A NEW TOOL FOR IMPROVED COASTAL HAZARD MAPPING

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Abstract

WorleyParsons has recently completed development of the waterRIDE™ Coastal Hazard Toolkit in an effort to streamline the process for investigating vulnerable coastal areas. The Toolkit represents an advance in current coastal hazard mapping practice, in that coastal hazard lines can be output in GIS format for use by Councils in assessing development applications and by coastal managers to quickly and efficiently assess the impact of various scenarios for sea level rise. The Toolkit is based on the widely accepted storm erosion schema of Nielsen *et al* (1992) and uses available LiDAR data to construct GIS layers of coastal hazard lines quickly and easily. Data for mapping can be output at any spatial resolution limited only by the quality of the underlying data. The user can instantly assess the sensitivity of different values of storm erosion demand, long term coastal recession and sea level rise on the spatial location of the mapped erosion lines.

The waterRIDE™ software is currently in use by various consulting and government organisations for water resources applications and can be linked to a number of other software packages for interrogation of flood modelling results. Future developments include being able to run wave models for known offshore wave conditions and linking these to values of storm erosion demand, which can enable real-time forecasting of coastal erosion extents at the location of interest.

Introduction

Coastal erosion risk assessment mapping has been undertaken at many coastal sites in NSW, using a range of methodologies which reflect varying interpretations of the existing guidelines by various coastal engineering practitioners.

Typically, the quantification of coastal hazards assessed in the coastal risk assessments undertaken in NSW includes the following:

- beach erosion hazard;
- shoreline recession hazard;
- sand drift hazard;
- coastal inundation hazard;
- stormwater erosion hazard;
- climate change; and
- slope and cliff instability hazard.

Various techniques have historically been applied at different sites throughout NSW to quantify these hazards and present them in a format that can be used by coastal managers to set coastal management policy for their communities. Typically this has resulted in coastal hazard mapping which is a representation of the level of risk which nominally applies to an area of coastline. This level of risk has not been clearly defined at a Statewide level but is typically decided upon by the coastal managers and key stakeholders at each local area. The clear definition of coastal risk has to date been constrained by the availability of historical data, the lack of understanding of the complexity of the joint probability of occurrence of the various coastal hazards and the level of confidence in the hazard definition that can be obtained through the use of various data analysis techniques. Varying approaches have been used by different coastal practitioners which have been based on their individual interpretation of the coastal data and varying approach to the data analysis, which can lead to different mapping outcomes for the same nominal level of risk.

Historically, limited data has been available at the beaches in NSW to enable the coastal hazards to be quantified with a high degree of confidence. However, the quality and quantity of data has been steadily improving over time and the tools available to analyse this data have also improved, which has aided our understanding of coastal processes and enabled coastal engineers to refine estimates of coastal hazard risk. The ongoing improvement in quality and quantity of data and improved computing power has led to significant research effort being applied to our understanding of coastal processes, including the use of numerical models in an attempt to quantify the hazards under a probabilistic framework. This has been the approach used in the related field of floodplain risk management for the last few decades, but the added complexity of hazard definition in the coastal realm has restricted the application of a similar approach.

In a classical risk assessment, overall risk is assessed as the product of *likelihood* and *consequence*. This paper discusses the development of a tool for general use by coastal practitioners and managers that has the aim of linking defined risk likelihood levels to a measured consequence on the coast. The tool provides GIS output in a form readily adaptable into Council's databases. Future developments of the tool will enable the sensitivity of the coastal erosion hazard to varying external factors to be examined, including varying scenarios for sea level rise, variations in storm direction and intensity and eventually real-time forecasting of coastal erosion extents.

Representation of Coastal Hazards – Storm Erosion Demand – A unified approach

The principal coastal hazards that have been recognised for the NSW coast include:

- coastal erosion as a result of the impact of individual storm events
- shoreline recession as a result of local sediment budgets and morphological changes as a result of future sea level rise
- coastal inundation due to the impacts of wave runup and future sea level rise.

The basic framework for identifying the coastal hazards for mapping purposes has depended on the conceptualisation of the coastal processes and the representation of their impact on the ground.

In many coastal hazard studies undertaken in NSW, coastal erosion hazard has been conceptualised as a storm erosion demand, with a volume of sand removed from the beach. The erosion can be measured in terms of the volume of sand transported offshore or in terms of the landward movement of a significant beach feature (such as the back beach escarpment). The volume is usually expressed in terms of cubic metres per metre run of beach (m^3/m). During storms with relatively large waves, the beach is cut by storm waves with beach sand moving offshore to form bars in the surf zone. This process typically occurs over a period of hours to days. When extended periods of calmer waves occur, the material held in these bars migrates onshore to re-build the beach berm. Depending on the magnitude of the preceding storm, this beach building process can occur over a time scale of days to years.

The amount of sand that can be removed from a beach during a storm event (or series of closely spaced storms), and transported offshore, is referred to as the "storm demand" (Chapman at al. 1982).

