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REVIEW OF BEACH PROFILE AND SHORELINE MODELS APPLICABLE TO THE STATISTICAL MODELLING OF BEACH EROSION AND THE IMPACTS OF STORM CLUSTERING

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Cover: Gathering data at Old Bar Beach, NSW. Photo by Geoscience Australia.

Contents

1 Introduction

The Bushfire and Natural Hazards CRC project, Resilience to Clustered Disaster Events on the Coast – Storm Surge proposes to develop a beach profile or shoreline evolution model appropriate for assessing the behaviour of selected beaches to clustered storm events. This paper outlines the characteristics required of an appropriate model and reviews literature and model results to determine if existing approaches include the required physics and can be embedded within a suitable statistical framework for a stochastic analysis. It is anticipated a priori that a hybrid model approach will be required, utilizing existing process models in a new model suite. A discussion of modelling approaches is provided, together with a justification of the model proposed for the project.

The chosen model, with appropriate refinements and modifications, will be applied at two case study sites; Old Bar (NSW) and Adelaide Beaches (SA). This review focuses on models that can be applied at these field sites within the constraints imposed by the available data. These data are summarized in a previous report - Identified data on study sites: *Old Bar and Adelaide Beaches* Geoscience Australia (2015), IDSS henceforth. Coincident with the model development, will be the development of a model framework for its implementation. These potential approaches for model and modelling frameworks are discussed in this paper. This modular separation of the model and model framework allows for an iterative development approach where refinements can be made as they are required.

While the overarching aim is to develop a model and model framework that accurately quantifies erosional risk at these study sites, the approach should be transportable to other coastal sites of interest. Even in the development stage we may include third site at Narrabeen beach due to its rich data history and relative close proximity to the Old Bar site. Furthermore the authors have an active study site at Wooli beach where we also expect to test the model.

This report is structured as follows. Section 2 discusses the requirements of the model with regard to the coastal processes characteristic of the field sites and outlines the basic model types for coastal morphodynamic modelling. Section 3 reviews general coastal morphodynamic modelling and lists specific models considered to potentially suit the project aims and discusses the merits of each with respect to the dominant coastal sediment processes at the two field sites. Section 4 provides details on common statistical modelling frameworks and those considered for this study. A concluding discussion and preliminary recommendation for the model and model framework are presented in section 5.

2 Field sites overview and model requirements

2.1 Overview of coastal process and climate at field sites

Two field sites were selected based on the criteria that each location is characterized by different coastal processes and wave climates. This guideline was imposed to encourage the development of a model and methodology which is transportable and not only applicable for sites with one set of coastal processes characteristics. Also contributing to the site selection criteria was that the locations exhibited coastal erosion threats that require quantification and risk assessment for optimal future planning and mitigation strategies. Old Bar and Adelaide Beaches fit these criteria and the main differences between these two field sites are described here.

Exposure to the open ocean in regards to fetch for wind sea generation and propagation of swell waves is drastically different at these two field sites. Old Bar's location on the east coast of New South Wales (31.967 S, 152.588 E) is highly exposed to swell waves from the South, East and North, which can originate in the Southern Ocean, Tasman Sea, South Pacific and Coral Sea. Additionally, there exists large reaches of fetch for the growth of locally generated wind sea. In contrast, Adelaide's beaches (31.929 S, 152.601 E) are more sheltered by their location inside the Gulf of St. Vincent. There is a generally limited fetch distance and blocking from remotely generated swell waves with the exception of the WSW direction where there is large fetch and window for swells to propagate from the Southern Ocean through the Investigator Straight. Several recent reviews detail the directional wave climates in the Southern Hemisphere and south east Australia. Further details and references to previous studies and publications on the coastal processes at these two sites are given in the IDSS report. Additionally, to better understand the complex dynamics of the regional wave climate in southeast Australia, a review pertinent literature (Alves 2006, Young, Zieger et al. 2011, Hemer, McInnes et al. 2012, Hemer, McInnes et al. 2013, Mortlock and Goodwin 2015) is underway.

