SWASH MODELLING OF A COASTAL PROTECTION SCHEME

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The Beresford shoreline, Australia, is subject to a complex interaction of coastal processes and associated erosion. In support of the design of a coastal protection scheme a SWASH model has been set up capable of accounting for all the complex processes at hand. The model has successfully been validated against measured wave and current conditions. In the design process the validated SWASH model proved to be a valuable tool to assess the impact of various coastal protection schemes like groynes on the wave-driven current patterns and associated sediment pathways.

Keywords: SWASH; wave-driven currents; coastal erosion; coastal protection

INTRODUCTION

Shorelines are dynamic environments which are constantly changing in response to external factors which can be both natural and anthropogenic in origin (French, 2001). Erosion and accretion of shorelines throughout the world has occurred for millennia and will continue to occur in the future. Due to increased coastal development over the last century there has been an increase in locations where coastal erosion is considered to be an issue. The typical response to coastal erosion has historically been to construct a structure to create a fixed, permanent boundary between the land and the sea. More recently, the suitability of this approach in providing long term solutions has been questioned and as a result more innovative approaches which work with the natural coastal processes are being considered.

There have been issues with ongoing shoreline erosion and recession in Geraldton, Australia. In response to the erosion a series of groynes and a detached breakwater were constructed and annual sand nourishment was initiated. Despite these measures, shoreline recession has continued at Marina Beach in the Beresford Foreshore area. To manage this erosion a better understanding of the processes driving it is required to allow an effective long term solution to be developed. As such, the aim of this study is to develop a better understanding of the erosion processes and to use this to develop a long term solution to manage the ongoing shoreline recession at Marina Beach. A final solution is required which will protect community infrastructure and community assets, minimise the long term annual mechanical sand bypassing required and enhance the foreshore environment including the swimming area at Marina Beach (Fig. 1).

SITE DESCRIPTION

The Beresford Foreshore area is located to the north of the town centre of Geraldton, in the suburb of Beresford within the City of Greater Geraldton (Fig. 1) in Western Australia. The Geraldton coastline has been heavily modified over time, with the largest constructions being the Port of Geraldton and the Batavia Coast Marina (BCM). These developments have changed the natural sediment transport processes in Champion Bay as well as interrupting the predominant northerly longshore sediment drift. Increased erosion occurred in a number of locations as a result of the dominant sediment transport pathway being interrupted and a reduction in sand supply from various sources in Champion Bay. To try and manage the erosion a series of groynes were constructed at the Town Beach (between the Port and the BCM) and the southern end of Marina Beach, sand nourishment was undertaken at Town Beach and the Northern Beaches (Marina and Beresford Beaches) and a detached breakwater 400 m north of the BCM was constructed. Despite these shoreline protection schemes there is still periodic shoreline recession along the Beresford Foreshore to the north of the BCM and persistent recession at Marina Beach.

The Beresford shoreline is characterised by narrow sandy perched beaches (10 to 20 m wide at low tides in summer, narrower in winter and at high tides) with underlying limestone rock platforms. The subtidal areas offshore of the beaches are characterised by inshore limestone reef platforms with isolated pockets of sandy deposits with some areas of seagrass meadow. The inshore waters along this area of the shoreline are relatively sheltered from large offshore swell waves because of the presence of

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an extensive offshore reef. Therefore the beach can be influenced by short period locally generated wind waves along with large swell events with sufficient energy to propagate to the shoreline. Due to these natural features and the dominant processes the Beresford shoreline is subject to a complex interaction of coastal processes.

Figure 1: Locality plan of Beresford Foreshore and the surrounding area.

APPROACH

To better understand the existing coastal processes which influence the Beresford Foreshore a combination of targeted field data collection and numerical modelling was adopted. This multiple lines of evidence approach provides increased confidence in the results which is important given the complexity of the natural environment. Details of the field data collection and the numerical modelling approaches are provided in the following subsections.

Data Collection

The aim of the targeted data collection was to provide local bathymetrical, hydrodynamic and wave data to improve the understanding of the coastal processes directly offshore of Marina Beach and to provide data to allow validation of numerical models.

Two field campaigns were undertaken with a bed mounted Nortek Acoustic Waves And Currents (AWAC) profiler to collect wave and current data offshore of Marina Beach (Fig. 2). Coinciding wind and wave data was provided by Geraldton Port Authority (GPA) – now known as Mid West Ports Authority (MWPA) – at the offshore end of the navigational channel and water level data was provided by the Department of Transport in Geraldton Port (Fig. 1). The first deployment at Site 1 was aimed at collecting wave data offshore of Marina Beach to better understand the wave refraction and attenuation which occurs between the offshore WRB and Marina Beach. The second deployment at Site 2 was aimed at collecting current data at the offshore end of the Batavia groyne at the southern end of Marina Beach.

Preliminary numerical modelling identified that during sufficiently energetic swell events a distinct wave-induced current in an offshore direction occurred at the offshore end of the Batavia groyne and so the data was collected specifically to verify the model results. For both deployments the instruments were setup to measure water levels, directional waves and current speed and direction every 0.5 m through the water column. Part of the measured wave and current time series are depicted in Fig. 3 and Fig. 4. The vertical dashed blue lines in these plots indicate the events that have been used for the validation of the SWASH model.

