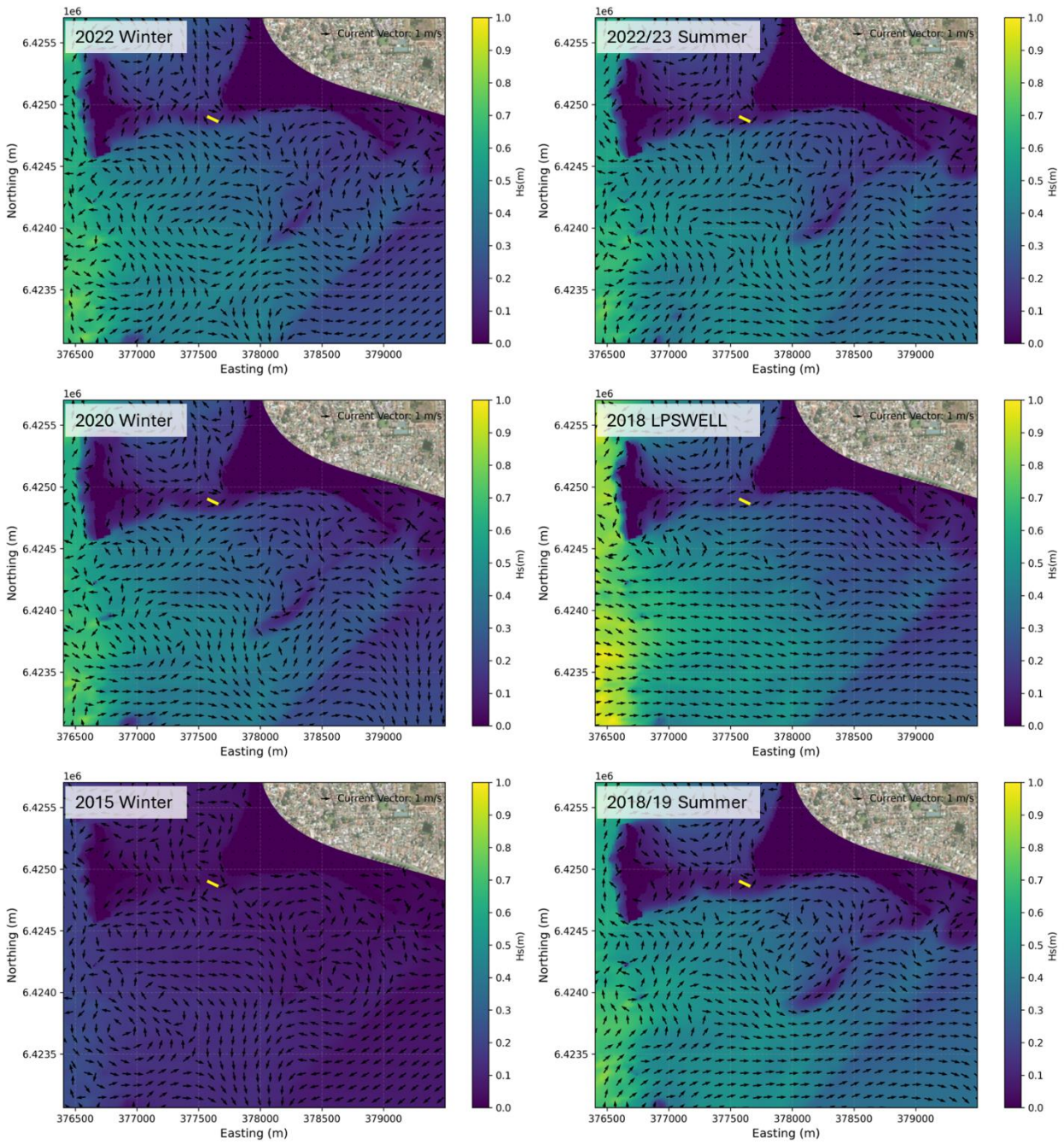


Fig. B.2.3-9: Mean wave heights and current vectors within Warnbro Sound modelled with an offshore breakwater.

