HYBRID SHORELINE MODELLING OF SHORELINE PROTECTION SCHEMES, PALM BEACH, QUEENSLAND, AUSTRALIA

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In this study the use of a hybrid shoreline model, namely the Mike21FM Shoreline Model, has been applied to investigate the effectiveness of three different coastal protection schemes for Palm Beach in Southern Queensland, Australia. The yearly littoral drift on this shoreline is approximately 500,000 m3 to the north. The three coastal protection schemes are: Nourishment, Nourishment plus a submerged control structure and Nourishment plus artificial headlands. The coastal impact due to the three schemes is quantified and compared using the shoreline model. The results assisted the Gold Coast City Council in their decision on which option to bring forward to the detailed design phase.

Keywords: hybrid shoreline model, Palm Beach, coastal management schemes, coastal protection, erosion

INTRODUCTION

On a long term basis Palm Beach is a stable beach but high density developments and infrastructure in close proximity to the backshore has resulted in an insufficient beach volume to absorb potential short term fluctuations in the shoreline position due to storm events. As a result infrastructure and beach front developments could be susceptible to damage during large and/or prolonged erosion events. Figure 1 shows three photos of the erosion on the most vulnerable section of Palm Beach.

Figure 1: **Examples of erosion on Palm Beach.**

The present study has investigated the relative performance of three different shoreline protection schemes:

- Option 1: Targeted placement of ~750,000 m3 of sand on the beach and near-shore.
- Option 2: Targeted sand placement and a near-shore submerged control structure to stabilise and enhance the longevity of the nourishment. A secondary objective of the structure is to potentially enhance surfing amenity at Palm Beach.
- Option 3: Targeted sand placement and two artificial headlands designed to stabilise and enhance the longevity of the nourishment while avoiding downstream erosion.

The structure of the present paper is: First, the erosion problems as well as the coastal processes on Palm Beach are described. Then the mitigation schemes are presented. Next the numerical model is described together with the calibration of the model. Last, the predicted coastal response due to the three mitigation schemes is presented and discussed.

COASTAL PROCESSES ON PALM BEACH

Palm Beach is a sub-tropical Pacific Ocean beach located in southern Queensland, Australia. The wave climate is quite severe with extreme wave heights around 7 meters and extreme wave periods of 15 to 20 seconds.

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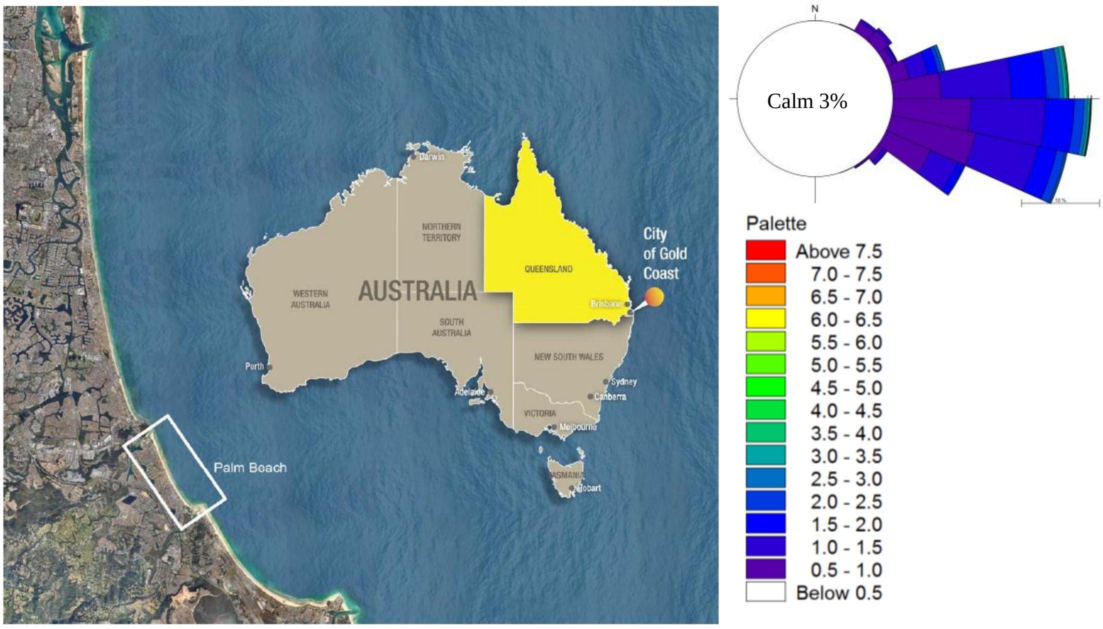

Figure 2: Location of Palm Beach and wave climate measured by Gold Coast Wave Rider

Palm Beach is enclosed by Currumbin Creek Groyne at the southern end and Tallebudgera Creek Groyne at the northern end. The sediment budget for Palm Beach is shown in Figure 3.

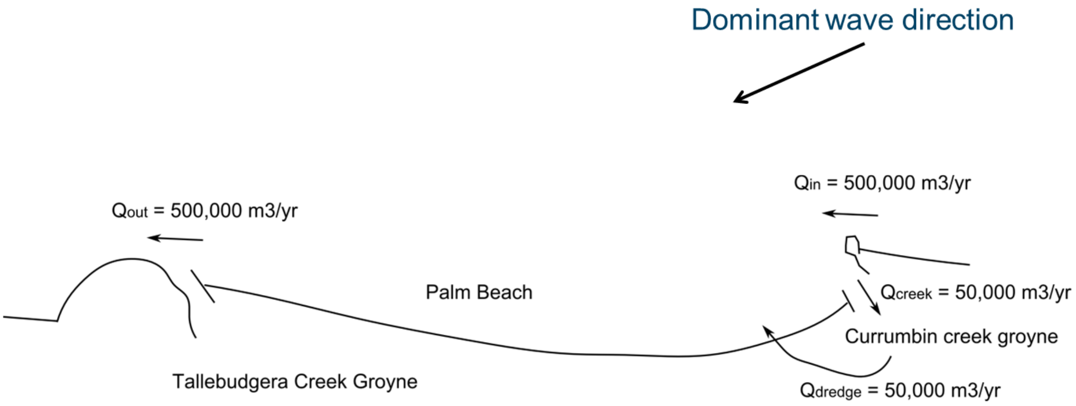

Figure 3: Sediment Budget for Palm Beach.

On Palm Beach, as on most other beaches, there are two causes for a change in the position of the shoreline: Changes in beach volume and changes in profile shape.

Variations in Beach Volume

On the longer term the beach volume in Palm Beach is more or less constant. Figure 4 shows the changes in beach profile volume at a number of beach profiles which have been surveyed irregularly since the 1960’s. As seen, there is no clear trend for the profile volume to increase or decrease during the measured period at any of the measured profiles, i.e. the volumes fluctuate around a mean value. This indicates a stable beach volume on the long term. However, large variations in the profile volumes are observed, indicating a very dynamic beach volume with large changes over the short term. Inter-annual changes of +/- 300 000 m^3 of beach volume have been observed. The large variation in beach volume can be caused by either variations in the sediment supply to the beach or variations in the wave climate or a combination of these.