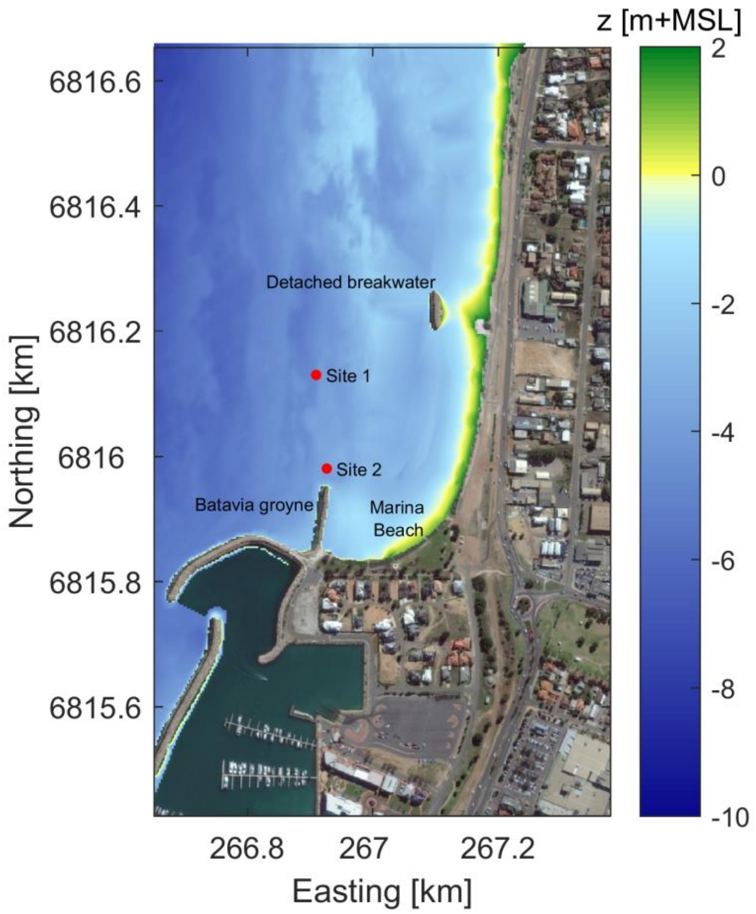

Figure 2: Locations of the AWAC instruments during Deployment 1 at Site 1, and Deployment 2 at Site 2 near the tip of the Batavia groyne.

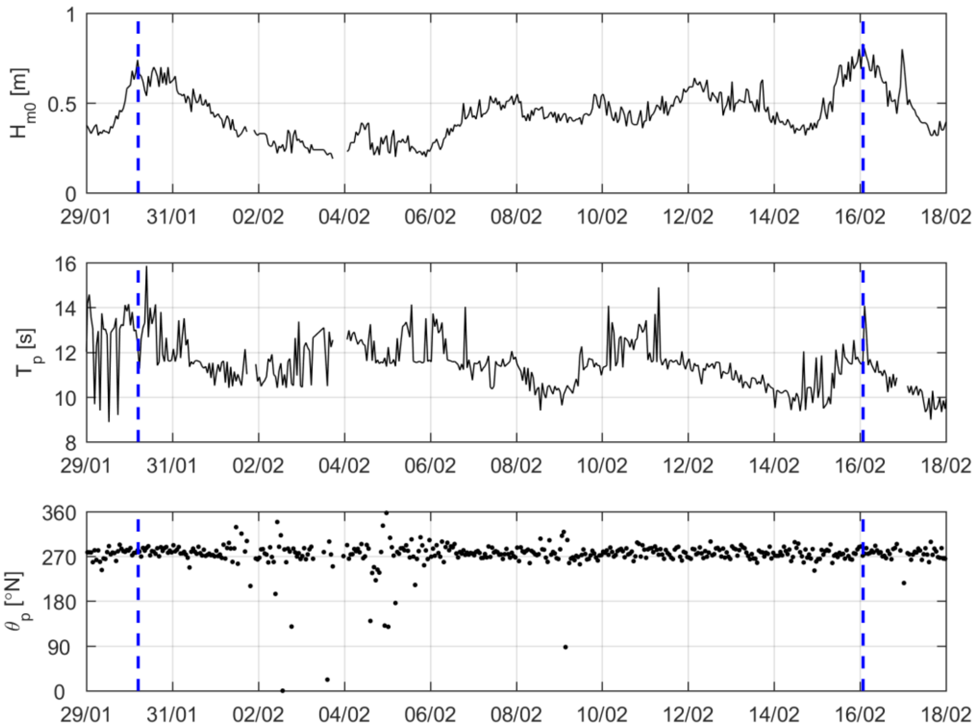

Figure 3: Part of the measured wave time series during Deployment 2. Vertical dashed blue lines indicate the events that have been used for validation of the SWASH model.