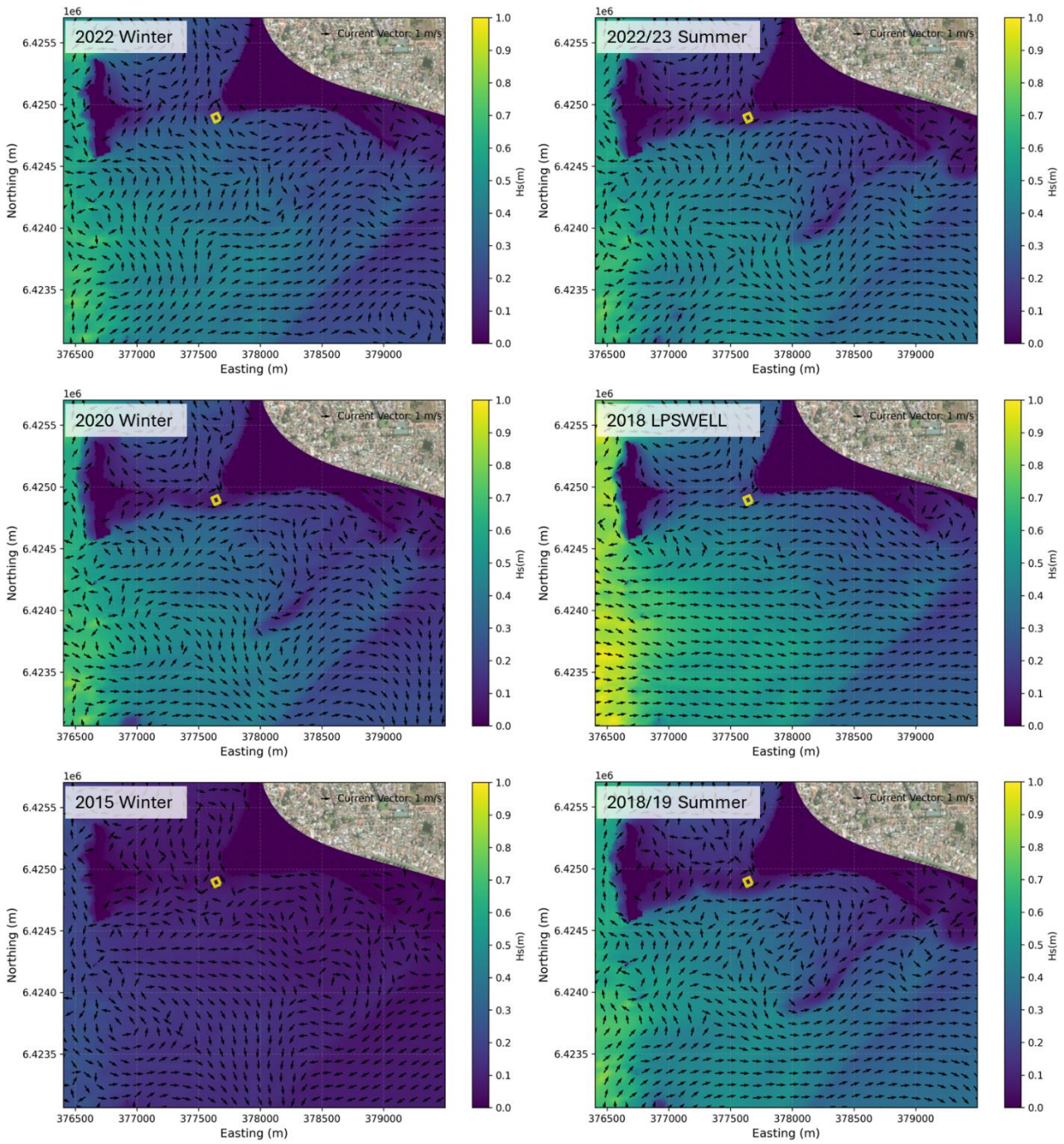


Fig. B.2.3-10: Mean wave heights and current vectors within Warnbro Sound modelled with nourishment in the surf-zone.

B.2.4 Morphological results

Results of local scale morphological modelling for the base case modelling scenario and the modelled interventions (offshore breakwater and surf-zone nourishment) are presented in Fig. B.2.4-1 to Fig. B.2.4-3. The modelling results show the impact of various management strategies, including the offshore breakwater structure and the surf-zone nourishment zone, on coastal dynamics. The base case scenario, representing current conditions without intervention, serves as a reference for comparing the effectiveness of the proposed strategies. The modelled scenarios highlight changes in sediment transport, erosion patterns, and the stability of key coastal features, such as Mersey Point and the Tern Bank.