Various estimates of the storm erosion demand along the NSW coast have been assessed by different practitioners since this concept has been applied for coastal hazard mapping. Gordon (1987) estimated that for the exposed NSW beaches the storm demand above 0m AHD for a 100 year ARI event ranged from $140m^3/m$ to $220m^3/m$. This estimate has been assumed and applied for some of the hazard mapping studies that have been undertaken in NSW.

The storm erosion demand can be assessed by direct comparison of measured pre and post-storm beach profile data often captured through photogrammetry. However, this technique is limited by the following factors:

- The length of the historical record – for beach profile data derived from historical aerial photography, the length of storm erosion demand record typically extends back to around the 1940's and only provides a "snapshot" in time as opposed to a continuous data record;
- The data is constrained by the dates of available photography – this means that often, suitable pre and post-storm photography is not captured which has led to a coarse estimation in some cases of what the storm demand attributable to a particular storm was.
- The level of spatial accuracy of the photogrammetry data itself.
- There have been limited storm occurrences in the historical record that can be linked to particular instances of storm demand.
- The joint probability of the factors which lead to a particular storm erosion demand is still poorly understood. These factors include:
  - wave height and period as well as the duration of the storm;
  - state of the beach before the storm;
  - joint probability of occurrence of sequential storms;
  - direction of the storm relative to the orientation of the beach;
  - magnitude of the storm surge accompanying the event;
  - amount of wave setup and runup on the beach during and immediately following the storm;
  - tidal range at the time of the storm;
  - state of the tide at the peak of the storm;
  - presence of rip cells;
  - presence and influence of local topography including adjacent headlands or coastal structures, or both, which can modify local wave and current conditions and the supply of sediment;
  - existence and strength of longshore currents;
  - sediment grain size of the beach and surf zone; and
  - for embayed beaches, the prevalent stage of the beach rotational cycle due to climatic variability (i.e. Southern Oscillation Index) impacts (Chapman et al 1982).

Despite the above limitations, the voracity of storm erosion demand estimates for use in hazard mapping has been improving over time. This is due to the following factors:

- Improved beach DTM data collection, including the collection of LiDAR data sets which provide a much improved vertical and spatial resolution when compared to historical photogrammetric techniques
- Continued data collection on wave height, period and direction as well as water levels – which has allowed us to estimate the joint probability of these key parameters and enabled storm characteristics to be directly related to storm erosion demand at many locations and for an increasing length of historical record
- Technological advances in computer technology, which has allowed a greater quantity of data to be processed and analysed quickly and efficiently.

The ongoing improvements in data accuracy, increasing length of historical record and improvements in computing technology have allowed research to be undertaken with the aim of improving coastal hazard estimation. In particular, numerical modelling techniques are being increasingly applied to capture the key physical processes which lead to storm erosion. Improved data collection is also allowing these models to be calibrated against measured storm erosion values.

Such an approach to determining storm erosion demand has been presented in Adamantidis *et al.* (2005), where storm erosion demand at Callala Beach in Jervis Bay was estimated using a combination of SWAN (Delft University of Technology 2011) wave transformation modelling and SBEACH (Rosati *et al.* 1983) modelling. Using known storm input parameters (for example time series of wave height, water level and storm duration representing a 1% AEP storm event) and calibrating the models against the measured impact of a known storm event, such modelling can be used to predict the storm erosion impact of an event with a known level of risk, which would allow coastal managers to choose the level of coastal risk that they deem acceptable for existing and future foreshore development based on an AEP approach.

Other practitioners have correlated measured storm demand against wave energy (WorleyParsons 2014). At Gosford, the SWAN wave transformation model was used to obtain wave height coefficients at various locations along each of the beaches in the study area, which allowed the calculation of wave energy at each location (as wave energy is proportional to H^2T^2). This allowed the wave energy at each location to be determined for a 1% AEP offshore storm event (which is relatively well defined based on collection of directional offshore Waverider buoy data). The assessment of wave energy at each location was plotted in a two-dimensional domain and correlated against storm erosion demand, with a good correlation obtained (Figure 1).