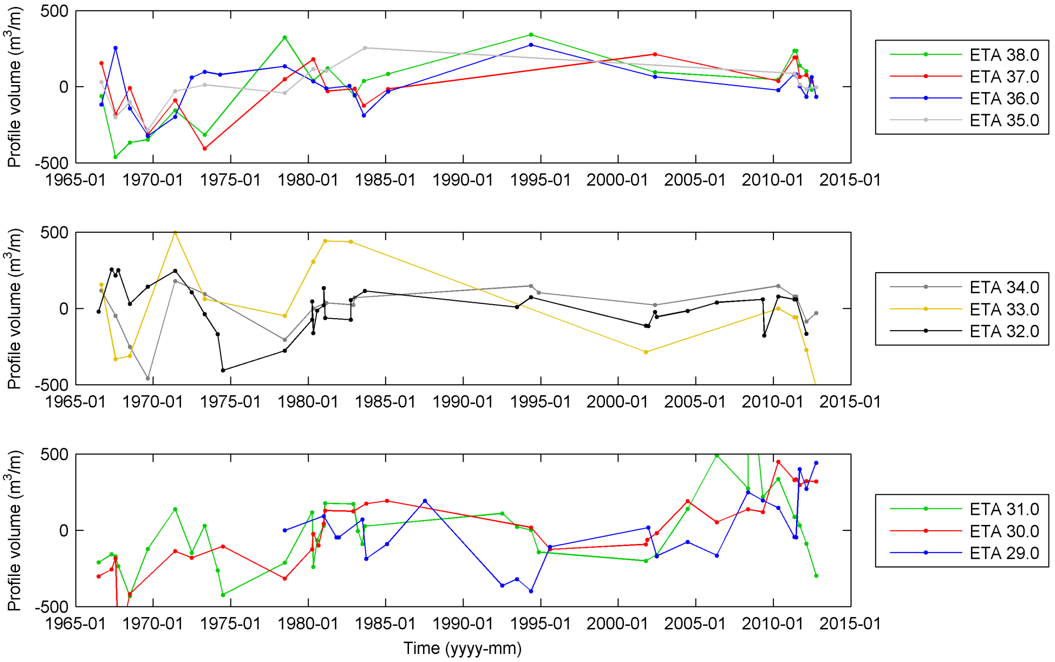

Figure 4: Calculated time series of the profile volume along Palm Beach. Station 29 is located in the southern end and Station 38 is located at the northern end. The volumes are adjusted such that each time series has a zero mean.

Changes in Coastal Profile

During storm conditions, sediment from the beach is transported off-shore to form a storm breaker bar (Figure 5), in this process the inner part of the beach profile becomes flatter. During subsequent fair weather conditions, the off-shore storm bar moves onshore (and changes to a 3D crescentic bar, see e.g. Ruessink (2013)), in this process the inner part of the beach profiles becomes steeper again.

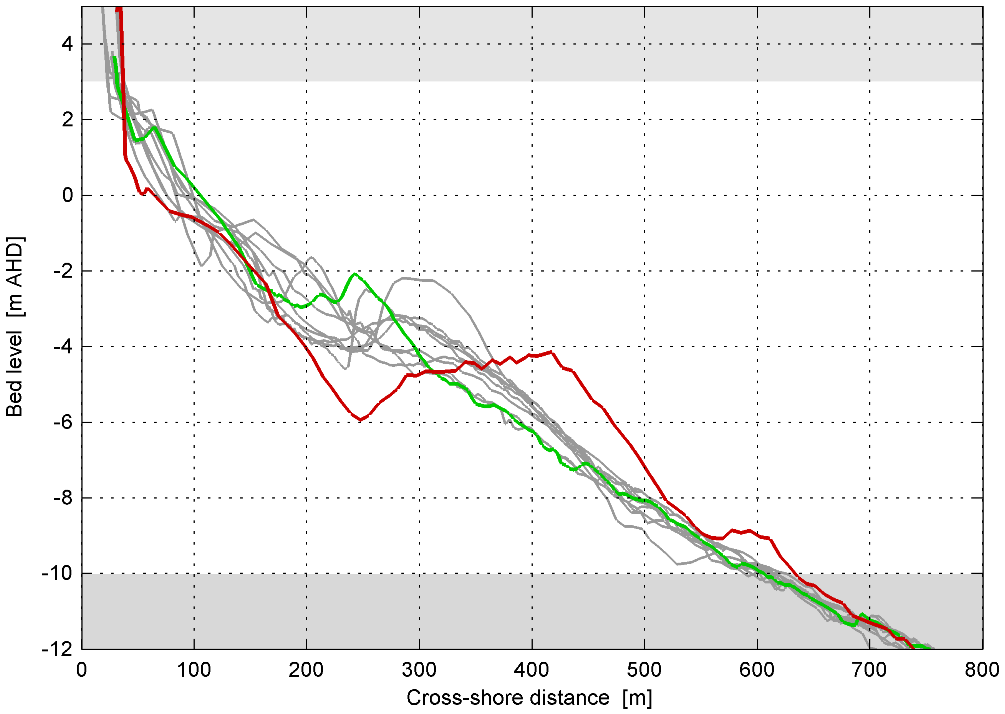

Figure 5: Variations in shoreline position due to changes in profile shape. Green profile shows a typical fair weather profile, while the red profile shows a profile with a clear off-shore storm bar.

Vulnerable Section

Palm Beach is not equally vulnerable to variations in the position of the shoreline all along the beach. The central and southern sections of the beach is the most vulnerable, this is mainly because there are no vegetated dunes in front of the houses on these sections of the beach; this is observed in Figure 6. Further north, around the northern of the two groynes the vegetated dune is observed between the buildings and the beach. The location of the groynes is also seen in Figure 12.

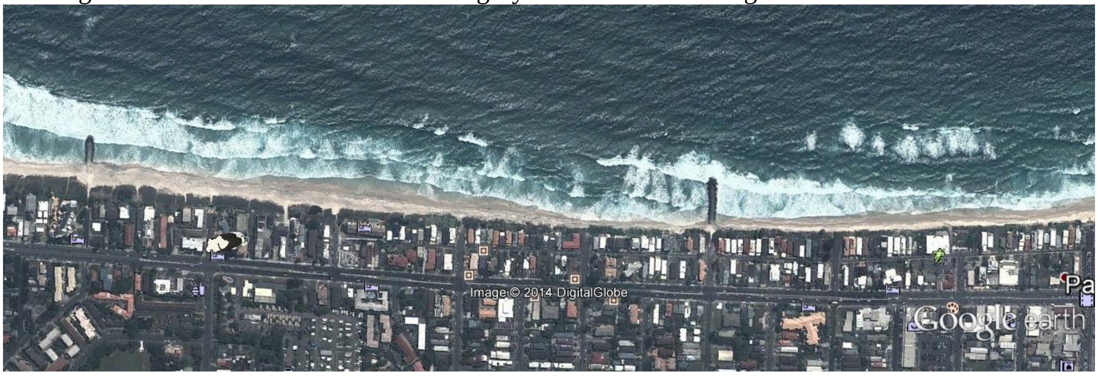

Figure 6: Google Earth image showing the most vulnerable section of Palm Beach.

MITIGATION SCHEMES

The objective of the mitigation schemes is to increase the width of the beach along the most vulnerable section of shoreline without any adverse down drift effect. Three options to increase the width of the beach on the most vulnerable sections were investigated:

- Option 1: Targeted placement of ~750,000 m3 of sand on the beach and near-shore.
- Option 2: Targeted sand placement and a near-shore submerged control structure to stabilise and enhance the longevity of the nourishment. A secondary objective of the structure is to potentially enhance surfing amenity at Palm Beach.
- Option 3: Targeted sand placement and two artificial headlands designed to stabilise and enhance the longevity of the nourishment while avoiding downstream erosion.

Option 1: Nourishment

The targeted sand placement in Option 1 is shown in Figure 7. As seen approximately half of the sand is placed near-shore and around half is placed on-shore. Only the southern and central sections of the beach are nourished as these are the most vulnerable sections. It was chosen to place half the sediment volume in the near-shore to limit the cost of the nourishment.

Option 2: Submerged Control Structure

In Option 2, the targeted sand placement is combined with an off-shore submerged control structure, intended to increase the longevity of the sand placement. A secondary objective of the submerged control structure is to increase the surfing amenity on Palm Beach.

