ASSESSING SHORELINE RESPONSE TO SEA LEVEL RISE: AN ALTERNATIVE TO THE BRUUN RULE

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Introduction

The Coastline Management Manual guided coastal hazard assessment in New South Wales for the last 20 years. In 2009 the NSW Government (DECCW) released its 'Sea Level Rise Policy Statement' and in 2010, *'Draft Guidelines for preparing Coastal Zone Management Plans'* (CZMP Guidelines), setting the minimum standard for assessing shoreline recession due to sea level rise and coastal erosion.

DECCW (2010) recognise the limitations of the nearly 50 year old Bruun Rule (1962) as a coarse first order estimate of recession due to sea level rise. DECCW (2010) noted the new techniques now available for assessing shoreline recession and erosion. This paper shall introduce the new techniques to the coastal management fraternity and demonstrate their superior predictive capacity over the Bruun Rule. Councils wishing to limit future liability from coastal hazards and climate change should make themselves aware of the new 'best practice' techniques.

First, a Shoreline Evolution Model (SEM) has been developed that includes the effect of headlands, reefs, breakwalls and other structures, the NSW wave climate and longshore transport in predicting recession due to sea level rise. The Bruun (1962) and Hallermeir (1981) equations cannot represent these three dimensional features. The SEM is able to predict spatial variations in recession along a coastline updrift compared with downdrift of headlands, and other structural effects.

Second, a Shoreline Response Model (SRM) capable of predicting storm erosion and recession due to sea level rise and climate change induced shifts in wave climate has also been developed.

Using examples from NSW (e.g., Coffs Harbour, Wooli), traditional models (e.g. SBEACH) and approaches are compared to the new techniques. Traditional approaches cannot account for existing variability in the wave climate over the medium term (decades), and are unable to account for future change in the wave climate combined with sea level rise.

Context for Using Available Techniques

The CZMP Guidelines have reiterated the responsibilities of local councils in undertaking Coastal Zone Management Plans, including coastal hazards definition studies. Councils who undertake coastal management actions in 'good faith' shall gain exemptions from liability under the *Coastal Protection Act, 1979*. Decisions are said to be made in 'good faith' where they are based upon the best available information and sound science, and this implies the use of the best predictive tools available to investigate coastal hazards extents. The hazards should then be incorporated into a risk-based coastal planning approach, to account for uncertainties in assessment techniques and climate science.

The capability of assessment techniques to provide the best available information is dependent upon the aim of the assessment (e.g. storm erosion for planning purposes, beach nourishment design), but also, the predictive ability of the assessment technique itself.

Empirical and modelling techniques are reviewed here primarily in the context of their capabilities in estimating the beach erosion and long term recession hazards at the current and future timeframes, as part of a coastal hazards definition study. The hazards definition directly influences future planning efforts, forming the basis of local/regional Coastal Zone Management Plans. Due to this, the hazard estimates must be suitable for planning purposes, particularly, for managing existing and future development in the coastal zone.

The CZMP Guidelines define beach erosion as the short term response of the sandy beach to waves and water levels during storms. This response may occur in relation to a single event or series of events in succession (DECCW, 2010). Shoreline recession is defined as the long term permanent landward movement of the shoreline in response to a net deficit in sediment budget over time (DECCW, 2010). This may be caused by an interruption in longshore sediment transport, lack of sediment supply, as a response to sea level rise, or a combination of these processes.

Available Assessment Techniques

There are a range of available assessment techniques, including empirical approaches and modelling approaches. The common techniques used in NSW for beach erosion and recession estimates include photogrammetric (and other data) assessment, SBEACH, the Bruun Rule, Hallermeier equations, and two new models, namely the Shoreline Evolution Model and Shoreline Response Model. The capabilities and limitations of each technique are summarised in Table 1.