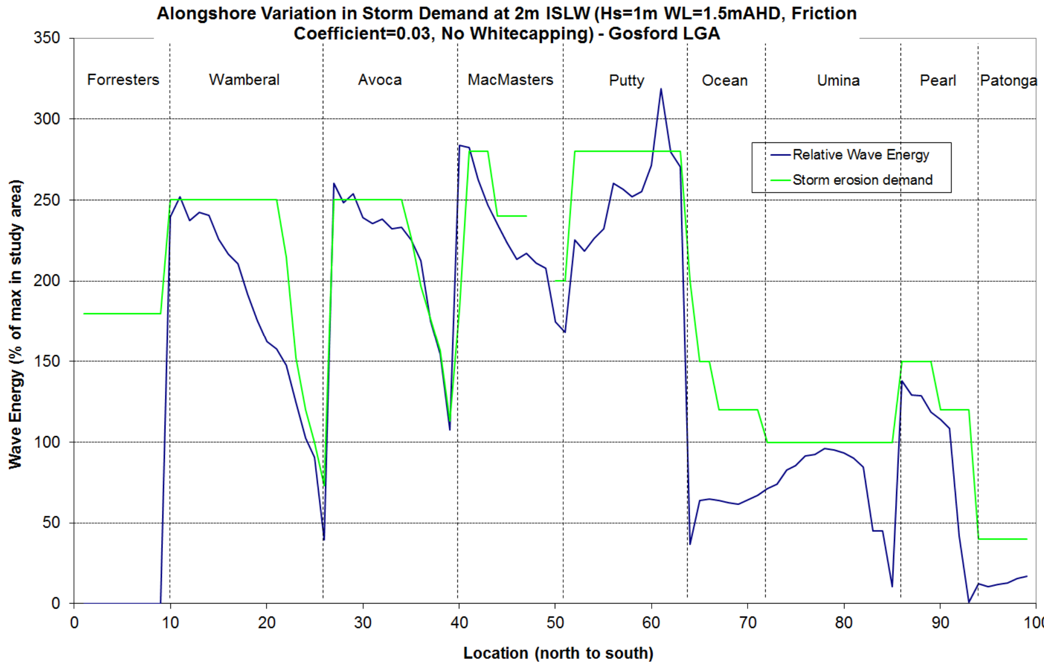

Figure 1 – Correlating modelled wave energy to storm erosion demand (WorleyParsons 2014)

Slope Stability and Reduced Foundation Capacity

Further to the immediate storm erosion hazard, there is a slope instability for sandy dune areas. Following storm cut the dune face dries out and typically slumps to its stable angle of repose. This results from the dune sediments losing their apparent cohesive properties that come from the negative pore pressures induced by the water in the soil mass. This subsequent slumping of the dune face causes further dune recession.

Dune slumping is treated as a slope instability hazard and can be quantified with stability computations, which can serve as a guide to determining safe setback distances on frontal dunes that are prone to wave attack and slumping during storms.
Typically in coastal hazard studies undertaken in NSW, the dune erosion hazard is defined as:

- a line delineating the limit of wave impact and dune slumping (*Zone of Wave Impact and Slope Adjustment*, refer Figure 2); and
- a line delineating the limit of the area behind the dune face where the capacity of the sand to support building foundations is reduced because of the sloping dune escarpment (*Zone of Reduced Foundation Capacity*, refer Figure 2).

The calculation of these lines relies on the following:

- An assumption about the pre-storm beach state – usually taken to be an "average" profile or "beach-full" conditions;
- Accurate beach DTM representing pre-storm conditions – increasingly LiDAR data is available for this purpose;
- Knowledge of the frictional properties of the dune sand – typically an angle of internal friction of $\phi = 34°$ is applied for dune sands;
- Knowledge of subsurface conditions – i.e. the presence of indurated sands or bedrock which would impact on the scour levels and hence the location of the *Zone of Reduced Foundation Capacity*;

- A design storm erosion demand volume to be applied to a particular beach precinct linked to a nominal level of risk, estimated based on published values, empirical measurements or numerical modelling;

The technique of using LiDAR data to map the coastal erosion hazards represents a significant advance with respect to coastal hazard mapping done previously using photogrammetric profiles only, for the following reasons:

- Photogrammetric profiles are often not oriented precisely shore-normal, leading to localised errors in defining the location of the hazard line due to the storm erosion demand being taken at an oblique angle
- Photogrammetric profiles are often located too far apart to provide good resolution over the beach, thus variations in hazard line location due to local topographic variations are not captured adequately
- Photogrammetric profiles are sometimes subject to large localised horizontal and vertical errors when compared with LiDAR data, including datum shifts.

An example comparison of the dune erosion hazard lines calculated using LiDAR data with those calculated using photogrammetry data for a typical dune area is provided in Figure 3.