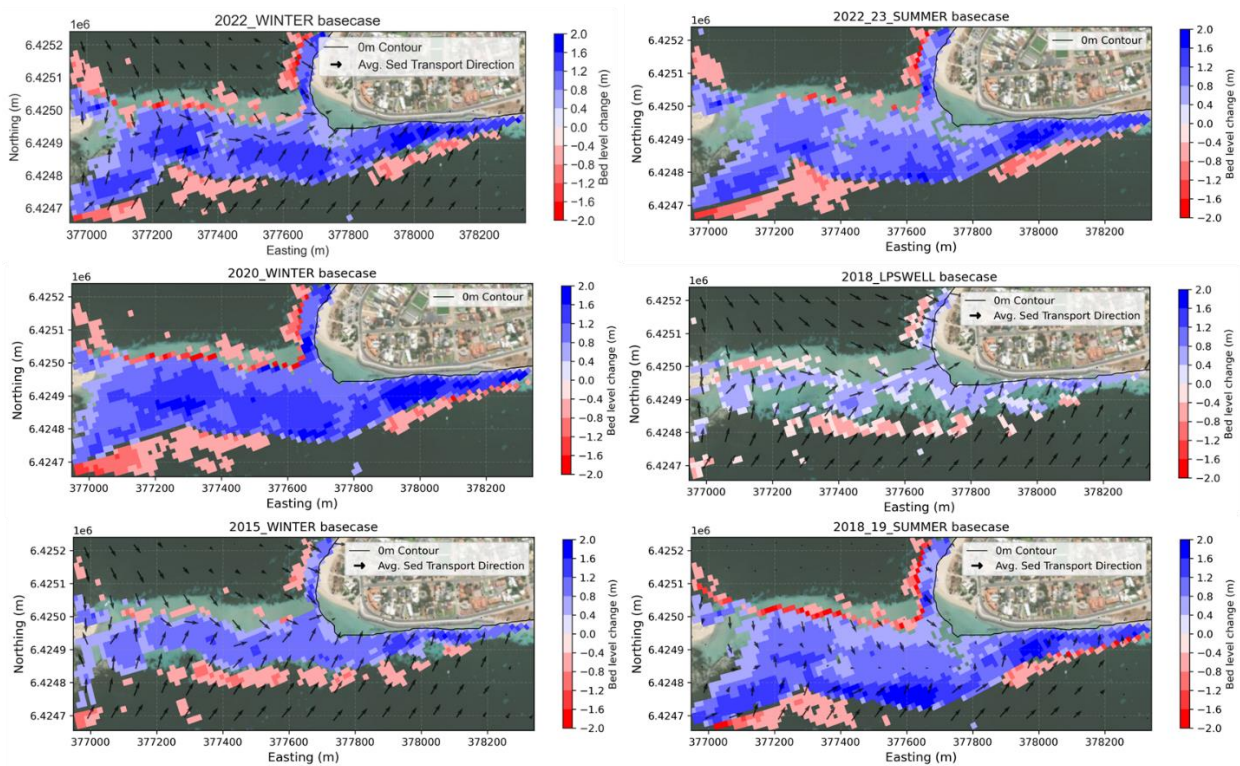


Fig. B.2.4-1: Baseline morphological modelling at Mersey Point.