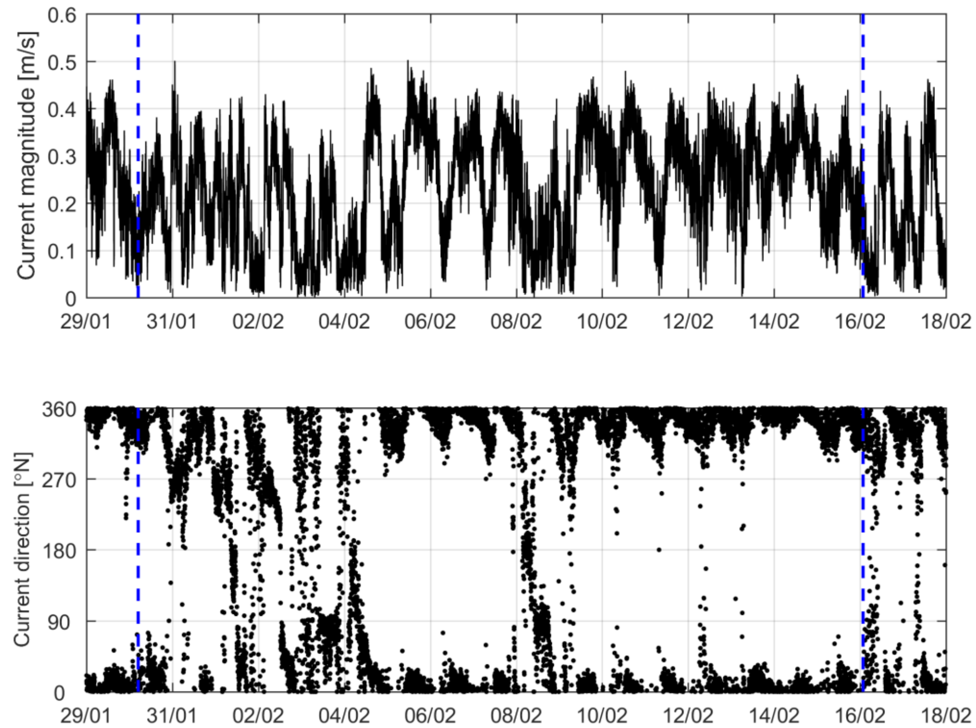

Figure 4: Part of the measured current time series (currents at z=0.4h) during Deployment 2. Vertical dashed blue lines indicate the events that have been used for validation of the SWASH model.

Numerical modelling

Hydrodynamic modelling with a 2DH flow model forced by tide and wind had already shown that tidal and wind-driven currents were insignificant and that wave-driven currents were the dominant process. The complex topography, the existence of man-made structures and the wave-driven nature of the coastal erosion requires a numerical model capable of accounting for wave propagation, wave breaking, diffraction and reflection. Although they are phase-averaged, spectral wave models like SWAN and MIKE 21 SW are sophisticated models capable of accounting for all relevant processes in many applications. However, this type of model is not known for its ability to accurately represent diffraction and reflection.

A model that is capable of accounting for all relevant processes is SWASH, a general-purpose numerical tool for simulating non-hydrostatic, free-surface, rotational flows developed at Delft University of Technology (Zijlema et al., 2011 and The SWASH Team, 2016). A SWASH model of the project site has been set up and validated against measured wave and current conditions.

The validated model has been used in the design process of the coastal protection measures. SWASH simulations have been performed to generate detailed wave and current fields resulting from a number of characteristic wave conditions to allow different coastal protection schemes to be tested. These wave and current fields were input to a sediment transport and morphological assessment to assess how effective various coastal protection schemes were.

DESCRIPTION OF SWASH MODEL

SWASH governing equations

SWASH is a general-purpose numerical tool for simulating non-hydrostatic, free-surface, rotational flows in one, two or three dimensions (Zijlema et al., 2011 and The SWASH Team, 2016). SWASH is an acronym for Simulating WAves till SHore though the model should be considered to be more than just a wave model as it can also simulate density driven flows, rapidly varying flows due to for example dam breaks or tsunamis and large-scale ocean circulation.

The governing equations are the nonlinear shallow water equations including non-hydrostatic pressure. The one-dimensional, depth-averaged shallow water equations in non-conservative form are shown as follows:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial hu}{\partial x} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial \zeta}{\partial x} + \frac{1}{2}\frac{\partial q_b}{\partial x} + \frac{1}{2}\frac{q_b}{h}\frac{\partial(\zeta - d)}{\partial x} + c_f\frac{u|u|}{h} = \frac{1}{h}\frac{\partial}{\partial x}\left(h\nu_t\frac{\partial u}{\partial x}\right) \tag{2}$$

$$\frac{\partial w_s}{\partial t} = \frac{2q_b}{h} - \frac{\partial w_b}{\partial t} \quad w_b = -u\frac{\partial d}{\partial x} \tag{3}$$

$$\frac{\partial u}{\partial x} + \frac{w_s - w_b}{h} = 0 \tag{4}$$

where t is time, x the horizontal coordinate, u the depth averaged velocity in x-direction, w_s and w_b the velocity in z-direction at the free surface and at the bottom, respectively. ζ is the free-surface elevation from still water level, d is the still water depth and h the total depth. q_b is the non-hydrostatic pressure at the bottom, g the gravitational acceleration, c_f the dimensionless bottom friction coefficient and ν_t the eddy viscosity. The bottom friction coefficient is expressed by Manning's roughness coefficient n as follows:

$$c_f = \frac{n^2 g}{h^{1/3}} \tag{5}$$

Eqs. (1) and (4) are the global and local continuity equations, respectively, to assure both local and global mass conservation. Eq. (2) is the momentum equation for the u-velocity which includes the effect of non-hydrostatic pressure, bottom friction and horizontal mixing. Note that momentum conservation is obtained at the discrete level in line with Stelling and Duinmeijer (2003). The first equation of Eq. (3) is the momentum equation for the vertical velocity at free surface w_s. The vertical velocity at the bottom w_b is described by means of the kinematic condition as presented by the last part of Eq. (3).

Note that the governing equations are based on the incompressible Navier-Stokes equations when multiple layers in the vertical are considered. In this way we take into account the vertical structure of the horizontal flow. In this study all calculations have been conducted with 2 layers, which appeared to be sufficient in terms of accuracy with respect to frequency dispersion related to wave transformation.

A full description of the numerical model based on a staggered, conservative, finite-difference scheme, different kinds of boundary conditions, and different types of applications are given in Zijlema et al. (2011), Smit et al. (2013) and Rijnsdorp and Zijlema (2016).

SWASH model of Beresford foreshore

A SWASH model was setup along the Beresford shoreline, focused on Marina Beach. The simulations were performed with SWASH version 3.14A. The model extent adopted was 1.6 km by 2.7 km with a grid resolution of 3 m in both directions (Fig. 5). The model was set up with 2 layers.