Submerged control structures have a history of varying success in coastal protection. The design of such structures is difficult due to the complexities of the processes involves. One of the critical points when designing these structures in the past has been to determine the water depth over the crest height which determines how large a wave can pass unbroken over the structure and reach the shoreline. During storm conditions the water level usually increases thus increasing amount of wave energy passing unbroken over the structure and reaching the shoreline.

To help avoid the problem of unbroken waves passing over the structure and reaching the shoreline during high water level conditions, the structure has been designed to focus the wave energy on the crest of the structure thereby increasing the wave breaking on the structure. This is accomplished by making the off-shore side of the structure fan out with a relatively flat slope of 1:12 which becomes even flatter down to 1:20 as we move towards the shore along the north side of the structure, see Figure 8. This design means that more and more wave energy is drawn towards the crest of the structure as the wave propagates towards the shore, thus focusing the wave energy at the crest. The 1:12 slope is chosen such that the size of the structure is approximately ½ a wave length such that the wave has enough time to refract on the structure and focus on the crest. In a recent study by Gajá et al. (2014) it was found that for elliptical submerged structures, the maximum wave focusing on the structure was obtained for a horizontal extent of the structure of ½ a wave length consistent with the present design.

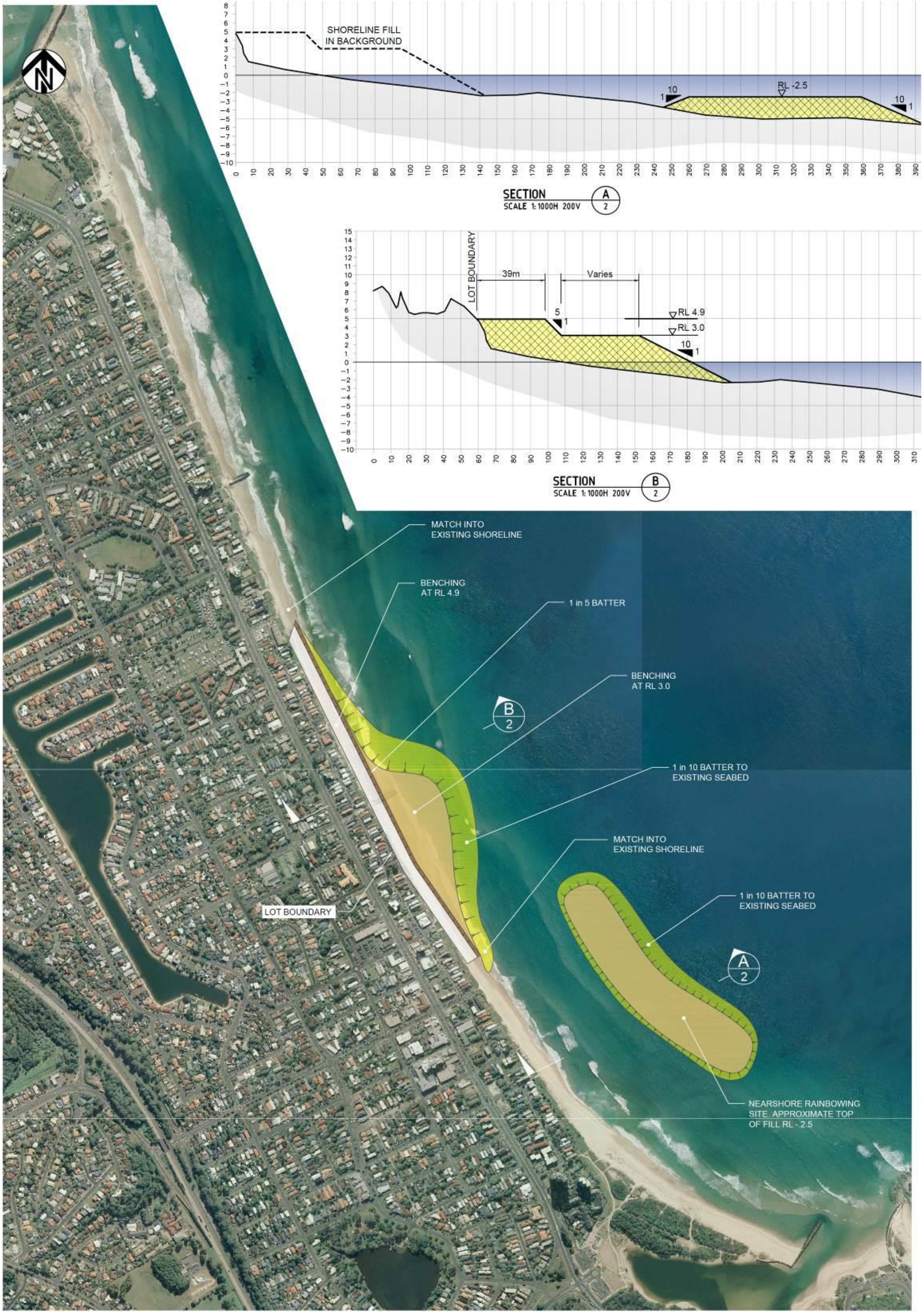

Figure 7: Targeted sand placement

Focusing of the wave energy on the structure also helps accomplish the secondary objective as larger waves are better for surfing. The orientation of the crest of the structure is such that on most days there will be a nice peeling wave along the crest of the structure; this wave will be almost ideal for surfing. The location of the submerged control structure is such that the expected accumulation of sediment up-drift of the structure is located at the most vulnerable sections of Palm Beach. It will be hard to design the structure such that no down-drift erosion happens; therefore the structure has been placed such that any down-drift erosion happens around and north of the 21st Ave. groyne where the beach is less vulnerable. Furthermore, due to the presence of the natural reef, there are three zones along the beach where wave energy is focused resulting in larger waves; the submerged control structure is located in the northern most of these zones to increase the wave breaking on the structure.

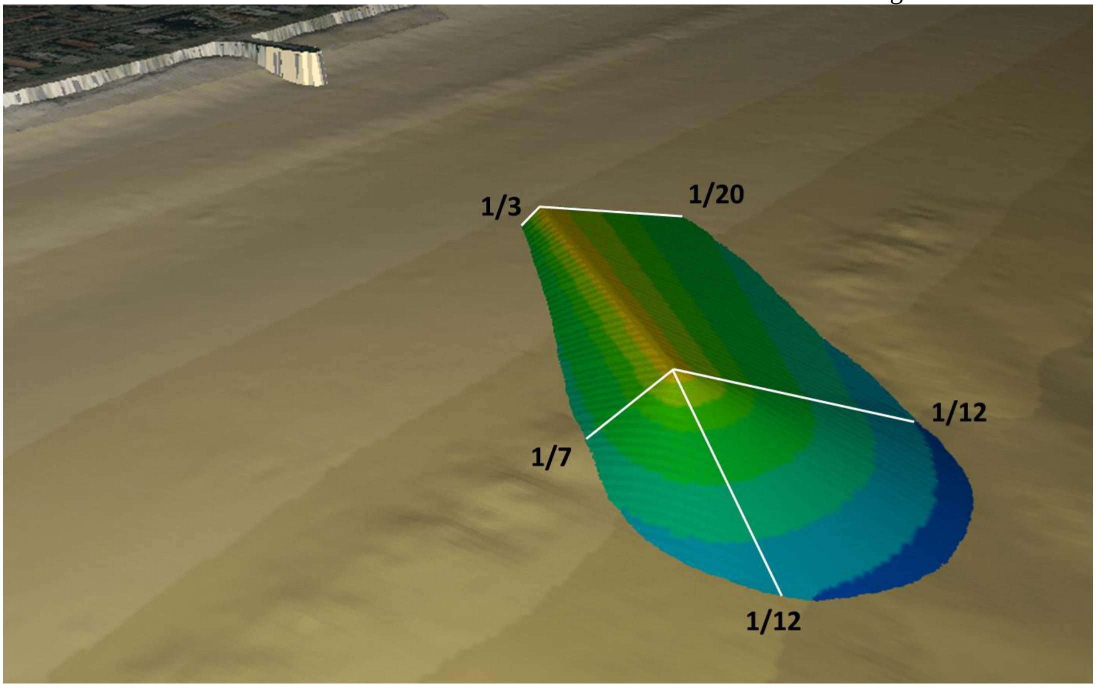

Figure 8: The dimensions of the submerged control structure.