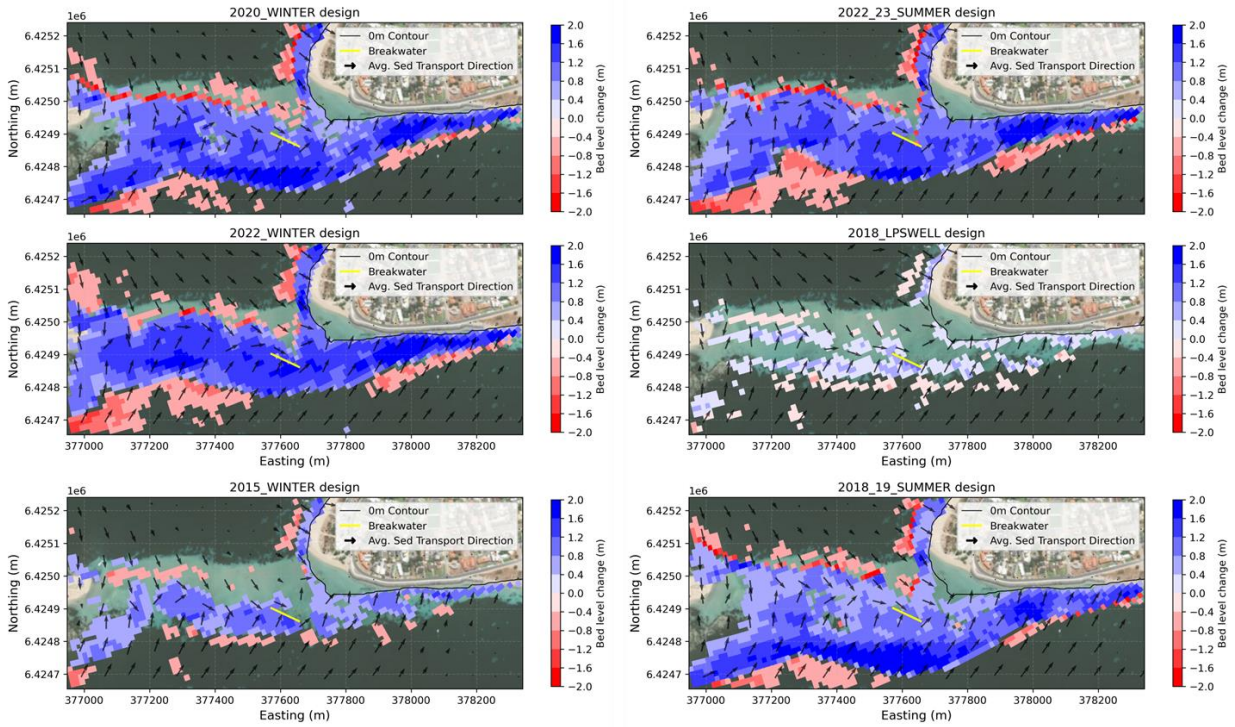


Fig. B.2.4-2: Morphological modelling at Mersey Point, modelled with an offshore breakwater (yellow line).

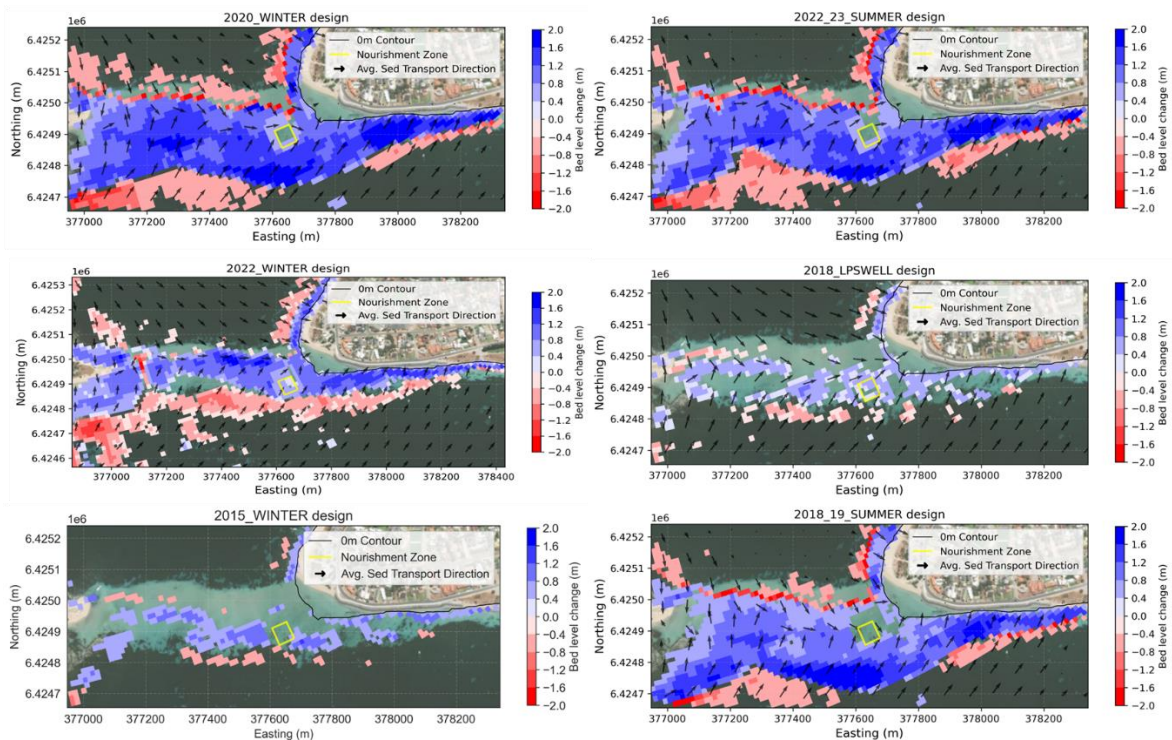


Fig. B.2.4-3: Morphological modelling at Mersey Point, modelled with surf-zone nourishment of ~2,000 m³ (yellow line).