The wave boundary conditions of the SWASH model were derived by means of a SWAN spectral wave model that transformed offshore waves, measured by GPA/MWPA's waverider buoy, to the nearshore. That SWAN model had been validated against wave measurements conducted during deployment 1 at Site 1. The wave conditions on the offshore boundary of the SWASH model were imposed as a JONSWAP spectrum with a peak enhancement factor of 3.7.

Hard structures which influence wave conditions were represented both in the bathymetry and as porosity and structure height layers which control the reflectivity of the structure. The breakwater around Batavia Coast Marina was included in the model but the marina itself was excluded.

All SWASH simulations were run for 180 minutes: 20 minutes of spin-up time and 160 minutes to generate the average wave and current fields. With a peak wave period of 14 s, the average fields are based on nearly 700 waves.

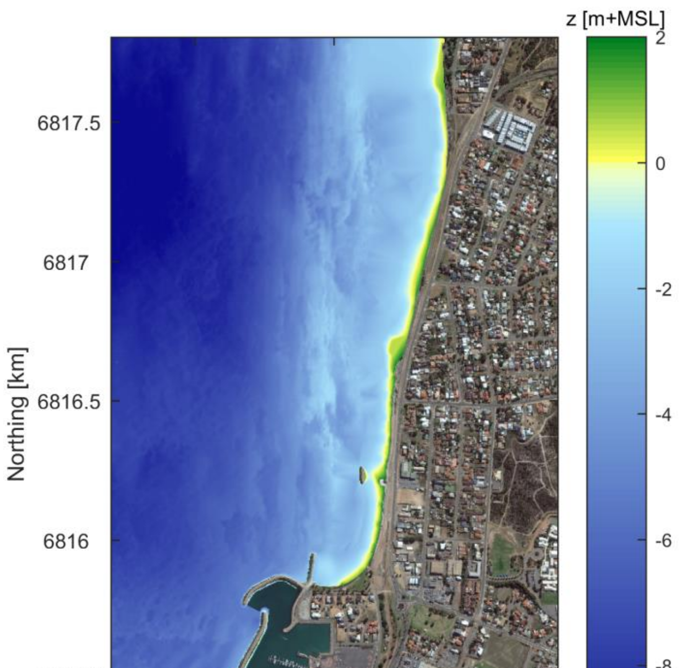

Figure 5: Outline and bathymetry of the Beresford Foreshore SWASH model

Validation of the SWASH model

The SWASH model has been validated against measured wave and current data collected during Deployment 2. The two largest wave events recorded were selected and simulated using SWASH, see Table 1 and 2. The main purpose of the SWASH validation at site 2 was to demonstrate that when the swell waves were sufficiently large an offshore current occurred adjacent to the Batavia groyne. This current in combination with the suspension of sediment due to wave action is considered to be the driving mechanism for a regular ongoing loss of sediment from within Marina Beach.

The first event occurred on 30 January 2015 and concerned a 1.93 m high offshore swell wave, see Table 1. With the SWAN model the significant wave height on the offshore boundary of the SWASH model was predicted to be 0.5 m whilst the peak wave period was 14 s and the peak direction 280°N. With these boundary conditions the SWASH model was run yielding a simulated significant wave height of 0.61 m versus a measured one of 0.70 m. The difference in the measured and the simulated peak wave period was minimal. The spatial distribution of the significant wave height in the vicinity of the Site 2 is depicted in Fig. 6.

The breaking of waves results in gradients in the radiation shear stress and gradients in the water level set-up resulting in wave-driven currents which are included in SWASH as well. During Event 1 the depth-average current magnitude at Site 2 amounted to 0.15 m/s with a direction of 296°N. SWASH predicted that current magnitude to be 0.13 m/s with a direction of 299.7°.

The spatial distribution of the depth-average current magnitude and direction is depicted in Fig. 7. It shows that the Site 2 survey location is located in an offshore directed current adjacent to the groyne, the site was specifically located here as the current is of importance to the coastal erosion issue under consideration.

Table 1: Wave Event 1 at Site 2 used for the validation of the SWASH model

Parameter		Offshore	Imposed to SWASH	Conditions in Site 2	
				Measured	Simulated
H_{m0}	[m]	1.93	0.5	0.70	0.61
T_p	[s]	14	14	14	13.9
Θ_p	[°N]	243	280	-	-
Depth-averaged current speed	[m/s]			0.15	0.13
Depth-averaged current direction	[°N]			296	300