2.2 Overview of waverider buoy data and wave model hindcast for use as morphological model input

The ability to model beach morphology for the purposes of this project will require the effective hindcast of the bulk directional spectral wave parameters nearshore to the field sites, namely the wave heights, periods and directions. Ideally there will exist good agreement between the reanalysis wave model hindcasts described in the IDSS report and the measured buoy data. If this correlation is suitable, then wave model outputs near the field sites could be used directly. Presumably this model output would be near the 80 m depth contour offshore, which is also the typical buoy depth. At this depth the effects of refraction and shoaling are relatively small and the wave field can be considered spatially homogeneous along the coast on the scale of the project beaches. Using a model hindcast is beneficial to resolve the full spatial and temporal resolution of the directional wave fields for the time periods simulated. For the scale of ~ 100 km there is variability in the space and time of wave parameters on the 80 m contour. However, one issue with this approach is inaccuracy in the wave hindcast model and the length of simulation of only 30 years.

The approach of calculating the extreme statistics measured directly by the offshore waverider buoys is more ideal. This approach is desirable because generally the buoy data is believed to be more accurate than the wave model hindcast. However, the method of using buoy measurements has obstacles as well. Specifically, issues arise for cases where there is substantial separation between the site of interest (study site) and the buoy location and for cases where there are data gaps in the wave field record. These are both artefacts of the spatially and temporally nonhomogeneous wave fields along the 80 m contour i.e. between some waverider buoys when the spatial scale reaches ~ 100 km.

The direct input to the morphodynamic model will require bulk wave parameters in shallow water just offshore of the surf zone. The spatial scale for alongshore homogeneity of the wave field at these depths shortens because of depth refraction and shoaling. Therefore, the measurement depths dictated by the buoys is convenient for this project because this roughly delineates where alongshore variation of wave parameters begins to become significant. This is critical because we can generate one set of statistics for each study site at one representative location. Then these wave statistics (time series of bulk wave parameters) can be transferred to shore using wave modelling, often at times with a stationary lookup table approach. A number of recent reviews and discussions exist on techniques for wave transformation from offshore to the nearshore (Work and Rogers 1997, Callaghan and Wainwright 2013, Long, Plant et al. 2014).

2.3 Overview of model requirements

To enable confidence in the model capability for assessing the impact of storm clusters, the selected model should ideally satisfy or demonstrate the following model principles or characteristics:

Cyclic ability: The cyclic ability refers to the model capability to transition between realistic beach states i.e. dissipative to reflective (Short 2006) on all time scales. For example, the model should be able to reproduce observed erosion and accretion cycles from storm to seasonal to decadal scales.

Sensible asymptotic behaviour (equilibrium principles): the model should converge to an equilibrium beach profile or shoreline position under constant input forcing as time tends to infinity. This concept is elaborated on in section 3

Include cross-shore and longshore transport processes: The model should contain mechanisms to transport sediment in both the cross shore and alongshore directions, further discussion of this is given in section 3.

Sensible computation time for statistical modelling: This requirement lead to the exclusion of extremely complex models and a choice of a simple and pragmatic sediment transport or beach profile model. Added model complexity does not necessarily lead more realistic results, especially for morphodynamic modelling where the many aspect of the physical processes are not fully understood (Miller and Dean 2004).

Demonstrate physically sensible profile and shoreline evolution: Ideally the model will be able to reproduce beach profiles found in nature. While this is not expected to be perfect, in the cross shore direction the general shape of the beach should be represented such as the slope at the shoreline, and erosion shape of the dunes. Inclusion of bar morphology to make the model self-limiting probably requires excessive computation times. In the longshore, this requirement entails balancing the sediment budget such that results are realistic and not out of line with those that are observed in nature, or ideally match field observations.

Be verifiable from the literature or in-house testing: Substantial literature exists on the development and testing various models. This knowledge base supports model selection based on those that have been successfully implemented and validated in the past. The model should also be validated for the hindcast as is discussed in section 5.