B.3 Coastline modelling

Coastline modelling has been used to model management options at Mersey Point to assess the feasibility of implementing defence options such as groynes, revetment wall extensions and beach nourishment.

Modelling of these options has adopted the industry standard model UNIBEST from Deltares to support the understanding of long-term longshore sediment transport and the potential scale of coastline evolution that may result due to conceptual shoreline protection measures. The numerical model is comprised of two primary modules: the Longshore Transport (LT) module and the Coastline (CL) module.

UNIBEST employs empirical and semi-empirical sediment transport formulas to estimate sediment transport rates. In this study, we use the Van Rijn (2004) formulation for sediment transport. The Van Rijn (2004) approach has been selected because it:

Accounts for mixed sediment transport, incorporating both bedload and suspended load for various grain sizes.

- Considers grain size effects (D_{50} , D_{90}), which are critical in environments with both fine sand and coarser sediment sizing.
- Includes adjustments for critical shear stress, ensuring a more realistic prediction of sediment mobility.
- Better represents wave-current interactions, improving accuracy in dynamic coastal environments.

Longshore Transport (LT) Module

The UNIBEST-LT module calculates longshore sediment transport based on wave climate data and profile characteristics. It includes a built-in random wave propagation and decay model (Battjes and Stive, 1984) to simulate surf zone dynamics. The model accounts for key wave transformation processes, including:

- Bottom refraction and shoaling, which modify wave energy as waves approach the shore.
- Dissipation due to wave breaking and bottom friction, influencing sediment transport rates.

Longshore currents are derived from the momentum equation, incorporating factors such as bottom friction, radiation stress gradients, and tidal surface slope. The cross-shore distribution of sediment transport is determined using multiple total-load transport formulas available in the model, allowing for a more detailed assessment of alongshore sediment dynamics.

Coastline Evolution (CL) Module

The Coastline (CL) module predicts shoreline changes along a predefined one-dimensional numerical grid, representing a simplified coastline model. Shoreline evolution is driven by variations in longshore sediment transport, which are precomputed in the LT module using S- Φ curves (sediment transport relationships).

As coastal development alters the shoreline orientation, it influences sediment transport magnitudes, creating a feedback loop that the CL module captures efficiently. This computationally efficient approach allows for long-term simulations of shoreline response to interventions, such as groynes, breakwaters, or nourishment schemes.

The model's ability to simulate coastal evolution under different scenarios makes it a valuable tool for coastal management and engineering applications. However, site-specific calibration and validation remain critical to ensuring reliable predictions, particularly in regions with complex sediment dynamics or exposure to extreme wave events.

B.3.1 Coastline model setup

The UNIBEST-LT and CL models has been used to develop the coastline model at Mersey Point. The LT model has been set up using a schematised coastline based on cross-shore transects. Input cross-shore profiles were established based on extracted data from coastal surveying provided by CoR, 1m Landgate LiDAR and the AusBathyTopo 250m 2023 grid. Nearshore elevation data was prioritised using coastal survey data and 1m Landgate LiDAR, with the AusBathyTopo data supplementing areas with insufficient data (i.e. bathymetry). The locations of these transects are shown in Fig. B.3.1-1.

Grain size inputs for the coastline model was informed by sediment sampling results, as detailed in Appendix B.2.2. A representative mean grain size (D50) of 0.2mm was adopted based on the predominance of fine to medium sands within the Bent Street navigation channels. A 90th percentile grain size (D90) of 0.5mm was adopted based on the same findings.

For the CL model, input shorelines were derived from satellite imagery. The model was validated using derived present-day sediment transport rates from the Seashore Engineering Coastal Processes Assessment.