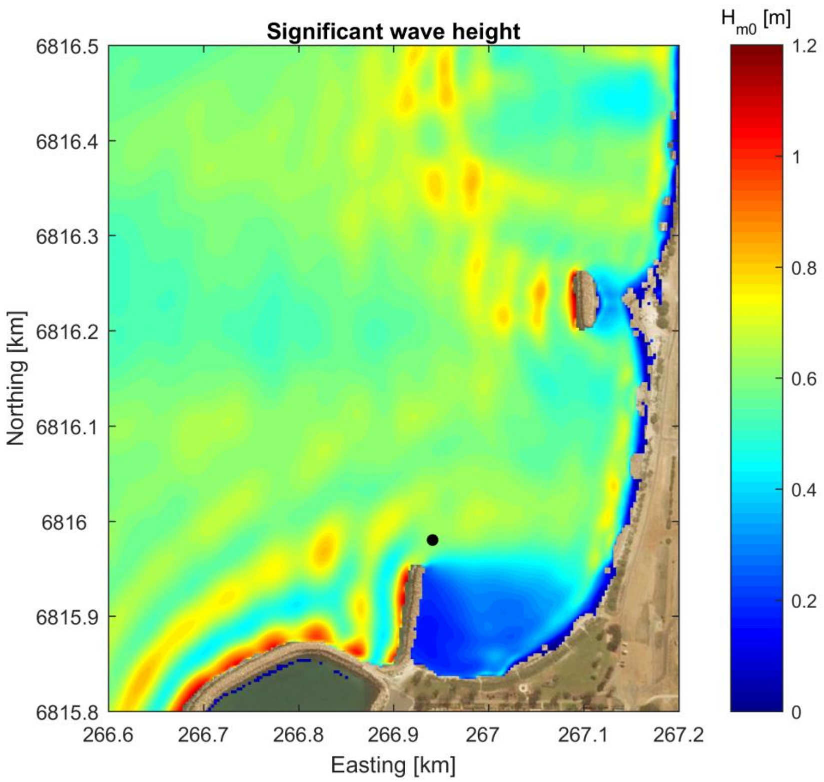

Figure 6: Spatial distribution of the significant wave height of wave Event 1.

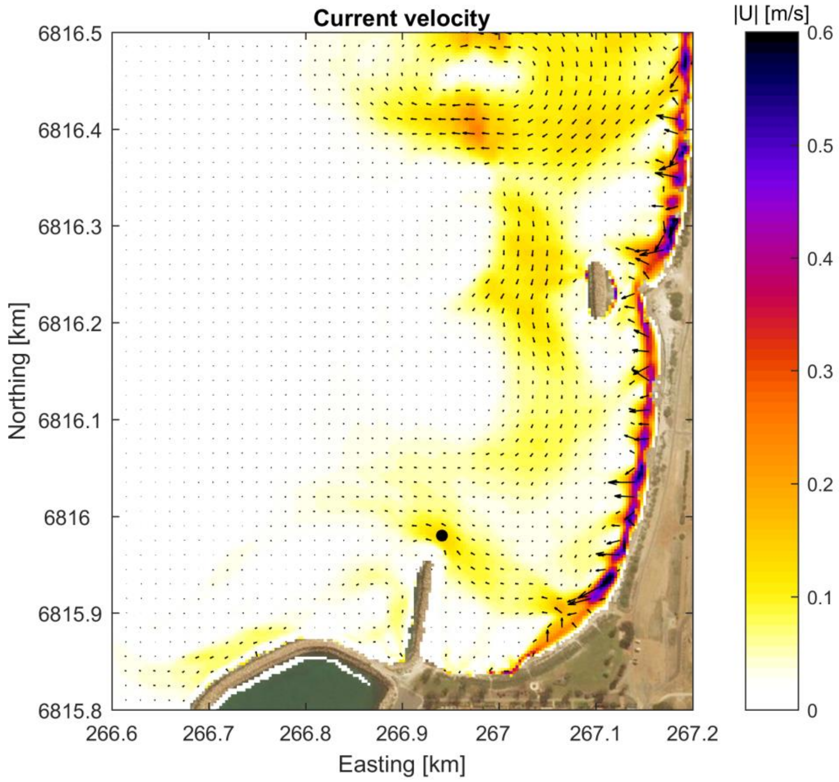

Figure 7: Spatial distribution of the current magnitude and direction of wave Event 1.

The second event occurred on 16 February 2015. The offshore significant wave height for the event was 2.35 m, see Table 2. Due to wave attenuation the significant wave height at the SWASH model offshore boundary had reduced to 0.8 m whilst the peak wave period was 12 s and the peak wave direction 270°N.

With these boundary conditions the SWASH model was run yielding a simulated significant wave height of 0.85 m compared to a measured wave height of 0.83 m. The spatial distribution of the significant wave height in the vicinity of the Site 2 is depicted in Fig. 8.

During Event 2 the depth-average current magnitude at Site 2 peaked at 0.25 m/s with a direction of 306°N. SWASH predicted the current magnitude to be 0.31 m/s with a direction of 308.3°N.

The spatial distribution of the depth-average current magnitude and direction is depicted in Fig. 9. It shows that similar to Event 1 the site 2 location is in an offshore directed current adjacent to the Batavia groyne.

Table 2: Wave Event 2 at Site 2 used for the validation of the SWASH model

Parameter		Offshore	Imposed to SWASH	Conditions in Site 2	
				Measured	Simulated
H_{m0}	[m]	2.35	0.8	0.83	0.85
T_p	[s]	12	12	12	12
Θ_p	[°N]	245	270	-	-
Depth-averaged current speed	[m/s]			0.25	0.31
Depth-averaged current direction	[°N]			306	308.3