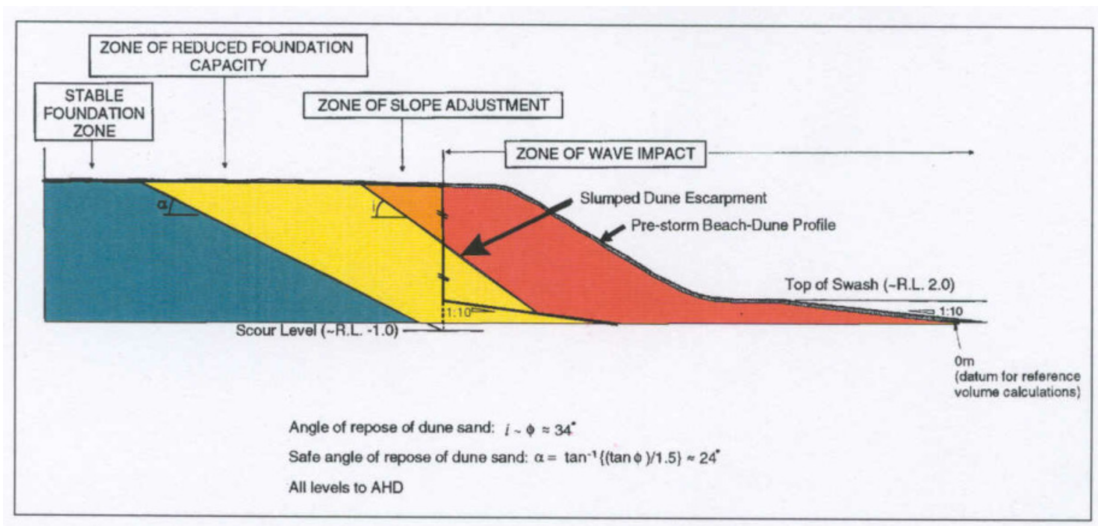

Figure 2 - Schematic representation of dune erosion hazard (after Nielsen et al, 1992)

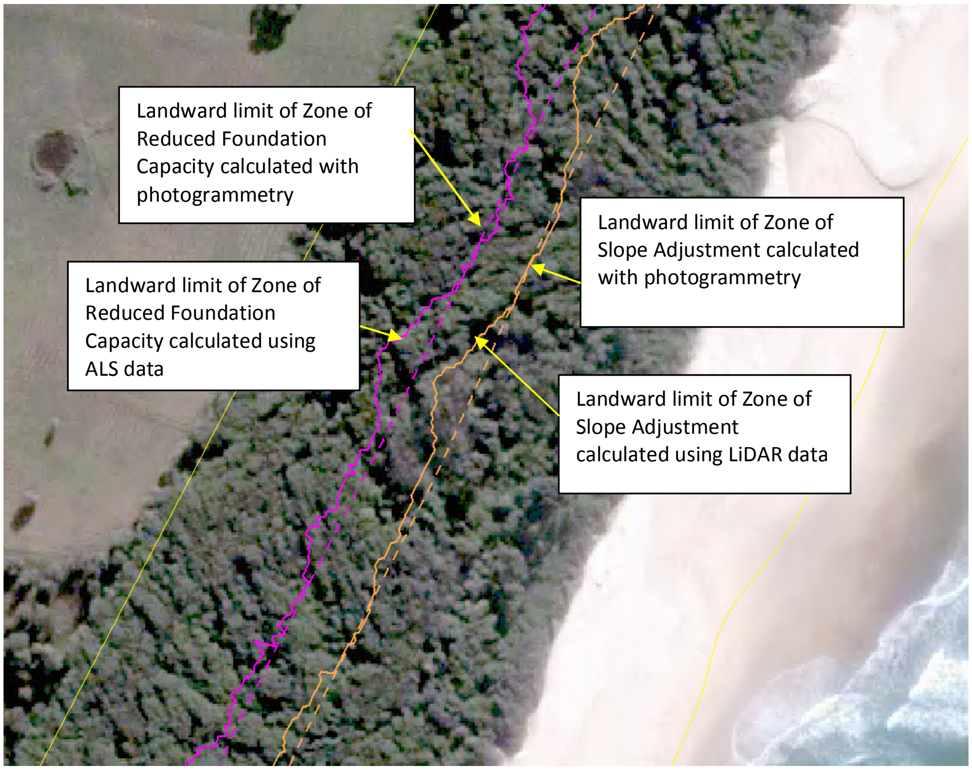

Figure 3 – Dune erosion hazard lines derived using LiDAR data vs. hazard lines derived using photogrammetry data

Long term beach recession and Climate Change

Long term recession due to net sediment loss is a long duration process (period of decades), and can lead to continuing net loss of sand from the beach system. According to the sediment budget concept, this occurs when more sand is leaving than entering the beach compartment. This recession tends to occur when:

- the outgoing longshore transport from a beach compartment is greater than the incoming longshore transport;
- offshore transport processes move sand to offshore "sinks", from which it does not return to the beach; and/or,
- there is a landward loss of sediment by windborne transport.

Shoreline recession is a long term process which is overlain by short term fluctuations due to storm activity. For coastal hazard mapping purposes in NSW, estimation of historical shoreline recession has been undertaken by analysing historical photogrammetry data, with measured long term trends often projected into the future. An understanding of the local coastal processes and sediment budget is required to assess the underlying causes of the observed trend.

Climate change will affect future erosion hazard in the following ways:

- Storm erosion demand may change in the future due to changes in wave climate, wave approach direction and storminess;
- Morphological changes to the beach profile would occur in response to sea level rise – this is often estimated using the Bruun Rule (Bruun 1954, 1962, 1983) and applying a "closure depth" based on the bathymetric profile and wave

conditions (Hallermeier 1978, 1981, 1983), or by use of a shoreline evolution model which takes into account longshore as well as cross-shore processes.