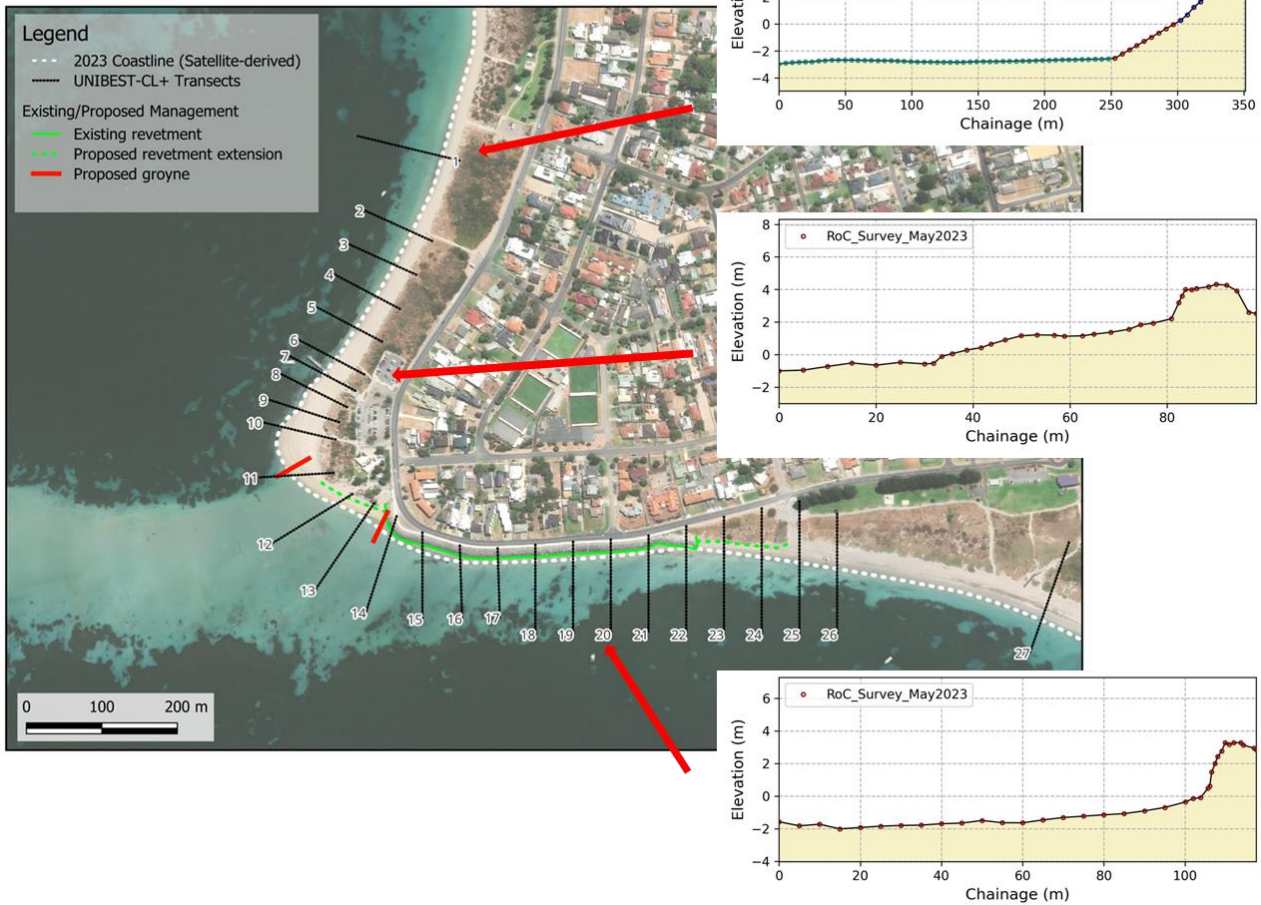


Fig. B.3.1-1: Mersey Point UNIBEST model schematic.

B.3.2 Wave conditions

To determine the input wave climate for coastline modelling, modelled wave data established in Appendix B.2 has been reduced to a series of combinations that represents the annual climate. This has been done to reduce the computational time during model simulations. For each transect, wave conditions were extracted and have been divided based on wave height (classes of 0.1m) and wave direction (classes of 36 degrees). For each class an average wave condition is calculated.

Longshore sediment transport rates were computed for each baseline wave condition and aggregated to estimate the annual transport rate at each transect.