To have the wanted effect and avoid any adverse down-drift effects, the wave breaking on the submerged control structure must be such that enough wave energy is dissipated that the shoreline accretes with the amount of sediment (or less) which is available for nourishment; a very difficult task indeed

Option 3: Artificial Headland

Option 3 combines the sand placement from Option 1 with two artificial headlands to increase the longevity of the sand placement. Artificial headlands have a track record for providing coastal protection to eroding beaches; as such the artificial headland solution is a well proven solution. A sketch of this option is shown in Figure 9.

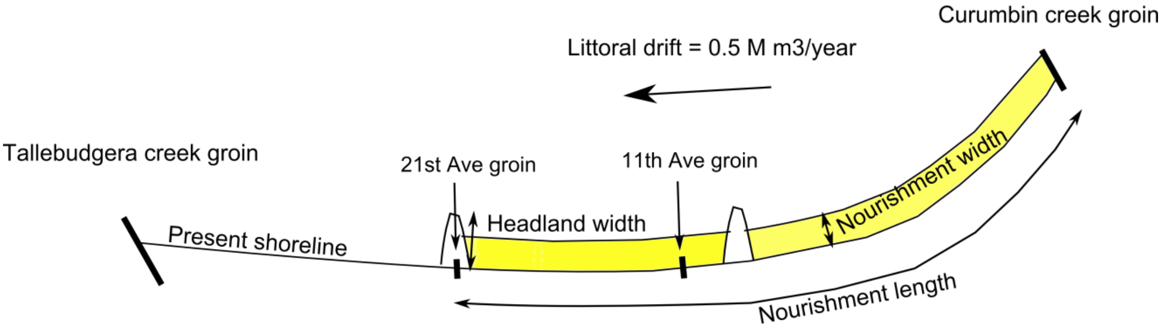

Figure 9: Sketch of the proposed artificial headlands.

To have the wanted effect while avoiding any adverse down-drift effects, the headland width must match the nourishment width such that there is close to full bypass of sediment past the headlands. For this reason, the whole nourishment volume will be placed on-shore from the 21st Ave. groyne to the southern end of the beach.

NUMERICAL MODEL DESCRIPTION

Traditionally two main types of numerical models have been applied in coastal engineering: long term models and short-intermediate term models.

Long term models will apply a number of simplifying assumptions, for example using a littoral transport model combined with a one-line model for the shoreline evolution. The models are based on the assumption, that conditions are fairly uniform along the shoreline. 2D effects such as recovery of the longshore current behind Palm Beach Natural reef or the conditions near a strongly curved coastline are not represented correctly in these models and they can therefore lead to erroneous results in such cases. Finally, the models include coastal structures in a simplified parametric fashion which can easily lead to erroneous estimates of beach response due to these structures.

The more detailed area models aim at making as accurate a representation of the physical processes as possible. Improvements in the computer power has allowed longer simulations with the detailed morphological models but there are problems with accumulation of small errors, in particular gradual deterioration of the coastal profiles in the model predictions because the delicate balances behind the cross-shore sediment transport forming the profiles are not represented accurately enough in the detailed area models.

MIKE21 FM Shoreline Model

This problem has been addressed by introducing a hybrid modelling concept, aiming at bridging the gap between the two types of models. In the hybrid models the description of wave-, current- and sediment transport fields is maintained from the detailed area models, while constraints are introduced for the morphological update.

The basic concept for the MIKE21 21 FM Shoreline model is similar to a regular 2DH area model and is shown in Figure 10

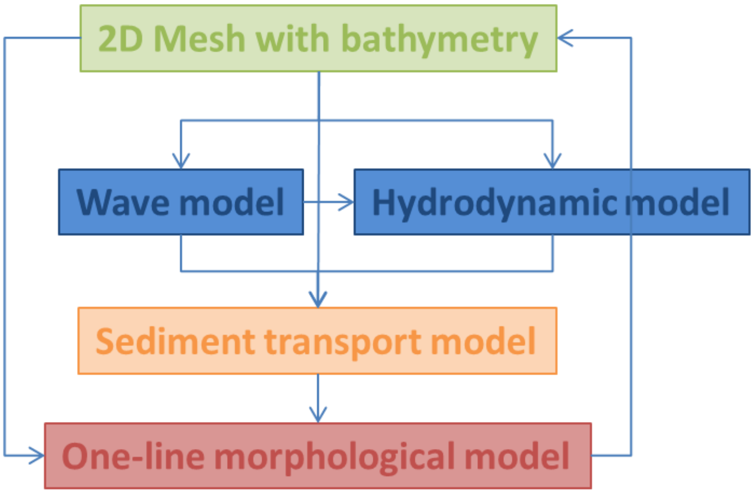

Figure 10:The concept of the MIKE21 FM Shoreline model.

The MIKE21 FM Shoreline model uses a one-line equation for the shoreline response similar to previous long term models. However, because the sediment transport description occurs in full 2D the impact from e.g. coastal structures is included without further assumptions.

The connection between the 2D area mesh and the one-line model used for the shoreline change is made using a map of shoreline edges, which specifies which shoreline edge each computational element in the near-shore area belongs to. It is noted that the near-shore area is divided into strips, where each strip belong to a specific shoreline edge.

For each strip a modified one-line equation can be formulated as:

$$\frac{dn}{dt} = \frac{vol}{dA_z}$$

Where dn is the change in shoreline position during the time step dt, vol is the volume of sediment deposited/eroded on the strip during the time step. The deposited/eroded volume is calculated by the sediment transport model based on the gradients in the sediment transport. dA_z is the area of the shoreline strip projected onto the vertical axis, shown as the grey area in Figure 11.

Validation of the modelling approach is found publications by Kristensen et al (2012), Kaergaard and Fredsoe (2013) and in Dronen et al (2011).

The wave model, the hydrodynamic model and the sediment transport model are all 2D area models solved on a flexible mesh. Each of these models are standard models in the Mike by DHI software package, see DHI (2014a, b and c) for more information. The computational mesh is shown in Figure 12 together with a detailed view of Palm Beach where the natural reef is clearly visible on the bathymetry.

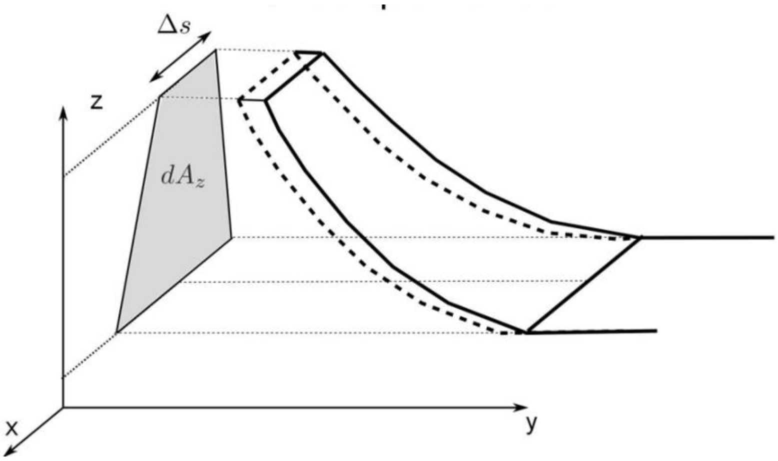

Figure 11: Sketch showing a strip of the near-shore area.