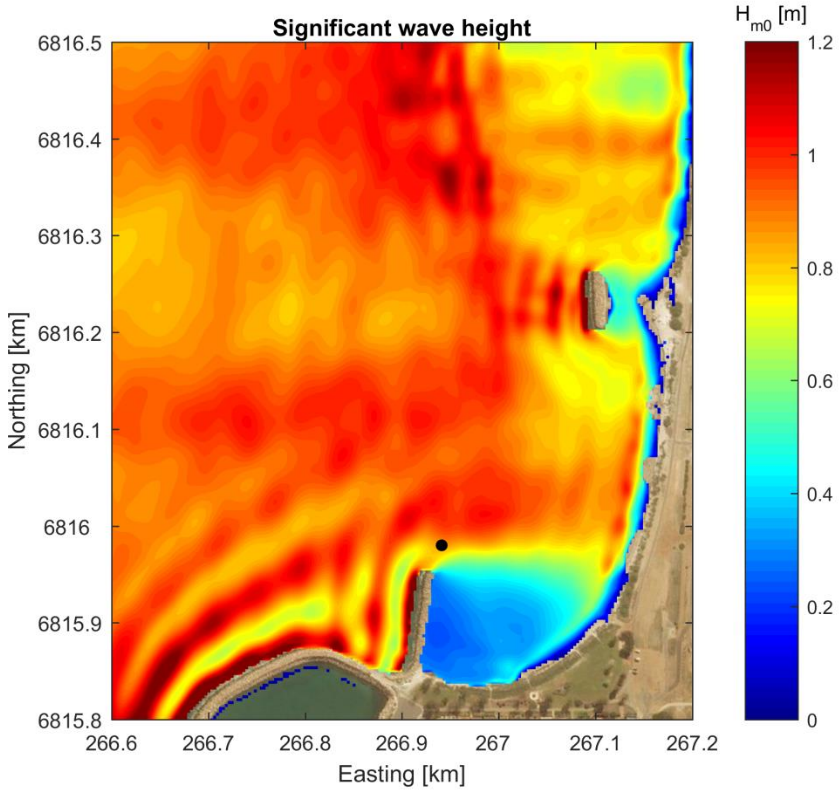

Figure 8: Spatial distribution of the significant wave height of wave Event 2.

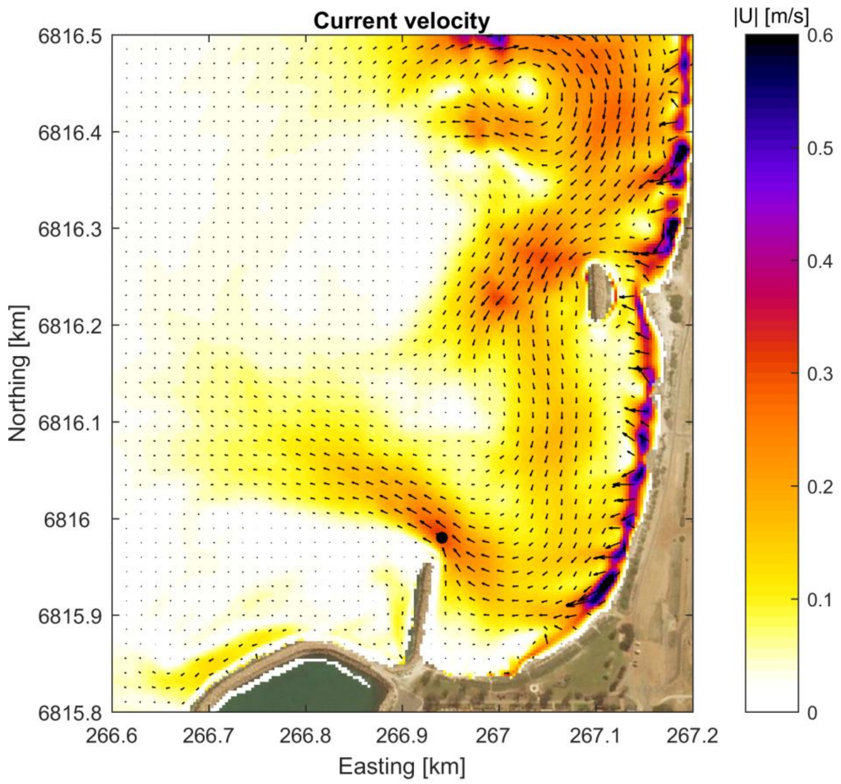

Figure 9: Spatial distribution of the current magnitude and direction of wave Event 2.

Though the simulated wave and current conditions are quite close to the measured ones for both events, sensitivity runs have been performed with the purpose to further improve the model results. In these sensitivity simulations the friction formulation and the friction coefficient have been varied but none of those resulted in significant change of the wave height and current velocities. It means that the overall SWASH results are quite robust to changes in the friction formulation and friction coefficient.

DESIGNING A COASTAL PROTECTION SCHEME USING SWASH

Figures 7 and 9 clearly depict an offshore directed current along the Batavia groyne. This offshore directed current is part of a larger-scale circulation current induced by breaking waves and associated gradients in the water level set up. This current in combination with the suspension of sediment by waves is considered to be the key driving mechanism behind the regular ongoing loss of sediment from within Marina Beach.

The next stage in the project was the design of mitigating measures that reduce or prevent this offshore-directed current. To do so, various options were tested with the SWASH model. Options considered included artificial headlands, groynes and alterations to the existing offshore breakwater. The options were tested with various hydrodynamic forcings; the examples shown in this paper are forced by a wave condition on the offshore SWASH boundary with H_{m0} = 1.5 m, T_p = 12 s and θ_p = 270°N. The significant wave height and current patterns associated to that wave condition in the present situation are plotted in Fig. 10 for reference.