Table 1 Comparison of Available Hazard Assessment Techniques

	Photogrammetry Analysis	SBEACH	Bruun Rule (1962)	Hallermeier (1981)	SEM (Patterson, 2009)	SRM (Huxley, 2009)
Cross-shore transport	Provides snapshots of beach state, thus shows outcome of combined transports, not separate transports. Analysis is limited by coverage of data both over time and along a beach.	Yes. This is done in 2D cross-section form, ignoring longshore effects.	Is an equilibrium cross-shore profile concept, but does not calculate transport under waves.	No. This equation only estimates the *depth of closure* term for use in the Bruun Rule.	Yes. Calculates transport outside surfzone and interchange of sediment across the closure depth.	Yes. Calculates transport within the beach and surfzone region.
Longshore Transport		No	No		Yes	Yes
Combined cross & longshore transport		No	No		Yes	Yes
Beach erosion hazard for planning purposes (i.e. including longshore processes)	Yes, but skill and care required to interpret data to separate data inaccuracies from short term (storm) processes, medium term wave climate variability, long term change (sediment deficit). Analysis is limited by coverage of data both over time and along a beach.	No. SBEACH cannot model shoreline evolution with longshore gradients.	No		Yes. The model can be applied to regional scale and individual beach units over long term or shorter time frames to calculate shoreline evolution.	Yes. This is the only model capable of modelling short term (hourly) to long term (up to 100 years) shoreline response. Capable of modelling recovery between storms, as well as storm erosion.

	Photogrammetry Analysis	SBEACH	Bruun Rule (1962)	Hallermeier (1981)	SEM (Patterson, 2009)	SRM (Huxley, 2009)
Storm Demand (e.g. during single design storm)	No. Data is too coarsely spaced (> 1 year) to capture erosion during a single storm event	Yes, but limited to cross shore component only. Longshore transport is ignored. Effects of rip cells are not included.	No		No.	Yes. Calculates combined longshore and cross shore transport during storms, to represent design storm effects along a beach unit. Effects of rip cells are not included.
Shoreline Response to Existing Wave Climate Variability	Yes, but care and skill required to interpret data for short, medium and long term signals must be separated. Analysis is also limited by coverage of data both over time and along a beach.	Analysis limited to cross shore component only. Longshore transport is ignored, thus errors in estimation are likely.	No		Yes. Model is run with time series (height, period and direction) representing existing wave climate	Yes. Model is run with time series (height, period and direction) representing existing wave climate
Shoreline Response to Future Wave Climate due to Climate Change	Limited projections are possible only where sufficient data is available to assess beach response to various wave climates. In most cases, coverage of data both spatially and over time would preclude such an assessment	Analysis limited to cross shore component only. Longshore transport is ignored, thus errors in estimation are likely.	No		Yes Model can be run with time series (height, period and direction) representing projected changes to wave climate with climate change.	Yes Model can be run with time series (height, period and direction) representing projected changes to wave climate with climate change.

	Photogrammetry Analysis	SBEACH	Bruun Rule (1962)	Hallermeier (1981)	SEM (Patterson, 2009)	SRM (Huxley, 2009)
Recession Due to Sea Level Rise	No. There has been a small rise in sea level over the prior 100 yrs (~ 10 cm), however this is within natural sea level variability (10 -15 cm on decadal scale). Further, data limitations limit assessment of such impacts.	Analysis limited to single profile response only.	Limited to unstructured open, long coastlines only. Concept is unable to account for regional longshore transport and effects of coastal structures. Likely to under- or over-estimate recession on shorelines with structural features that interact with longshore and cross-shore transport.		Yes. Regional scale simulations provide superior prediction of alongshore variation in recession, for example, enhanced recession at southern ends of beaches compared with Bruun Rule. The model includes features such as longshore transport (regional and/or local scale), back- barrier levels, headlands, seawalls, reefs and breakwaters..	Yes. Single beach unit scale simulations can model combined sea level rise and changes in wave climate, including enhanced recession at southern ends of beaches
Recession Due to Structures (e.g. breakwaters)	Yes. However, data limitations may limit the extent to which recession processes can be separated from other natural shoreline change in response to wave climate.	No	No.		Yes. Capable of modelling impact on shoreline of structures with and / or without sea level rise on regional / multiple beach unit scale.	Yes, within single beach units.

Empirical Approach using Available Data

Empirical methods involve the use of photogrammetry, beach survey, hydrographic charts, aerial photography, maps and geomorphological indicators to assess the beach erosion and shoreline recession hazards. Typically, the main component of available data is photogrammetry. Photogrammetry analysis requires experience to include or exclude data for accuracy (e.g. elevation inaccuracy from older photographs, sand mining, changes in vegetation height etc). Excluding inaccurate data, photogrammetry analysis then requires sound knowledge of coastal geomorphology to calculate and separate short term erosion and long term recession processes. For example, to recognise erosion scarps, features of the beach system such as incipient dunes, contemporary dune evolution, medium term beach cycles (accretionary or erosionary decadal cycles), ongoing permanent recession and so on.