Require limited site-specific calibration: The chosen model should not require excessive tuning to the extent that it is not transportable for implementation at other sites. By limiting the site model free parameters and imposing the constraint that there should ideally be some physical basis for these free parameters, we hope that the developed model can be applied at other sites without changing the overall model approach.

Require typically available data for input conditions: The typical model inputs for beach morphology are tide, significant wave height, peak wave period, mean wave direction, initial beach state, sediment grain size, and wind. For the wave inputs, the integral or bulk wave parameters of the directional wave spectrum have traditionally been used successfully as morphological model inputs. These are also the typical output parameters from wave models and wave buoys. A potential future improvement to these traditional bulk wave parameter inputs is the partitioning of the directional spectrum into several distinct wave field each with their own height, period and direction (Hanson and Phillips 2001). This approach inherently identifies swells from separate storms and may provide an alternative means to identify storm clustering.

Enable hybridization: Considering the abovementioned restraint for model computational efficiency, it is desirable that two distinct models may be combined to form a hybrid. Specifically, we expect to couple separate longshore and cross shore models. Further discussion on the separation of longshore and cross shore models is explained in section 3.

3 Types of coastal morphodynamic models

Traditionally, coastal morphodynamic models can be divided into separate categories based on their governing principals for derivation and general model approach. While coastal erosion is influenced by both longshore and cross-shore processes, the prediction of beach morphology can be simplified by separating the longshore and cross-shore processes (Miller and Dean 2004).The following is a review of these basic model types. It is stressed here that many models cannot be strictly classified into a specific type and many are indeed some combination or hybrid of these types, as is the likely model for this project.

3.1 General model approaches

3.1.1 One-line shoreline models

One-line models refer to two-dimensional alongshore transport models that describe the time evolution of the shoreline. A key principal of one-line models is the assumption of predefined and constant profile shape perpendicular to the shoreline. The model calculates profile shifts in the cross-shore to conserve sediment entering and exiting a given longshore section of control volume. These require a model for the longshore transport across the active beach profile. Arguably, the most well know is the CERC (Coastal Engineering Research Center) equation, formulated based on total or bulk sediment transport (Coastal Engineering Manual). These models typically track the shoreline contour, hence the name one-line models. Implementation of these models varies in regards to the exact mechanism driving sediment transport. The first one-line model was presented by Pelnard-Considere (1956) which has the form of a diffusion equation (Dean and Dalrymple 2001). This method of modelling coastal morphodynamic has continued to be useful and has been applied for many applications (Larson, Hanson et al. 1997, Ashton, Murray et al. 2001, Zacharioudaki and Reeve 2008, Walton and Dean 2011). Arguably the most common model is Genesis (Kraus 1989). There is a lengthy rhetoric between proponents and critics of this model starting with the publication by Young, Pilkey et al. (1995). While these models can respond to storm events, when the longshore transport rate increases, they do not model cross-shore transport which is the dominant mode of beach erosion over storm durations.

3.1.2 Multi-line shoreline models

Alongshore variation of beach profiles leads to a natural progression to extend from one-line to two-line models. Along a beach, each location might be at presumably different stages relative to equilibrium, especially for cases with hardened structures that exhibit clear variations between the up-drift and down-drift sides. These models split the cross shore profile into two sections with each following the equilibrium profile concept (Bakker 1968). This same approach can be expanded further, to n-line models (Perlin and Dean 1983). A recent thorough review of these one-line and multi-line “planform“ approaches, as well as the stability of these models is given in Reeve (2014).

3.1.3 Conceptual or equilibrium type models

The equilibrium type model is conceptually based on the balance between destructive and constructive forces acting on a beach (Dean and Dalrymple 2001). An example of the equilibrium concept is in the laboratory wave flume. When wave forcing is held constant, the beach eventually reaches some steady state which is known as the equilibrium beach profile (EBP).