While there has been considerable research undertaken in recent years in quantifying the future response of the shoreline to sea level rise, there remains considerable uncertainty in predicting the quantum of future sea level rise and its potential impact on the coastline.

Future directions for coastal hazard assessment have been suggested by Kinsela and Hanslow (2013) to include probabilistic assessment techniques, such as statistical simulations, to consider the full range of uncertainty in historical measurements and future coastal processes and responses. To enable the response of the coastline to erosion and long term recession to be visualised quickly and efficiently in a probabilistic-type framework, a visualisation and GIS tool is required that can rapidly process multiple risk scenarios and output data in a format that can be readily adapted by coastal managers and integrated into Council databases.

Coastal Hazard Analysis Tool - Overview

WorleyParsons has recently developed the waterRIDE™ Coastal Hazard Toolkit in an effort to streamline the process for investigating vulnerable coastal areas and meet the goal of examining coastal hazards in a probabilistic framework. The tool allows the time-varying results of two-dimensional and three-dimensional models to be visualised and integrated with GIS data in a live GIS environment. The toolkit has built upon the existing flood manager geospatial interface, which currently includes a suite of hydrodynamic models, to include wave transformation models such as SWAN. The interface also provides an environment which allows the model infrastructure such as a finite element mesh to be built efficiently and simply. An example of a model finite element mesh constructed using the interface is provided in Figure 4. The interface enables time-varying output from such models to be interrogated at any point within the model domain, with the output able to be visualised and exported to an external GIS platform or spreadsheet application.

The analysis tool has been linked to the output from global oceanographic models such as BLUElink, HYCOM and WWIII which allows time series of oceanographic data to be extracted at any point on the globe without the need for complex pre-processing. This allows historical wave conditions to be estimated at any location globally even where wave data are scant or non-existent.