Photogrammetric data cannot be used to estimate the storm demand occurring during an individual ‘design’ storm, because the dates of data are coarsely spaced in time (> 1 year between dates) and may not capture a ‘design’ event. However, for planning purposes, for example, deriving setbacks for housing development in the coastal zone, measuring erosion from a single ‘design’ storm event only involving water levels and waves does not fully describe the potential erosion risk. In addition to water levels and waves, the extent of beach erosion is also affected by the beach state prior to storm impact (e.g. eroded or accreted), wave direction, longshore transport processes and sediment bypassing of headlands, and the impact of consecutive, closely spaced storms.

The envelope of natural shoreline movement relating to climatic processes, rather than erosion from a single storm, is more appropriate for planning development setbacks. Photogrammetry and beach survey can provide a picture of the envelope of beach change. However this analysis is dependent upon the quality and amount of available data.

The assessment of long term recession with photogrammetry requires careful analysis and professional experience to separate short term storm processes, medium term shoreline variability from a permanent landward movement of the shoreline. An extended period (decade(s)) of wave climate promoting erosion may appear as long term recession in the photogrammetric data, but may actually be part of a cyclic, reversible process. For example, when photogrammetric data was reviewed in the late 1980s after the stormy decade of the 1970s, many NSW beaches were determined to be receding. From the 1980s to ~ 2007, a number of NSW beaches have demonstrated prolonged accretion, with the growth of incipient dune features (for example, Bongil Beach, Moonee Beach and Station Beach in Coffs Harbour and the majority of Wollongong’s beaches). When all of the data is combined, the assessment indicates such beaches to be stable.

Empirical analysis is dependent upon data availability both over time and spatially along the beach. Analysis with photogrammetry is limited by the number of reliable surveys, the timing of surveys in relation to wave climate and storm events, and the extent of beach measured. Photogrammetric data provides only snapshots over time, and greater extents of change (erosion, accretion) than captured by the data are possible. All but very few beaches have fongoing and regular beach survey programs (e.g. Narrabeen, Moruya).

Where data is limited to develop clear conclusions, modelling may assist in data interpretation and prediction for hazard extents. The limitations in the historical data also limit the ability to define the likely shoreline response to a higher sea level and modified wave climate in the future due to climate change. Once again, new modelling techniques such as the Shoreline Evolution Model and Shoreline Response Model are capable of providing predictions of future shorelines in response to climate change.

SBEACH

The Storm-induced BEAch CHange model (SBEACH) is a numerical model developed in 1989 by the US Army Corps of Engineers for estimating erosion of the beach, berm and dune by storm waves and elevated water levels. SBEACH is a two-dimensional (in profile cross section) cross-shore transport model. The erosion of beach to dune is based on the concept of an equilibrium cross-shore profile occurring during storm events. The primary application was for the design of volumes for beach nourishment projects, such as calculating the beach profile response of alternative beach nourishment designs to storms of varying intensity.

In Australia, it has often been used to estimate the “storm demand” of a single ‘design’ storm event, to form the basis of the beach erosion hazard for subsequent use in coastal planning. As stated by the model’s developers (Wise, et al., 1996),

> *“A fundamental assumption of the SBEACH model is that profile change is produced solely by cross-shore processes, resulting in a redistribution of sediment across the profile with no net gain or loss of material. Longshore processes are considered to be uniform and neglected in calculating profile change. This assumption is expected to be valid for short-term storm-induced profile response on open coasts away from tidal inlets and coastal structures”*

SBEACH is an effective assessment tool for certain applications. However, it has often been criticised for underestimating storm erosion demand, and this relates to the key assumptions given above. In the USA, SBEACH is widely reported to have inaccurately predicted volumes required in beach nourishment projects, underestimating the volumes required for ongoing programs or the time between subsequent nourishment operations (e.g. Pilkey, 1994; Libbey et al., 1998). In Australia, the program is also reported to underestimate potential storm erosion, compared with measured data.

One key reason for such underestimates is that SBEACH does not include longshore transport in erosion estimates, treating the surfzone as a two-dimensional system. Longshore processes are a very important component of sediment transport during short term storm events. For a storm arriving from an oblique direction, the ‘protected’ end of the beach will be eroded as sand is transported alongshore by oblique waves to build sand bars at the opposing ‘impacted’ end of the beach. This is not represented in SBEACH storm erosion calculations.

As for other one-line and 2D cross-shore models, SBEACH also cannot represent rip currents. The landward end of rip currents are often the site of the largest erosion extents, for example, the highest recorded erosion extent at Wamberal Beach of 240 m^3/m after the 1978 storms (NSW Government, 1990).