Equilibrium models can take two forms – profile models or beach state models. The former attempt to model the profile adjustment to waves and storm surge (Kriebel and Dean 1985, Kriebel and Dean 1993, Davidson, Lewis et al. 2010) and the latter model the beach state (Wright, Short et al. 1985) or shoreline models (Miller and Dean 2004, Yates, Guza et al. 2009, Yates, Guza et al. 2011, Splinter, Turner et al. 2014).

Equilibrium is likely never achieved in nature because wave forcing conditions are never constant. The theory assumes that for given wave condition an EBP does exist and that the instantaneous profile is actively adjusting towards this profile. The rate of profile adjustment is proportional to the disequilibrium between the beach profile at the current time and the EBP. The basic properties of EBP are (Dean 1991):

- They tend to be concave upwards.
- Smaller and larger sand diameters are associated with milder and steeper slopes, respectively.
- The beach face is approximately planar.
- Steep waves result in milder slopes and a tendency for bar formation.

3.1.4 2D process-based beach profile models

These models take known processes, with varying degrees of complexity, and attempt to model waves, currents, sediment transport and hence bed evolution on a time-averaged or wave-by-wave basis. While some success has been demonstrated in bot field and laboratory, models require a great deal of calibration and adjustment to match measured data. The author's experiences in "blind" simulations have not yielded significant confidence in model skill over anything but short durations. These models are discussed further below.

3.1.5 3D process-based beach profile models

Full three-dimensional sediment transport models are not currently practical for application in this project. Tracking bottom elevation changes in both the cross-shore and alongshore and the interactions with the wave and hydrodynamics is highly sensitive to the physical parameterizations used. Both 2D and 3D models have yet to demonstrate any consistent ability to model onshore sediment transport and beach accretion (Atkinson, McKee Smith et al. 2013)

3.1.6 Statistical model approaches

An alternative to the process based models it to look for patterns directly in beach response. This approach has been used via empirical orthogonal functions (Winant, Inman et al. 1975).

3.2 Models considered

For the purposes of this project, shoreline models, cross-shore transport models, longshore transport models, beach erosion models, statistical modelling, and models that have the potential to respond to storm clustering all have potential. Many work in effectively the same way. Based on previous experience, the following models are under consideration.

3.2.1 SBeach

Full details on the development of SBeach and the initial validation are given in the user manuals, which are technical reports by the US Army Corps of Engineers (Larson 1989, Larson 1990).

3.2.2 XBeach

A detailed description of the XBeach model is given in the user manual (Roelvink 2010) and several applications and validations are described in peer review publications by the model developers (Roelvink, Reniers et al. 2009, McCall, Van Thiel de Vries et al. 2010). These applications of the XBeach model focused on barrier island response to hurricanes and attempted to model the different regimes of impact by hurricanes described by Sallenger (2000). The XBeach model is a full process based model and thus is much slower to run relative to the Kriebel and Dean or SBeach models that are described above (Callaghan, Ranasinghe et al. 2013).

3.2.3 CERC Equation

The CERC equation is a simple longshore transport model that relates the sediment transport to the wave energy flux at the wave breakpoint, accounting for the angle between the breakpoint and the shoreline. It forms the basis for most longshore sediment transport models, with a few variants suggested for different beach types and larger grain sizes.

3.2.4 Shoreline Evolution Model (EVO)

The Shoreline Evolution Model (EVO) was developed by the private company BMT WBM (Patterson 2013). The Patterson report describes the EVO model as having the following key features:

- Linking to the external wave model SWAN for deep to shallow water wave transformation lookup table.
- Curvilinear grid to allow simulation of complex coastline shapes.
- Model is a hybrid with inclusion of both cross-shore profile evolution and alongshore transport gradients on shoreline changes.
- A cross-shore profile with a slope consistent with the beach shore-face, and which may be set consistent with that Bruun Rule response to sea level change.
- Models spans short time-scales from tide to storms to longer time-scales, including sea level rise.