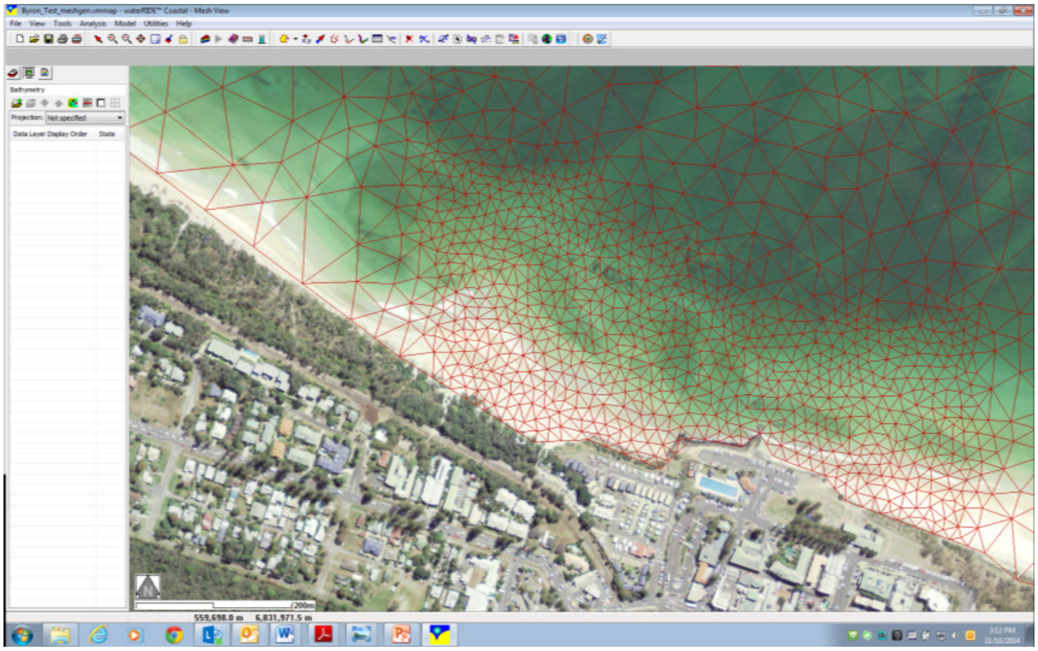

Figure 4 – Example finite element computational mesh generation

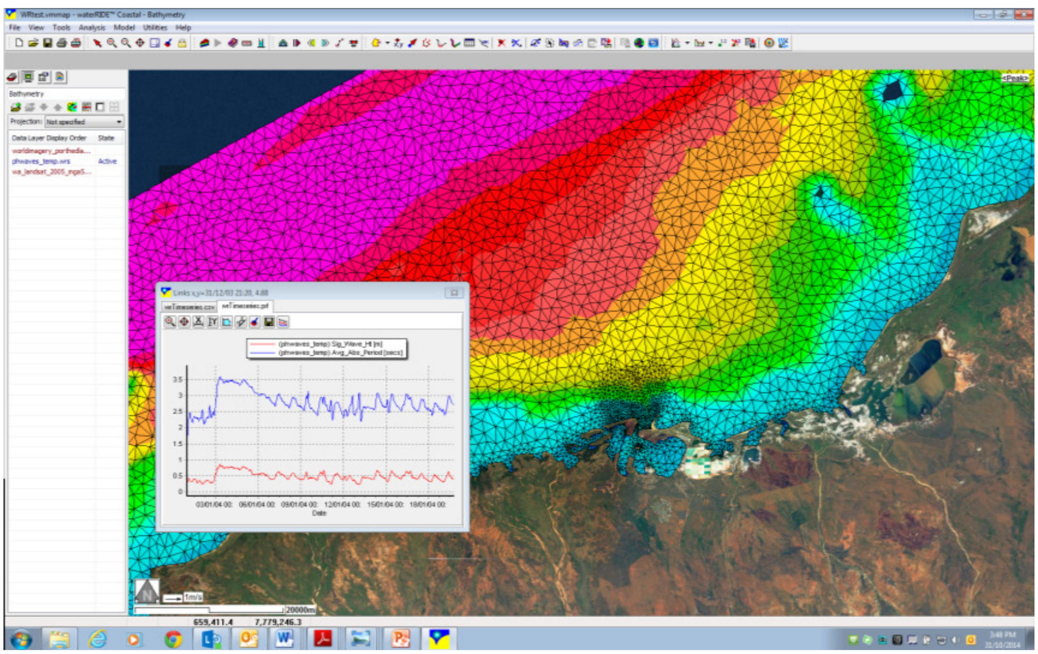

Figure 5 – Example SWAN spatial wave height model output and time-series output

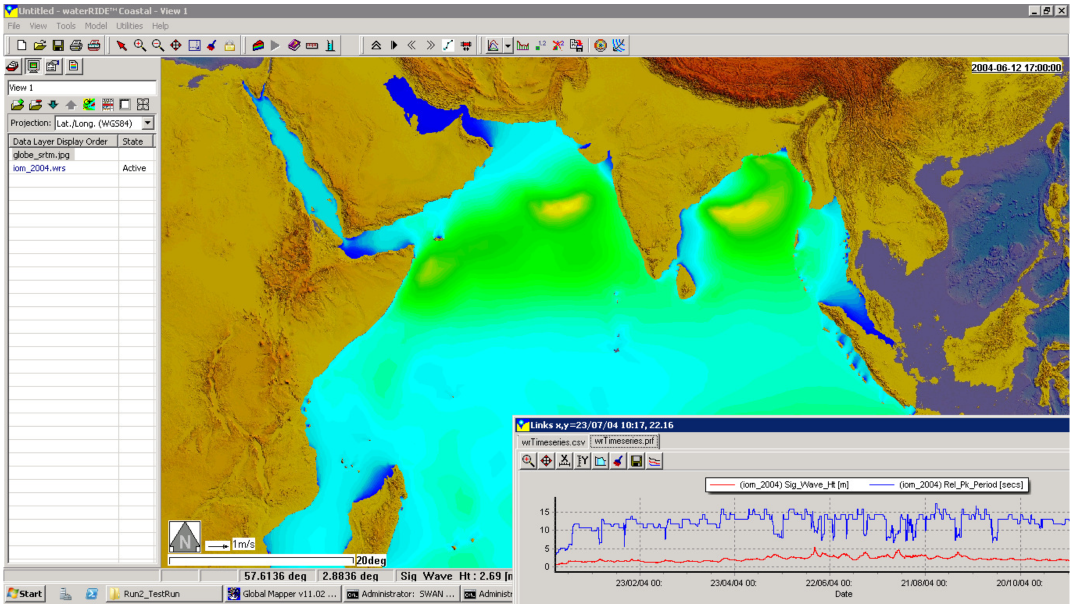

Figure 6 – Example extraction of time series from global oceanographic model data

Coastal Erosion Mapping Tool

The coastal hazard analysis tool has been integrated into the waterRIDE™ interface and provides instant visualisation of the coastal erosion hazard lines calculated based on the schema presented in Nielsen *et al.* (1992). The following steps are involved in the hazard mapping process:

1. Import raw terrain data into the program in the form of xyz ASCII data, in a known geographic projection – this data would ideally be based on LiDAR terrain data covering the area of interest.
2. Delineate a GIS polyline along the centreline of the beach for which shore-normal beach profiles are to be calculated from the base terrain data.
3. Enter the number of shore-normal profiles which are to be generated along a particular length of beach. This will be a function of the accuracy and density of available terrain data. For example, if LiDAR data are available a large number of profiles can be generated for a particular stretch of beach. This enables beach profiles to be generated at close spacings.
4. Enter the local value of storm erosion demand in m^3/m for a particular section of beach. Multiple program runs with varying values can be undertaken which allows probabilistic hazard lines to be generated instantaneously.
5. Enter values for top of swash elevation, scour elevation and friction angle of dune sand to be used in the calculation. For open-coast sandy beaches these values are well known published values (e.g. Nielsen *et al.* 1992) but the sensitivity of the analysis can be tested by varying these parameters.
6. Enter a value for beach recession in metres, which incorporates sea level rise recession. Multiple program runs with varying recession values can be undertaken which allows probabilistic hazard lines to be generated instantaneously.