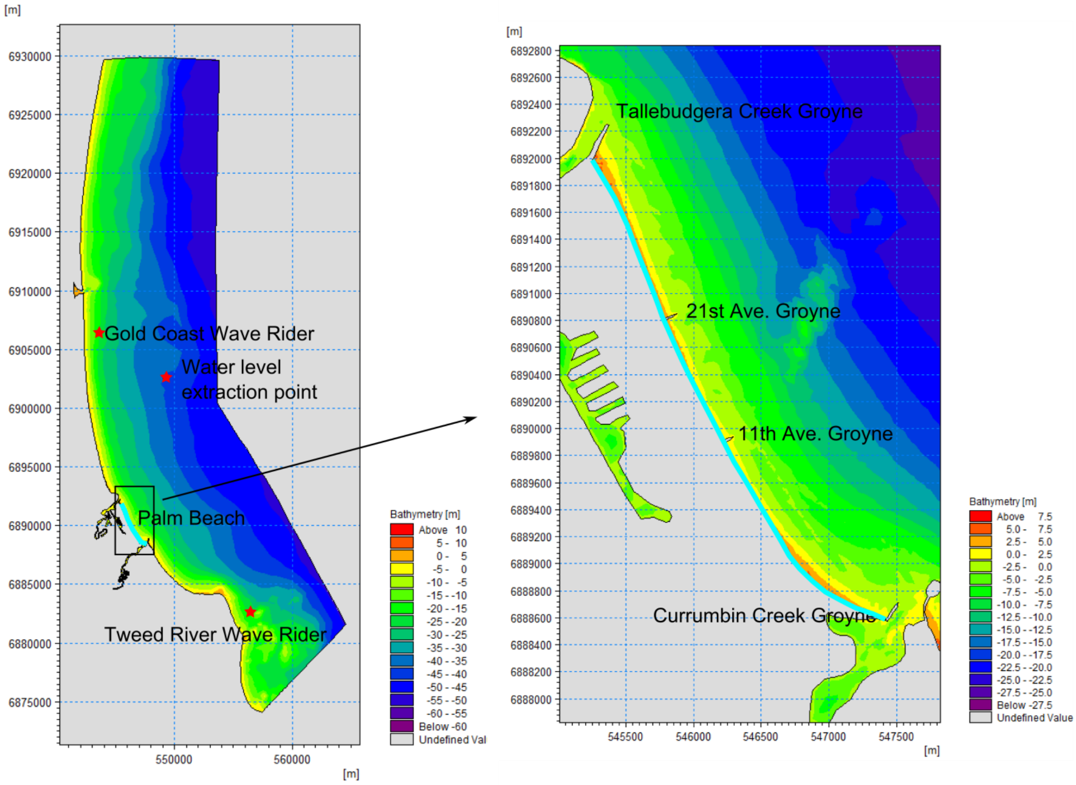

Figure 12: Left: Model domain. Right detailed view of Palm Beach

Figure 13 shows a snapshots of the wave, current and sediment transport field calculated by the models for Option 2A during a low and a high energy event.

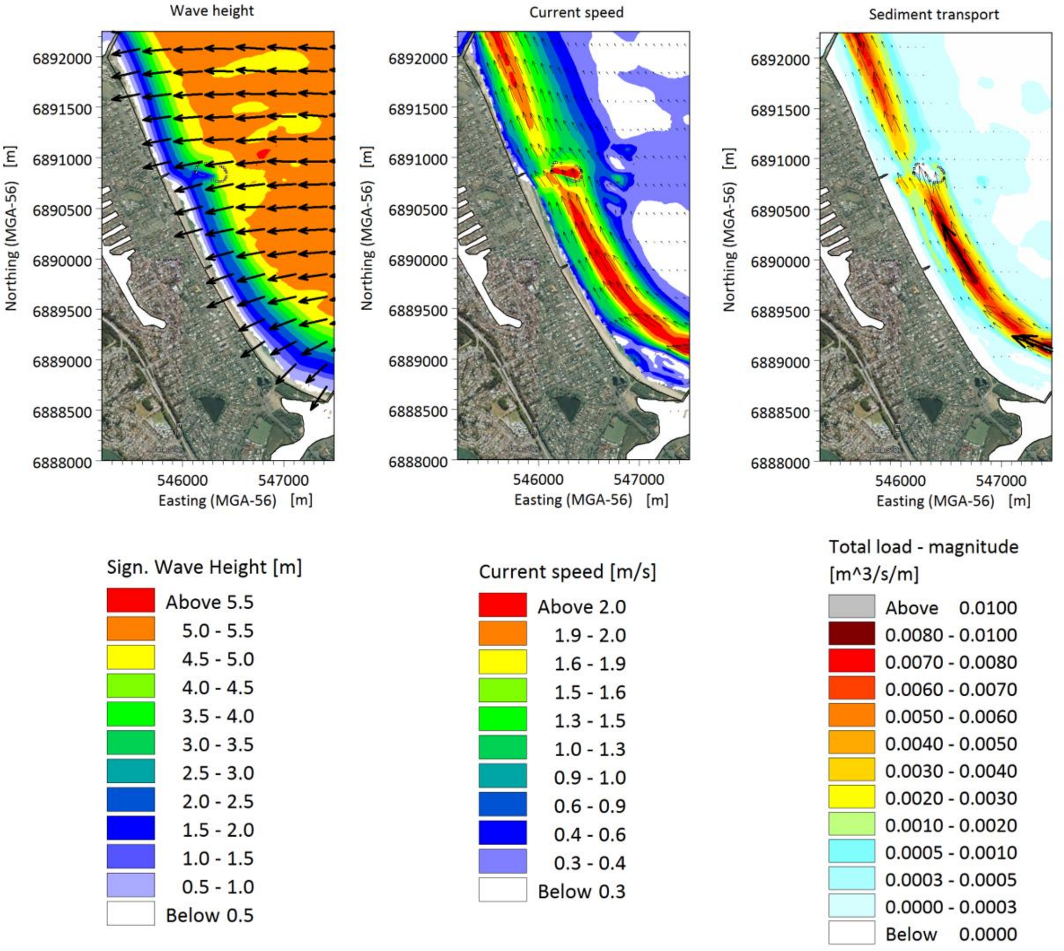

Figure 13: Snapshots of wave field, current field and sediment transport field during a high energy event. The submerged control structure is implemented in the model.

Model Calibration

A well calibrated shoreline model can adequately predict the longshore sediment transport as well as the gradients in the longshore sediment transport. The longshore sediment transport along Palm Beach is approximately 500,000 m^3/yr; therefore the shoreline model should on average predict a similar value. Furthermore, over longer time periods Palm Beach is stable; therefore the modelled beach also needs to be stable over longer time periods.

On top of these very general requirements for the model, we also expect the model to reproduce observed variations in the beach volume along Palm Beach. This last requirement is by far the most challenging one due to the dynamic and cyclic behaviour of Palm Beach. It is usually easier to model a beach which shows persistent erosion or persistent accretion, than one which sometimes accretes and sometimes erodes.

Inter-annual Changes in Beach Volume

A large number of field surveys were available for calibrating the inter-annual changes in beach volume predicted by the model. A period of approximately one year was chosen from the available data: From 20th Feb. 2012 to 27th Mar 2013.

The calibration period was split in two periods: 20th Feb 2012 to 4th Oct 2012 and 4th Oct 2012 to 27th Mar 2013. The split was introduced because the measured shape in the beach profile is very different from Feb 2012 to Oct 2012, presumably due to a large storm event occurring near 6th June 2012. Changes to the beach profile may affect the longshore gradients in the littoral drift, thereby affecting deposition/erosion along the beach. The measured volume changes occurring during the second part of the calibration period were not as well described by the model, without introduction of the change in profiles, hence it was decided to use two characteristic profiles in the morphological simulations. The comparison between the measured and modelled beach volume changes is shown in Figure 14 for both periods.