B.3.3 Sediment transport rates

Alongshore sediment transport rates ($m^3/year$) were computed at Mersey Point using the UNIBEST-LT model. These rates were derived based on site-specific wave climate data (see Appendix B.1), sediment characteristics, and coastal morphology. Modelling focussed on Mersey Point where a mean sediment grain size (D_{50}) of 0.2mm was considered. Computed annual sediment transport rates for Mersey Point are presented in Fig. B.3.3-1. Historical analysis of coastal morphology indicates a net sediment deficit of approximately 3,000 $m^3/year$ at Mersey Point, with up to 1,000 to 2,000 $m^3/year$ of sediment travelling northward along the cusped foreland and 3,000 $m^3/year$ travelling eastwards towards Tern Bank. The computed sediment transport rates were specifically aimed at matching transport rates produced in the new Coastal Processes Study by Seashore Engineering; therefore no adjustments were made to adjust LST rates.

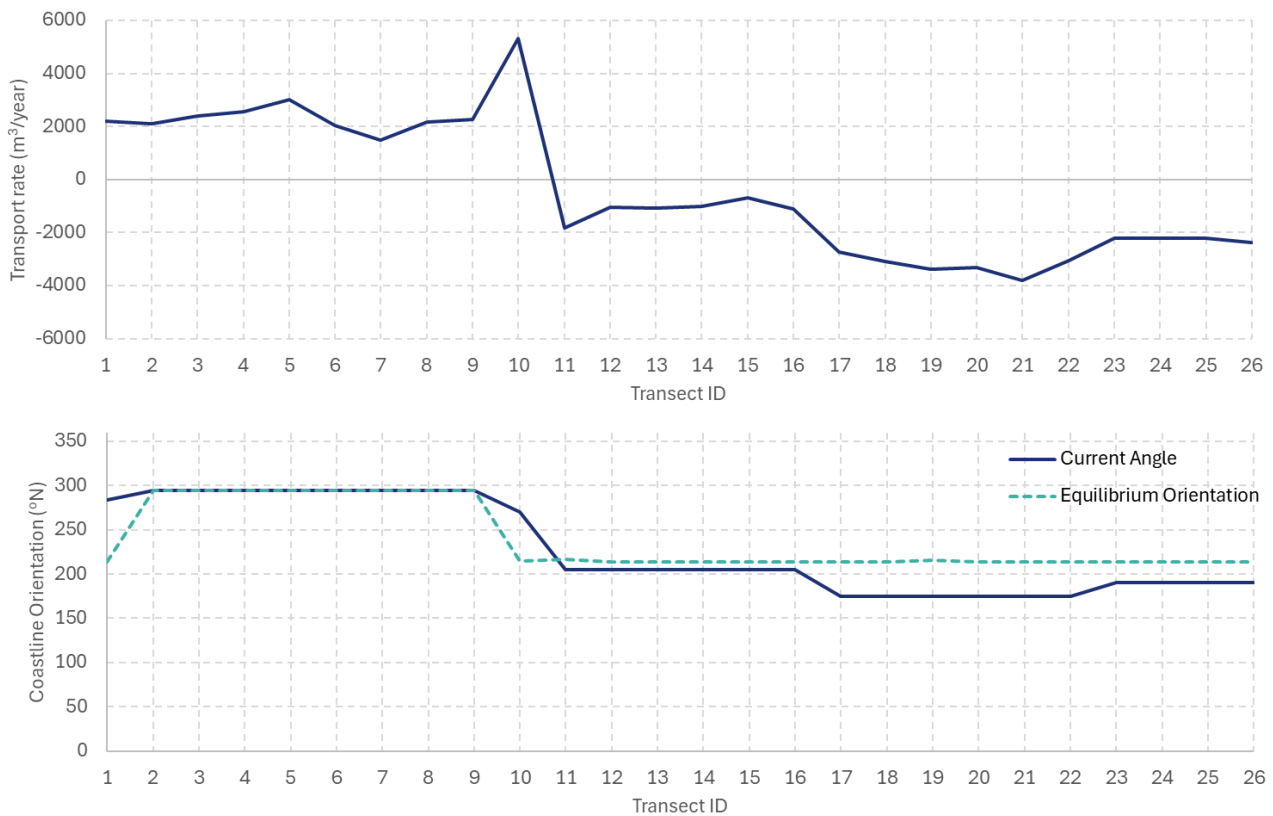


Fig. B.3.3-1: Computed annual longshore transport rates at Mersey Point.