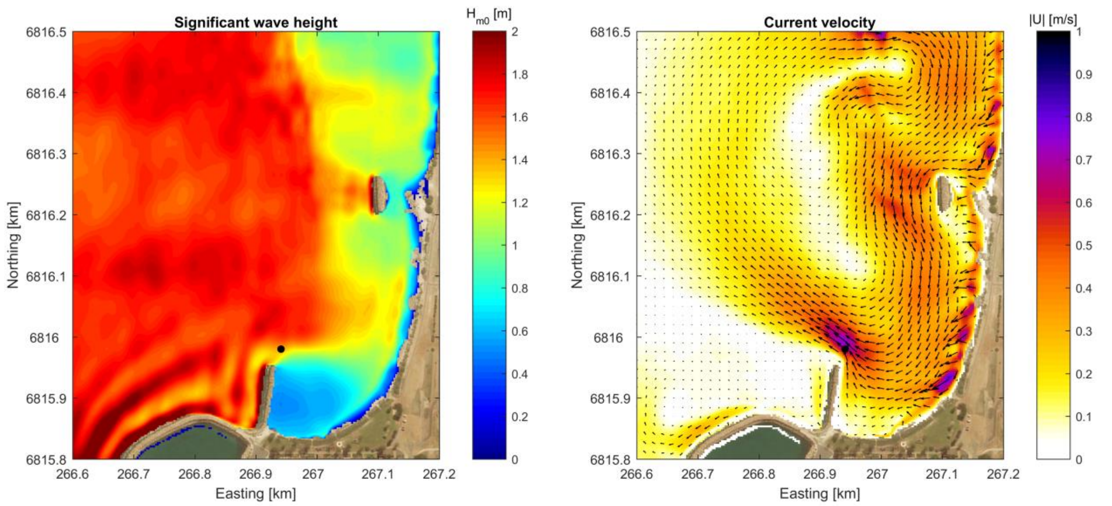

Figure 10: Spatial distribution of the significant wave height (left) and current magnitude and direction (right) for the present situation. Offshore condition: H_{m0} = 1.5 m, T_p = 12 s and θ_p = 270°N.

Fig. 11 depicts the significant wave height and the current patterns in case a circular, artificial headland is implemented at the location of the present offshore detached breakwater. A comparison of Fig. 10 and Fig. 11 shows that the headland does not essentially alter the wave and current pattern. The offshore directed current which under the present forcing obtains a velocity of approximately 0.7 m/s adjacent to the tip of the Batavia groyne still occurs. This means that this measure does not take away the cause of the regular ongoing erosion of Marina Beach.

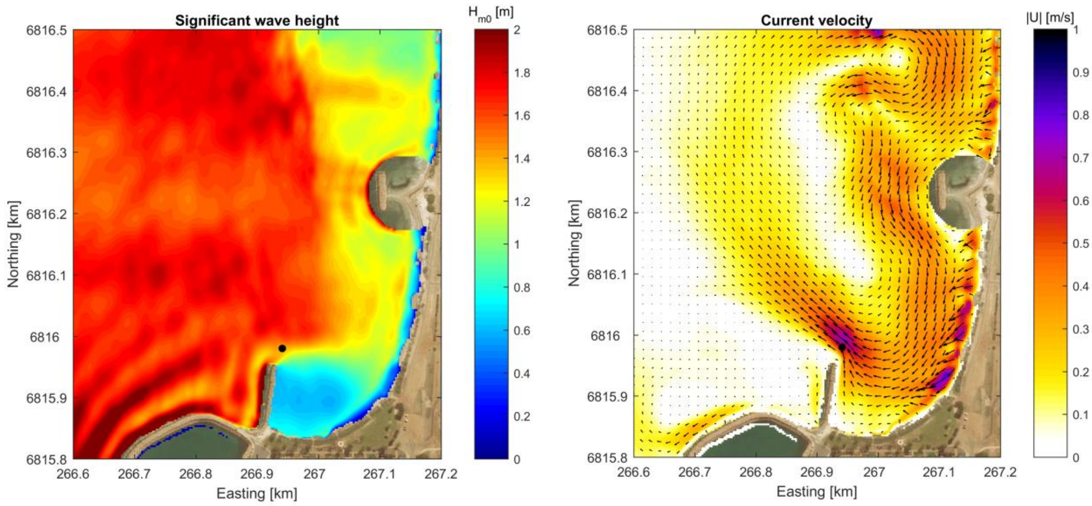

Figure 11: Spatial distribution of the significant wave height (left) and current magnitude and direction (right) for the <u>artificial headland</u> option. Offshore condition: H_{m0} = 1.5 m, T_p = 12 s and θ_p = 270°N.

Another option considered an extension of the offshore detached breakwater of 100 m in a southwest direction. This adjustment has a significant effect on the current pattern, see Fig. 12. It interrupts the large-scale circulation pattern thereby preventing the strong offshore directed current adjacent to the tip of the groyne. Instead, the current pattern between the breakwater and the groyne is characterised by two smaller and weaker eddies. That current pattern is already much more beneficial to the prevention of the ongoing loss of sediment from within Marina Beach though at the tip of the groyne there is still an offshore directed current though much weaker than without this adjustment.

This option has also been tested for a 50 m breakwater extension instead of a 100 m one. The SWASH results of this option however demonstrated that that length is too short to entirely interrupt the large-scale circulation pattern; the offshore directed current near the groyne still exists for this shorter breakwater extension.

A further extension of 50 m of the breakwater did not result in a further improvement of the current conditions along Marine Beach. Also with this 150 m long breakwater extension the current pattern is characterised by two smaller eddies confined between the breakwater and the groyne.