A further description and application of the EVO model to the Golf Coast is given by Teakle (2013). This model effectively combines the equilibrium model approach of Kriebel and Dean (1985) for storm erosion and recovery with the one-line model approach for longshore transport. To the authors' knowledge it is the only model form of this type, even though the hybridisation is a logical extension of both approaches.

4 Modelling frameworks

4.1 Deterministic vs Probabilistic Mathematical Modelling

Irrespective to the exact choice for the coastal morphological model adopted for this study, equally important is the selection of a modelling framework. A critical aim of this research is to provide risk analysis for erosional hazards and also to describe the uncertainty associated with given risks. The approach outlined here is in line with the recent developments on the subject (Callaghan, Nielsen et al. 2008, Callaghan, Roshanka et al. 2009).The critical distinction in this approach is to classify the storm erosion hazard return period or exceedance level directly from the morphological response. A similar approach has evolved in other hazard classification, such as flood and inundation return events rather than the rain or storm creating those events. The alternative that has often been used perhaps inappropriately in the past was to determine the morphological response for a given storm wave event of a certain return period or exceedance level. Essentially, the framework suggested here feeds the input variables through a structural function first and then calculates the associated return periods.

In deterministic modelling there is only one possible model result for each set of input conditions. In the case of beach erosion, this implies that for a given set of forcing such as significant wave height, peak period, mean wave direction, tide level, initial beach state, etc., there is always the same model response. In contrast, for probabilistic (or stochastic) models each of the input variables is given in terms of their probability distributions. This second method has the added benefit of allowing for the statistical calculation of probability or uncertainty for a given outcome. However, it is critical to note that probabilistic models are inherently more computationally expensive relative to deterministic models and thus the choice of hydrodynamic and sediment transport functions must be simpler and much more computationally efficient.

4.2 Modelling frameworks considered

4.2.1 Extrapolated Wave Exceedance Characteristics (EWEC)

This approach is similar to the structural variable method described by Callaghan, Nielsen et al. (2008) with the exception that the input is given by extrapolated extreme values for return periods from a peaks-over-threshold approach. An example calculation of the extrapolated extreme values is given in Figure 1 of Callaghan, Roshanka et al. (2009). This method for extrapolated extreme values is common for many disciplines in physical sciences. Inherently the deterministic approach does not account for the disparity between the storm wave heights of a given return period (RP) and the RP of the associated erosion volume. Further, there is no ability to account for storm clustering or wave directional effects.

4.2.2 Synthetic Design Storm (SDS)

The Synthetic Design Storm approach (Carley, 2003) is an improved version of the above described EWEC approach. The main difference being that the SDS approach accounts for temporal wave height variation during the storm event and given the design return period wave height. In this method, for each extrapolated return period, synthetic design storms are created based on an assumed temporal evolution. This synthesizing of storms is similar to the approach applied by Kriebel and Dean (1993) to achieve analytical solutions for their beach profile model. While all of the limitations inherent to the EWEC approach are also shared by the SDS approach, it is a more scientifically defendable approach owing to its representation of the temporal wave height variation during the design storm event.

4.2.3 Joint Probability Method (JPM)

A summary of the Joint Probability Method is given by Callaghan, Nielsen et. al. (2008):

“The joint probability method applies various statistical modelling techniques to all quantities required by the structural function, including any dependency between variates. These models are formulated into a single joint probability density function, which is integrated over all combinations of variate ranges that exceed a particular threshold to determine the exceedance probability. Hence, information from the structural function above the measurements is included. This method excludes temporal variations (e.g., sea-level rise or La Niña/El Niño) and the processes where independent events are merged into a single event. This very situation occurred at Narrabeen Beach in June 2007 where several independent (generated by different meteorological features) wave storm events that occurred in quick succession produce significant beach erosion. At Narrabeen, these events, in isolation, would not produce significant beach erosion. However, as there was limited time for beach recovery, subsequent events merely pick up from where the previous event left off. Consequently, excluding event merging is a significant limitation at Narrabeen Beach (and most likely other beaches). On a more practical note, it is very difficult, and often impossible, to determine the variate space that yields an outcome quantity that exceeds a particular threshold. For example, beach erosion is dependent on both the present storm parameters and antecedent beach conditions. Antecedent beach condition is very hard to describe in terms of just one or two parameters and is not typically measured like wave parameters and water levels. Hence, it is usually unavailable for inclusion into the joint probability density function. Consequently, it is impossible to determine the parameter space required to exceed a particular beach erosion volume.”