For the first calibration period, it is seen that the modelled beach volume changes deviate less than 100 m^3/m from the measured profiles for most of the profiles along Palm Beach. The largest discrepancy is located near the southern end of Palm Beach (longshore distance 3900 m). This is profile ETA 30.5 where beach nourishment presumably took place between the two field campaigns.

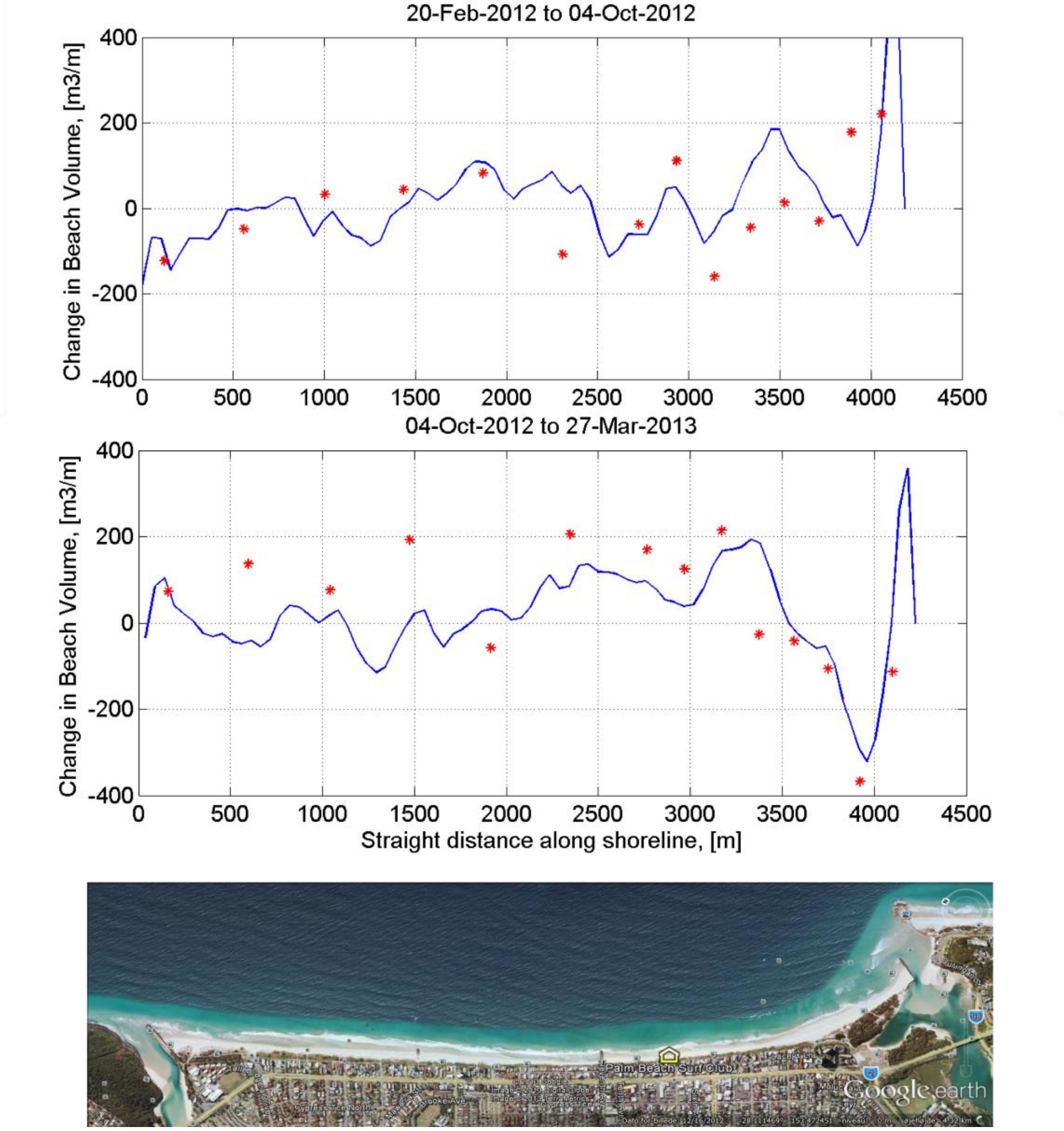

Figure 14: Comparison between the measured and modelled changes in the beach volume.

For the second calibration period, the model correctly shows erosion on the southern end of the beach and the accretion on the central part of the beach. On the northern end the model has trouble predicting the observed beach volume changes on two profiles where the measurements show accretion and the model predicts erosion or neutral beach volume.

Overall the calibration is considered good when taking into account the large uncertainty associated with the complex system being modelled. Uncertainties at many different levels contribute to the overall uncertainty in morphological modelling. Some of the uncertainty is related to the quality of the measured data used in the calibration, i.e. errors/inaccuracies in surveys have previously been shown to give volume differences in a profile of 130 m^3/m. Furthermore the calculated volume changes are based on differences in surveys between the +3 m AHD and the -10 m AHD contours, while in reality the upper and lower limits may vary in time in response to variations in the wave climate.

Model limitations also contribute to the overall uncertainty. As an example the morphological model does not update the shape of the coastal profiles continuously, but relies instead on abrupt changes which are imposed at certain intervals. Allowing the model full freedom over the shape of the coastal profile is not possible with the current state-of-the-art numerical modelling tools. Finally effects of nourishment have not been included in the numerical modelling because the associated volumes are not significant compared to the measured volume changes occurring along Palm Beach.

Long-term beach volume and littoral drift

The long terms beach volume and the littoral drift predicted by the model was tested by running the model for the current situation (i.e. without introducing a new management scheme); this *do-nothing* case was run for almost 6 years.

Figure 15 A shows the predicted changes in shoreline position at selected locations along Palm Beach while B shows the envelope of shoreline positions predicted by the model during the simulation period and C shows the yearly littoral drift predicted by the model along the shoreline. As seen the shoreline position does not drift, i.e. it varies around a mean value similar to what has been observed; furthermore the littoral drift is around 550 000 m3/year, quite close to the generally recognised value of 500 000 m3/year.

It is noted that the variations in shoreline position predicted by the model are smaller than what can be observed, this is partly because the shape of the coastal profile is much less dynamic in the model than in reality and probably also because the variability in the sediment supply to Palm Beach is not included in the model.

PREDICTED COASTAL RESPONSE DUE TO COASTAL MANAGEMENT OPTIONS

Model Setup

The model setup for each of the three management options is discussed below. Each management option presents a different challenge in terms of setting up the model to most correctly represent reality.

Option 1: Targeted Sand Placement

Both nourishment areas significantly modify the coastal profiles being nourished and reorganisation of sediment is therefore expected in the first couple of months following the nourishment campaign. This reorganisation is caused both by cross-shore transport processes which attempt to re-establish coastal profiles which are similar to the profiles occurring naturally at Palm Beach and alongshore redistribution of sediment because both nourishment areas are fairly short in the alongshore direction.

The shoreline model can adequately model the alongshore redistribution of sediment but does not address cross-shore redistribution. Therefore; prior to modelling redistribution of the nourished sediment with the shoreline model, a full morphological model was used to quantify the initial evolution of the shoreface nourishment while the shoreline model was used separately to quantify initial alongshore redistribution of the beach nourishment. The resulting initial shoreline position is shown in Figure 16.

Option 2: Submerged Control Structure

The submerged control structure was initially assumed to be located off-shore of the surf-zone, therefore sediment transport over the structure was expected to be very small. Due to economic constraints, the structure was later placed further in-shore (smaller water depths means less material to reach a certain crest level). The sediment transport by-passing over the structure was therefore significant during storm conditions and had to be included in the model. This was achieved by setting up the model such that the fully free 2D morphological description was used over the submerged control structure, whereas the constrained morphological description of the shoreline model is used elsewhere along Palm Beach.