The basis for the hazard line calculation is provided in Figure 6, and the input and output from the analysis is provided in Figure 7. The technique represents a considerable advance when compared with hazard mapping using traditional photogrammetry profiles for the following reasons:

- Photogrammetric profiles are often not oriented precisely shore-normal, leading to localised errors in defining the location of the hazard line due to the storm erosion demand being taken at an oblique angle. This problem is overcome as the program generates profiles that are precisely shore-normal;

- Photogrammetric profiles are often located too far apart to provide good resolution over the beach, thus variations in hazard line location due to local topographic variations are not captured adequately. This problem is overcome as the program is able to generate profiles at a spacing chosen by the user, and is only limited by the resolution of the underlying terrain data.

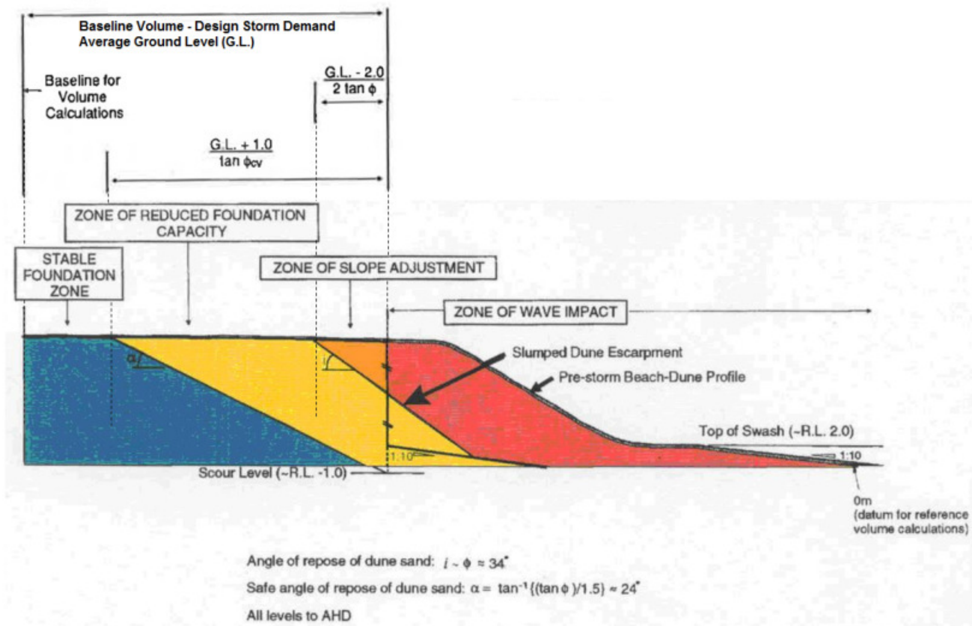

Figure 6 – Volume calculation in waterRIDE^{TM} for hazard mapping, after Nielsen *et al.* (1992)