It is questionable whether SBEACH is an appropriate tool to estimate storm erosion for planning purposes at beaches, where shoreline change (accretion, erosion, rotation) is affected by longshore transport processes (regional or within individual embayments) as well as cross-shore processes, interacting with coastal structures and headlands.

The Bruun Rule (1962)

The Bruun Rule (1962) concept is that the entire beach profile will shift landward and upward in response to a rise in sea level. The Bruun Rule concept is illustrated in Figure 1 below.

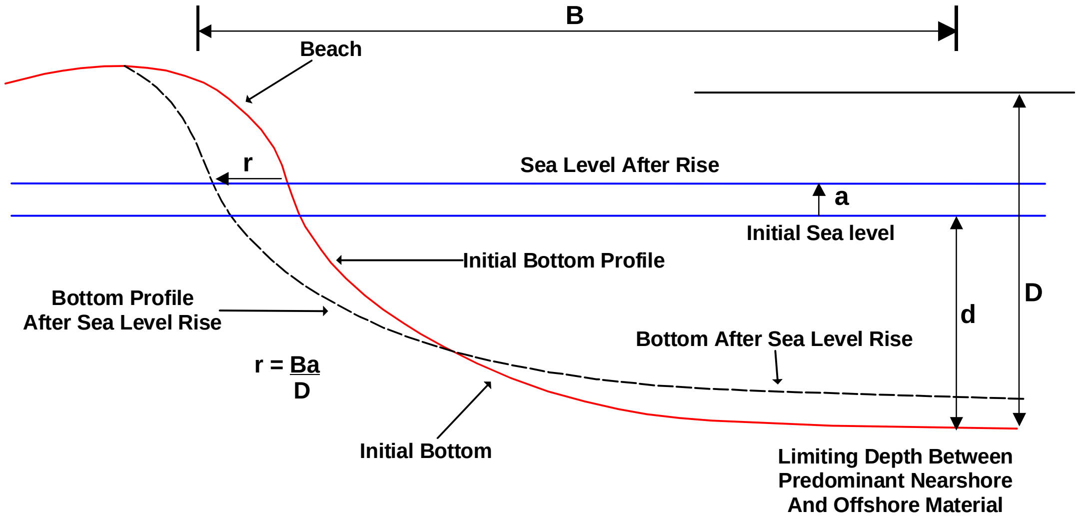

Figure 1 Bruun Rule for Shoreline Response to Rising Sea Level

Shoreline recession predicted by the Bruun Rule is given by:

$$r = \frac{Ba}{D}$$

where *a* (metres) is the sea level rise, *B* (metres) is the width of the bottom influenced by the sea level rise extending to *d* (metres), where *d* is the depth of closure or offshore limit of transport, and *D* (metres) is the depth to closure including the dune height. Both *B* and *D* can be calculated from the nearshore profile once *d* is known.

As cited in Ranasinghe et al. (2007), it is generally agreed by the scientific community that the Bruun Rule concept of a landward and upward shift in cross shore profile in response to sea level rise is valid. However, Figure 1 illustrates the problem with this approach in that it depends substantially on how the changes at the depth of closure are dealt with. The extent of recession calculated with the Bruun Rule (and various modifications to the equation) has not been successfully validated. The Bruun Rule is at best an ‘order of magnitude’ estimate, as there are very few coastlines at which longshore transport and structures can be ignored to satisfy the key assumption of a cross-shore profile response only (Ranasinghe et al., 2007). DECCW (2010) note that the Bruun Rule should be considered a ‘coarse, first-order approximate’.

The limitations of the Bruun Rule as summarised from Ranasinghe et al. (2007) are outlined below.

- The Bruun Rule does not include three dimensional variability, as it assumes two-dimensional (cross-shore) sediment movement only, therefore, the rule does not include alongshore gradients in longshore transport (such as a regional transport rate); alongshore features or structures such as headlands, engineering structures and nearshore reefs that control the shoreline shape due to their impact upon sediment transport; or estuaries/inlets which may act as both source and sink for sediments in the nearshore zone.

- The Bruun Rule is only applicable on ‘equilibrium’ beach profiles, that is, it is not applicable at beaches where there is ongoing profile change (for example, the profile is still evolving to the most recent rise/fall in sea level, or change in sediment supply)
- The Bruun Rule assumes there is no sediment movement (such as offshore sediment loss) seaward of the depth of closure
- The Bruun Rule does not allow for a majority of fine sediments in the dune, which when eroded would be too fine to deposit and remain in the nearshore, and it does not allow for variations in sediment between the nearshore, beach berm and dune.