The initial position of the shoreline was the same as for Option 1; it is seen in Figure 16 together with the location of the submerged control structure. Three different sizes of the submerged control structure were tested, namely A, B and C. Selected properties for these are shown in Table 1.

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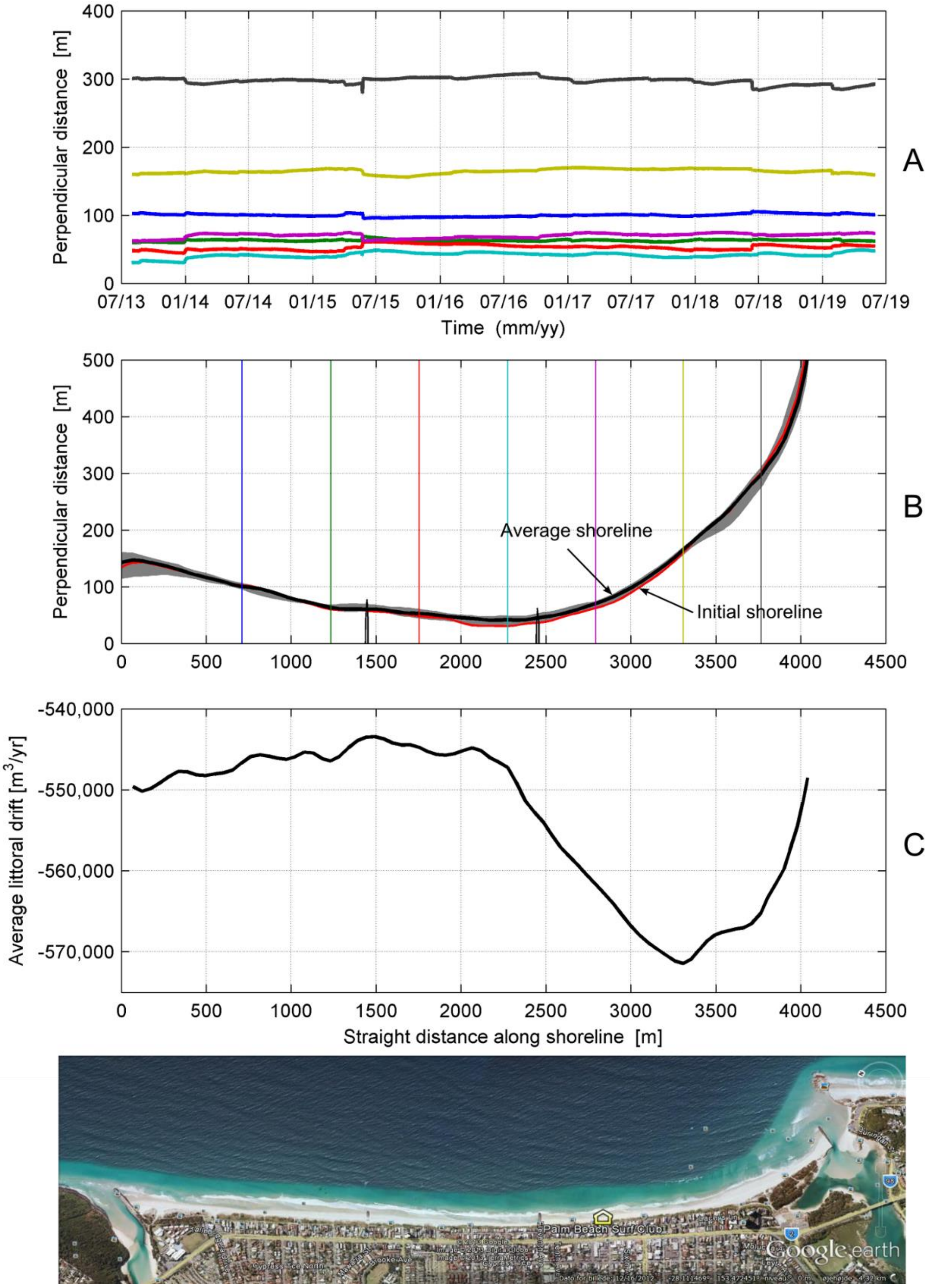


Figure 15: Model results from the Do-nothing case. A: Changes in shoreline position at selected locations along Palm Beach. B: Envelope of shoreline positions during the simulation. C: Average littoral drift along Palm Beach during the simulation.

Table 1: Selected properties for the three different submerged control structures.

Name	Crest Length	Off-shore Depth	Near-shore depth	Volume	Max Width	Max Length
Option 2: SCS A	190 m	11.6 m	4.7 m	96,248 m^3	154 m	309 m
Option 2: SCS B	60 m	11.4 m	6.6 m	53,319 m^3	144 m	175 m
Option 2: SCS C	30 m	10.6 m	6.9 m	37,112 m^3	138 m	142 m

Option 3: Artificial Headlands

The initial shoreline position for this option was slightly different than the other two options as the design required the sand to be placed between and south of the headlands to avoid intermediate down-drift erosion. The initial position of the shoreline for this case is shown in Figure 17

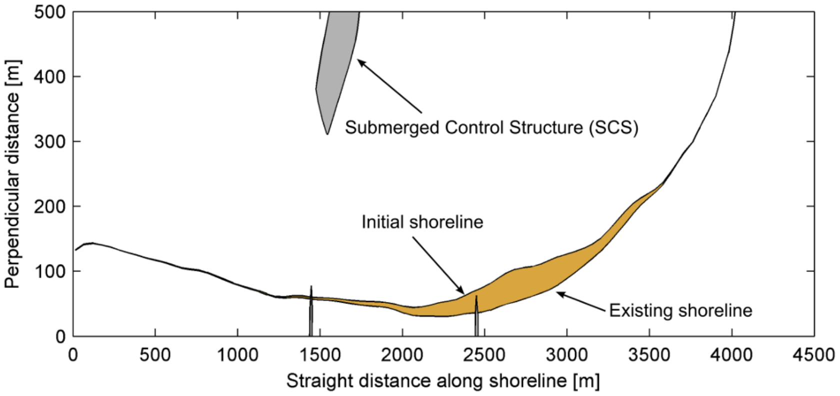


Figure 16: Initial shoreline position due to the redistribution of the sand placement