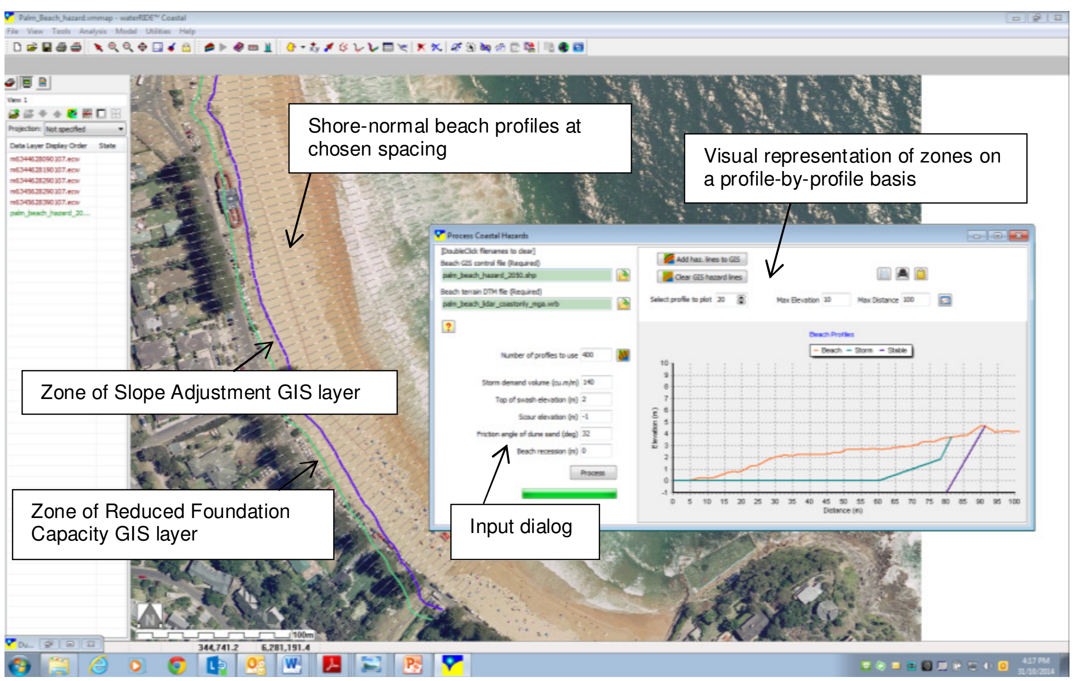

Figure 7 – Hazard mapping tool interface

The following additional advances are currently available within the tool when compared with standard analysis methodologies:

- The tool instantly produces GIS based coastal hazard lines that can be visualised against aerial photography and other GIS layers as well as being integrated into Council databases.
- The tool allows the visualisation of the hazard line calculation on a profile by profile basis for each of the generated beach profiles.
- Any planning horizon could be chosen for long term hazard forecasting.
- The tool is simple to use and can be implemented with minimal training, and sits as a module within the waterRIDE™ software package which is already owned by many Councils and government organisations, which makes it accessible to a range of users.

Future Directions

The following additional advances are being considered for integration into the tool and are currently under development:

- Real-time forecasting of coastal erosion hazard – linking wave transformation modelling based on offshore measured real-time wave data to storm erosion demand based on wave energy in the nearshore – wave energy has been shown to be reasonably well correlated with local storm erosion demand for Gosford's beaches (WorleyParsons 2014). The model-generated wave energy could be used to provide spatially-varying storm erosion demand estimates to the hazard mapping tool to estimate coastal erosion extents in real time or forecasting relating to an imminent coastal storm for emergency management applications.
- Incorporation of existing storm erosion modelling packages (such as SBEACH or XBEACH) within the waterRIDE™ interface to provide spatially varying estimation of storm erosion demand for use in the hazard line calculation.
- Incorporation of tools for estimation of long term shoreline response to sea level rise into the interface, such as the Bruun Rule (Bruun 1954, 1962, 1983) and the Hallermeier (1978, 1981, 1983) inner or outer zone limits or closure depth. This can be based on analysis of relevant data included in the waterRIDE™ interface, such as spatially varying wave height and bathymetry data based on LADS datasets.
- Incorporation of tools for historical data and photogrammetry analysis within the hazard mapping toolkit to improve the estimates of storm erosion demand and historical long-term beach profile change and calibration of storm erosion modelling.
- Incorporation of the ability to run multiple scenarios concurrently to produce a range of probabilistic hazard lines.

Kinsela and Hanslow (2013) advocate the use of a range of values for coastal erosion hazard components to enable the inherent uncertainty to be included in hazard definition. The coastal erosion hazard mapping tool presented here would allow the full range of values to be examined and a range of hazard lines to be instantly produced.

WRL (2012) have estimated generic coastal erosion hazard volume setbacks for the entire Australian coastline. With the use of existing terrain information available in databases held by organisations such as Geoscience Australia, these volumes can be converted to GIS coastal erosion hazard maps for all sandy coasts Australia wide, as part of a nationwide first pass assessment of coastal erosion hazard. The tool could also be used to develop coastal erosion hazard maps for remote locations where local wave data may be scant, due to the integration of global coastal wave forecast modelling such as HYCOM into the tool.

Conclusions

This paper has presented the application of a new tool that can be used to produce GIS coastal hazard mapping based on the analysis of terrain data and the application of storm erosion estimation methods that have been universally accepted in NSW.

Production of GIS maps based on coastal hazard calculations can be a time-consuming and laborious process, which is not conducive to adoption of a probabilistic approach to hazard mapping.

The tool presented herein allows the development and visualisation of coastal hazard lines in a format immediately useful to coastal managers and allows multiple hazard scenarios to be examined instantly and simply and within a risk-based framework. The tool presents a significant advance over existing coastal hazard mapping practice that takes advantage of the availability of improved data sets for coastal parameters including terrain, bathymetry, waves and water levels.

The tool has the potential to integrate coastal wave transformation modelling with the coastal hazard mapping which would allow real-time forecasting of coastal erosion extents for a section of coastline. Ongoing improvement and refinement of the methods for coastal hazard estimation would be possible through the use of such a tool and the ability to calibrate the results of the erosion mapping against measured data.

Critical to the ongoing development of hazard mapping technology will be the continued collection of coastal data and the ability for coastal managers to readily access to this data. The tool presented represents a significant step toward the stated goals of coastal management authorities in NSW that future coastal hazard mapping be undertaken using a unified approach, that the full range of uncertainties are taken into account and that the hazard lines are linked to a known level of risk, as is standard practice in the related field of floodplain management.

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