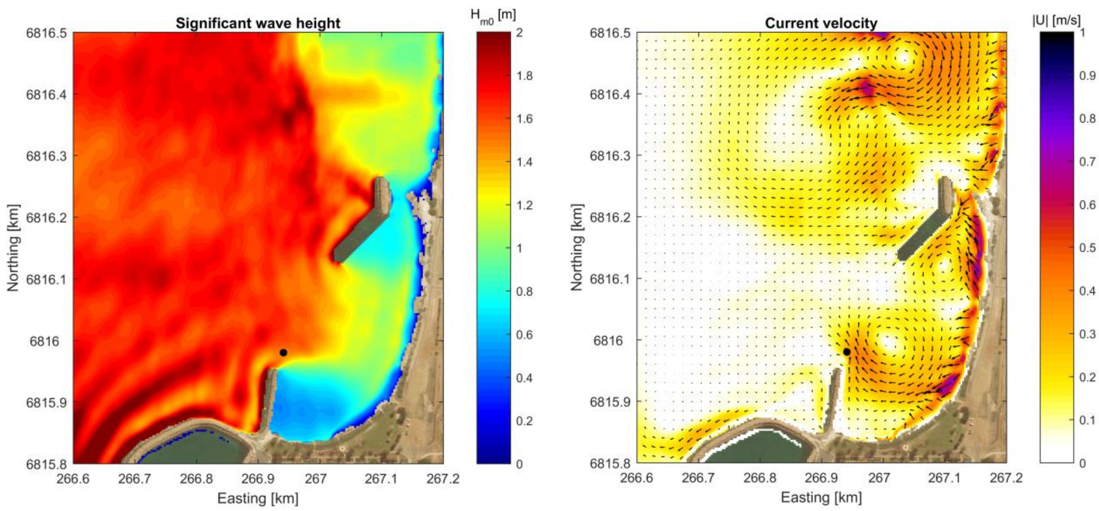

Figure 12: Spatial distribution of the significant wave height (left) and current magnitude and direction (right) for the option with <u>a 100 m breakwater extension</u>. Offshore condition: H_{m0} = 1.5 m, T_p = 12 s and θ_p = 270°N.

Based on the option with the 100 m breakwater extension, the final layout was developed. In addition to the 100 m extension it consisted of a connection between the original detached breakwater and the shore and a 40 m eastward extension of the Batavia groyne. The reason for this spur groyne was primarily to prevent the so-called mach stem effect from occurring, i.e. the wave 'attaching' to a structure, propagating along its entire length potentially resulting in erosion where the groyne connects to the shore. The length of the spur was then optimised to a length of 40 m to also contribute to the reduction of the export of sand from Marina Beach.

The average wave height and current velocity fields for the final option are depicted in Fig. 13. Comparing this flow field with the one presented in Fig. 12 clearly illustrates that the current pattern for the final proposed option is even more beneficial to keep sand in the Marina Beach system: the southern of the two eddies is much weaker in the final layout than in the layout with only the breakwater extension.

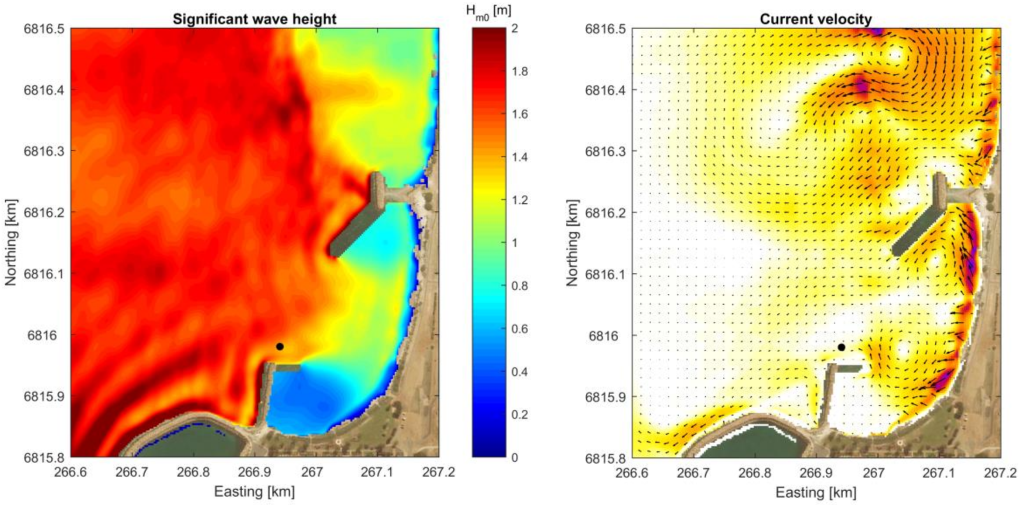

Figure 13: Spatial distribution of the significant wave height (left) and current magnitude and direction (right) for the proposed option consisting of a100 m breakwater extension, a connection to the shore and a 40 m spur attached to Batavia groyne. Offshore condition: H_{m0} = 1.5 m, T_p = 12 s and θ_p = 270°N.

This final mitigating scheme, consisting of a 100 m breakwater extension, a breakwater connection between the detached breakwater and the shore and the 40 m long spur at the head of Batavia groyne, was presented to and adopted by the client. In addition, a beach replenishment was proposed whilst the optimal grain size of the beach fill material was investigated using the SWASH model and the SBEACH storm erosion model by the U.S. Army Corps of Engineers. Construction of the mitigating scheme has commenced in January 2017.

CONCLUSIONS

A SWASH model of the Beresford Foreshore has been set up to assist the design process of a coastal protection scheme for Marina Beach. The SWASH model has been successfully validated against wave and current conditions measured near the tip of the Batavia groyne during two events of large offshore swell waves.

The SWASH model proved to be a very useful tool in designing a coastal protection scheme for Marina Beach as it is capable of providing detailed current and wave fields in complex topographies including man-made structures like groynes and offshore detached breakwaters.

The model first of all identified the current pattern that was the likely cause for the ongoing regular erosion of Marina Beach: near the tip of the Batavia groyne an offshore directed current develops when the wave conditions are sufficiently energetic. This offshore directed current is part of a larger-scale circulation pattern and is considered to be the mechanism of exporting sand out of the Marine beach system.

Secondly it supported the design process by generating detailed wave and current velocity fields for various mitigating options. One or two simulations usually sufficed to gain sufficient insight into the effectivity of the mitigating option under considerations. Though SWASH simulations can be lengthy, the limited number of simulations per option made the SWASH model a rapid assessment tool.

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