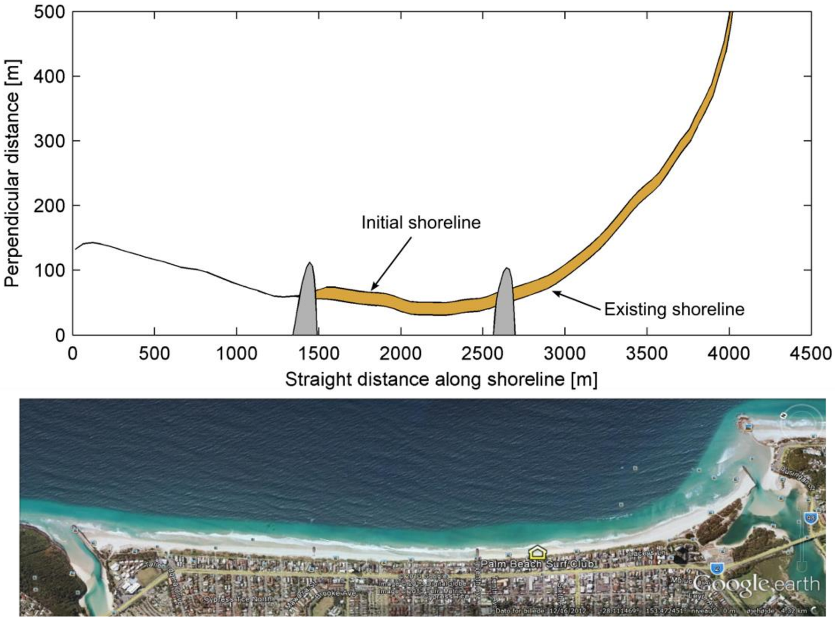
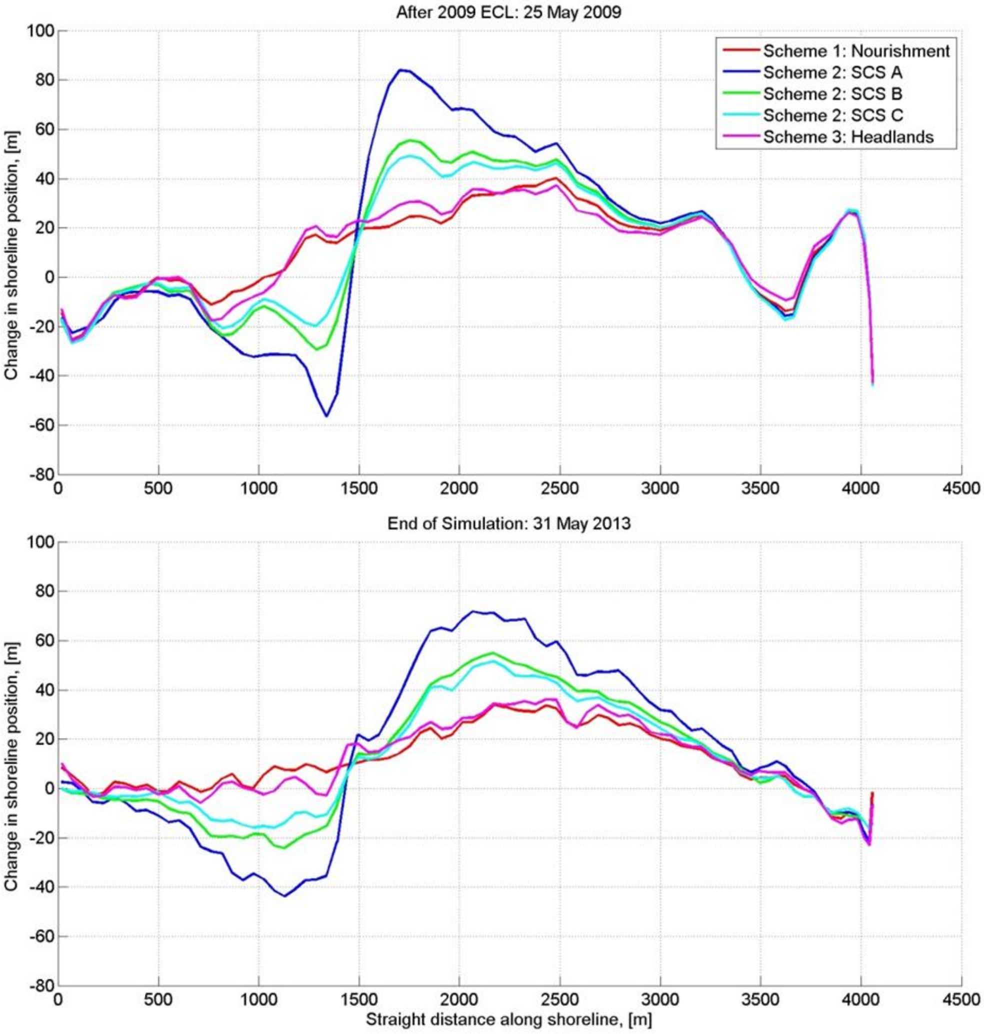


Figure 17: Initial shoreline position for the artificial headlands option.

Results

The predicted shoreline responses for the three options are shown in Figure 18. The shoreline response is shown both after the full ~6 years simulation and after a significant storm event termed the 2009 East Coast Low (2009 ECL). It is seen that south of 21st Ave. groyne (around shoreline distance 1500 m) the beach width increases for all management options. North of the 21st Ave. groyne, Option 2 A results in large erosion, of up to 60 meters right after the 2009 East Coast Low event. This large erosion was not acceptable which led to the testing of Option 2 B and Option 2 C.


After 2009 ECL: 25 May 2009

End of Simulation: 31 May 2013

Figure 18: **Predicted coastal response due to the different management options.**

From Figure 18, it is observed that the reduction in crest length from 190 m to 60 m between SCS A to SCS B almost halves the maximum down-drift erosion from 55 m to 30 m after the 2009 ECL event. After the entire simulation period, the down-drift erosion is reduced from around 45 m to around 25 m. The maximum accretion changes by 30 m from around 85 m for SCS A to 55 m for SCS B after the 2009 ECL event. After the full simulation the change is smaller; from 70 m for the SCS A to around 55 m for SCS B.

It is further observed that the additional reduction in length of the crest from 60 m (SCS B) to 30 m (SCS C) has a smaller impact. After the 2009 ECL event, the maximum erosion is reduced by 10 m and the maximum accretion reduced by around 5 m. After the entire simulation period the reductions are also 10 m for erosion and 5 m for accretion.

The small difference in the impact from SCS B and SCS C is due to the general layout and design of the SCS. The SCS is designed so waves arriving within the longshore extent of the SCS refract towards the crest of the SCS and create a surf-able wave which peels along the crest of the SCS as the wave approaches the shoreline. The alongshore extent of the perimeter of the SCS is almost the same for SCS B and SCS C; this can explain the relatively small change in the impact on the shoreline.

Note that in the above, the mentioned values have been rounded to nearest 5 m.

DISCUSSION AND CONCLUSION

The MIKE21 FM shoreline model, which is a hybrid between a traditional one-line shoreline model and a 2D sediment transport model, has been used to predict the coastal response to three different management schemes for Palm Beach, Queensland, Australia.

The key element in the MIKE21 FM shoreline model is the assumption of a constant coastal profile throughout the simulation period. It proved to be difficult to obtain a satisfactory calibration of the inter-annual changes in the beach volume using a single coastal profile for the entire 1 year calibration period, however using two different sets of profiles, one for the period Feb. to Oct and a second for the period Oct to Feb we obtained a satisfactory calibration. This shows the importance of the coastal profile for these simulations: A constant profile did not work. However it also shows that with very limited variability (just 2 profiles over a full year) we can obtain satisfactory results.

The simulations predict all three management schemes to increase the beach width along most vulnerable sections of Palm Beach and for all three options a design has been found for which the model predicts limited down-drift erosion. Thus it seems that all options fulfil the design criteria: Increase beach width along vulnerable sections and avoid down-drift erosion.

What cannot be seen from the model results are the confidence intervals for the model predictions; which are not the same for all three options. The uncertainty of the results is larger for Option 2 than for Option 1 and 3 because the complex processes of wave breaking and energy dissipation over the submerged control structure is what governs the impact of the structure on the shoreline morphology. This is not the case for the either Option 1 or 3, where the uncertainties to some extent have been removed or limited through the calibration process. It hasn't been possible to calibrate the model for the case of a submerged control structure.

Option 2, the submerged control structure was moved forward into the detailed design phase by the City of Gold Coast. From a technical point of view Option 3 was the preferred option, but it was considered a viable option since "social/cultural and political high risk items associated with the artificial headlands were deemed contentious and unlikely to be mitigated".

To increase the trust in the model predictions for the submerged control structure, a number of studies are planned in the detailed design phase which hopefully can help to quantify the uncertainty of the model predictions and preferably reduce some of those uncertainties. The studies include:

- Physical model tests
    - Structural stability
    - Wave breaking and dissipation over structure
    - Effect of structure on longshore current
    - Surfing amenity
- Numerical modelling refinement (among others)
    - Shoreline response for 30 years (in present study is was 6 years)
    - Sensitivity of model parameters
    - Performance assessment of lower crest level

ACKNOWLEDGMENTS

The study has partly been financed by the project: Danish Coasts and Climate Adaptation – flooding risk and coastal protection (COADAPT), financed by the Danish Council for Strategic Research (DFS), project no 09-066869.

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