B.3.4 Management strategies

A series of management options have been evaluated using the coastline model to assess their influence on shoreline evolution and sediment dynamics. The analysis focused on existing and proposed interventions including revetment walls, construction of groynes, and beach nourishment to determine their feasibility in mitigating erosion and stabilising the shoreline. A summary of the strategies is shown below:

Tab. B.3.4-1: Coastline modelling management strategies assessed.

Management Option	Modelling approach
Do Nothing	A base case scenario, modelling the shoreline evolution under a "Do Nothing" scenario i.e. If no management were undertaken at Mersey Point.
Groynes	Simulated shore-perpendicular groynes at Mersey Point to assess their impact on longshore sediment transport patterns, including the accretion on the updrift side and potential for downdrift erosion.
Groynes and Beach Nourishment	Evaluating the combined effect of groynes and beach nourishment to prolong sediment retention and mitigation of erosion.
Revetment walls	The extension of the Arcadia Drive revetment wall to evaluate its effectiveness in stabilising the shoreline, with a focus on potential impacts to the adjacent foreshore.
Beach Nourishment	Simulating the placement of sand along the southern compartment of the Cuspate Foreland and along the toe of the existing revetment wall to assess the redistribution, longevity and effectiveness of nourished material at Mersey Point.
Revetment walls and Beach Nourishment	To assess the combined effect of the extension of Arcadia Drive revetment wall in addition to beach nourishment along the revetment wall toe to assess the longevity of sediment retention and support the adjacent foreshore.

Coastline modelling results

Fig. B.3.4-1 through to Fig. B.3.4-4 presents coastline modelling results incorporating the various management strategies. Under present day conditions, the coastline model was used to predict where erosion and accretion may occur along different sections of Mersey Point. Modelled under a "Do Nothing" scenario, the UNIBEST-CL+ model predicts the continued erosion of the western and eastern ends of the Arcadia Drive revetment wall. If no intervention is undertaken, up to 25m of shoreline retreat is predicted to continue through to 2033 (eastern revetment wall), potentially becoming in issue on the longevity of key public assets such as the Carlisle Boat Ramp.

Modelling indicates that extending the Arcadia Drive revetment wall both westward and eastward will enhance the protection of key assets such as the Penguin Island Visitor Centre and Arcadia Drive. However, this intervention is predicted to redistribute existing erosion pressures, shifting them to adjacent areas. As a result, the Carlisle Street Boat Ramp is expected to come under increased erosion stress within the next five years, resulting in the potential loss of one of the city's beach access points due to shoreline retreat. To mitigate these issues, it is predicted that nourishment strategies will play a critical role in maintaining the sediment balance. The model results indicate that nourishment strategies, with and without hard engineering solutions (i.e. groynes and revetments), will act as an erosion buffer zone, with a large-scale nourishment campaign at the toe of the revetment wall alleviating the immediate erosion pressures seen on the eastern flank. Additionally, model results highlight that groynes significantly influence sediment transport, creating localized erosion hotspots. The eastern groyne is expected to obstruct northward sediment transport, accelerating erosion at the tip of Mersey Point, while the western groyne disrupts eastward transport, increasing erosion along the eastern flank of the Arcadia Drive revetment. These changes may require additional management interventions to address unintended sediment deficits.



Fig. B.3.4-1: Shoreline modelling results, Do-Nothing approach (no interventions).



Fig. B.3.4-2: Shoreline modelling results, modelled with sand nourishment at the Arcadia Drive Revetment wall toe and beach nourishment at Mersey Point.



Fig. B.3.4-3: Shoreline modelling results, modelled with present day shoreline and the extension of Arcadia Drive Revetment (green line).



Fig. B.3.4-4: Shoreline modelling results, modelled with sand nourishment (black dotted line) at the toe of the Arcadia Drive revetment wall (green line), and the extension of the revetment wall.



Fig. B.3.4-5: Shoreline modelling results, modelled with two groynes (red line) under a present day shoreline (2023).



Fig. B.3.4-6: Shoreline modelling results, modelled with two groynes (red lines) and sand nourishment at the toe of Arcadia Drive revetment (black dotted line).



Fig. B.3.4-7: Shoreline modelling results, modelled with beach nourishment (black dotted line) between the two groynes (red line) and a present-day shoreline (2023)

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