Callaghan et al (2008) then went on to adopt a technique that simulated the joint probability density function (i.e., that function determined in the JPM above), which consequently removed the temporal issues indicated when directly integrating the joint probability density function. To facilitate this extension, they introduced a storm arrival model (Poisson process) and included an accretive phase between storms to model beach recovery dynamics. This then yields antecedent beach conditions for each storm event, by considering the distance from equilibrium as the controlling parameter. This is similar to the approach later adopted by Yates et al., 2009.

5 Recommended model and model framework

An informed decision on the choice for morphological model to use for this project must also consider the ability for the model to be inserted into the chosen modelling framework. Similarly the choice of modelling framework depends on the model choice. Because of the two-way dependency, modularizing overall model system to enable seamless modification to either to choice for model or modelling framework is deemed important.

5.1 Model

It is recommended that the structural function be generated at least initially via the Time Convolution model (Kriebel and Dean 1993) due to its simplicity, fast computation time and physical basis. This model is capable of going to equilibrium, has a sensible computation time and a physical basis due to it being data driven. The use of the more complex semi-empirical SBEACH model should also be considered, as it can handle the desired event grouping of consecutive events, has the potential to include large-scale temporal processes and non-stationary processes such as climate change, and is more robust. The additional time and cost consumed in running a more complex model such as SBEACH must be contemplated – the most complicated model is not always the best approach. This will be combined with a longshore transport model based on the CERC equation, essentially following the EVO framework.

5.2 Modelling framework

5.2.1 Validation

At the Old Bar site, photogrammetry provides cross shore transects of beach and dune elevations dating back to 1940. These profile data extend from the shoreline well landward and provides a valuable historic sequence of the state of the dune and beach system. More recently, high resolution LIDAR of the beach and dune system was also measured. These data also contain some subaerial elevations of beach profiles, although limited by water turbidity. Additionally, hydrographic surveys were measured to provide the surrounding nearshore bathymetry.

These historical profile records are critical to develop and validate the morphological model. This temporal shoreline evolution hindcast demonstrates an excellent example of the deterministic approach where there is a single set of input parameters that results a unique outcome. These findings are necessary to develop the structural function for forecasting the beach response through probabilistic modelling. Rather than using a single set input parameters, probability distributions from the multivariate statistical analysis of forcing variables result in a probability for erosion.

5.2.2 Probabilistic Risk Analysis

Based largely on the previous recent success for similar applications (Callaghan, Nielsen et al. 2008, Callaghan, Roshanka et al. 2009, Callaghan, Ranasinghe et al. 2013, Wainwright, Ranasinghe et al. 2014), the full temporal simulation of the Joint Probability Method (JPM) for modelling storm erosion is suggested for this project.

6 Summary

This report provides an initial literature review of coastal morphodynamic models and model frameworks for the Bushfire & Natural Hazards CRC Project, Resilience to Clustered Disaster Events on the Coast – Storm Surge. It outlines the types of models and model frameworks presently available as practical tools for coastal management and reviews these with respect to their applicability to the Old Bar and Adelaide field sites. It recommends the project adopts the full temporal simulation of the Joint Probability Method (JPM) model framework as the most appropriate framework to achieve the model aims within the data constraints. Within this framework, the report recommends that a hybrid model of Kriebel and Dean for cross shore and CERC equation for longshore be adopted as the morphological model for sediment transport, beach profile evolution and shoreline translation modelling. The principal reasons for this choice of model are based on the model requirements outlined in section 2.3.

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