Hallermeier (1981, 1983)

A key input to the Bruun Rule is the depth of closure term, which is defined as the depth at which exchange of sediment between the nearshore and offshore is effectively zero. That is, the depth of closure is said to be the limit of nearshore sediment transport processes. Where nearshore bathymetry is not available to calculate the depth of closure, one method commonly used to estimate the depth of closure are the Hallermeier equations (1981, 1983). Thus, the Hallermeier equation does not add to or enhance the Bruun Rule concept, but provides an input to that equation.

Hallermeier depicts a shore normal beach profile in terms of three regions separated by two depth values, d_s that defines the depth limit of the littoral zone and d_0 that defines the depth beyond which shore normal sand transport processes may be considered negligible. Typically the latter term is the depth of closure value applied in the Bruun Rule. Inputs to the Hallermeier equations include local offshore wave climate (annual average significant wave height and wave period, 1 year recurrence interval 12 hour duration wave height), median sediment grain size, specific gravity of the sediment and acceleration due to gravity.

The need to estimate the depth of closure, such as with the Hallermeier equation, adds an additional factor of potential error in estimates with the Bruun Rule.

The Shoreline Evolution Model – A New Technique to Predict Recession due to Sea Level Rise

A Shoreline Evolution Model (SEM) has been developed by Dean Patterson (BMT WBM). The model has the capability to simulate short to geological time-scale coastline evolution including minor to major sea level change (0 to 100 m). Patterson developed the Shoreline Evolution Model as part of his current PhD studies investigating Pleistocene to Holocene evolution of the Far North Coast of NSW. It uses a quasi-2D extension of the conventional one-line shoreline representation to include cross-shore as well as longshore sand transport. A schematic of the model domain is given in Figure 2.

The effects of coastal structures such as headlands, nearshore reefs, groynes and seawalls are included. These processes and factors, together with the assumption of maintenance of an equilibrium shape to the upper beach and dune over the longer term are used to predict the shoreline response to sea level rise (Patterson, 2009).

The SEM uses a time stepping approach to drive shoreline evolution in response to deep water wave time series data and sea level. The model internally refracts waves from deep water into the near shore zone and calculates longshore sand transport at each longshore grid location using the standard longshore transport equation of CERC (1984).

The model is particularly effective at a regional scale, able to model multiple beach units along long coastlines. The model provides for shoreward sand transport and profile evolution below the depth of closure and accounts for cross-shore exchange of sand into and from the active upper beach zone above the depth of closure. The exchange is initiated by changes in the profile slope as the profile evolves, as shown in Figure 3.

The SEM allows input of variable back-barrier dune levels, important where sea level rise causes roll-back of the dune system, thus incorporating their effect on shoreline recession. As a result, it offers substantial advantages over the simple Bruun Rule (1962) for typical beaches along the NSW coastline.

By comparsion, the Bruun Rule will grossly under-estimate the potential for erosion at the southern ends of beach units with northward net longshore sand transport. An example of this at Coffs Harbour is given in Figure 4. As the sea level rises, headlands act to trap northerly sediment transport within each embayment, with the southern end of each beach starved of its full longshore supply. The southern end of each beach unit thus experiences enhanced recession. In contrast, the supply from the southern end of the beach is trapped by the bounding northern headland, reducing shoreline recession due to sea level rise at the northern ends of beaches.

The model caters for the impact of sea level rise upon shorelines in the lee of reefs. Sea level rise will tend to submerge reefs that are close to the current sea level and allow greater wave impacts at the shoreline in lee of the reef. This will lead to enhanced erosion of salients and reef-protected shorelines. Once again, the Bruun Rule cannot account for this structural effect from sea level rise.

The model can be used to assess the impact of coastal works such as structures (groynes, training walls and seawalls) and beach nourishment on sandy shorelines with or without sea level rise. For example, the model was used to investigate the impact of the harbour breakwaters at Coffs Harbour on updrift and downdrift beaches over the last century. Outputs from the model as given in Figure 5 illustrate the extensive accretion upon Boambee Beach updrift of the harbour. Downdrift of the harbour, the shoreline recedes, initially at Park Beach and sequentially at beaches further northwards over time. The erosion at Park Beach is limited by bounding headlands, progressively transferring the impacts to beaches further north, to meet the longshore supply of the shoreline. At the same time, Boambee beach continues to accrete until the shoreline has built out to such a level that bypassing of the harbour may commence. The model results were compared against the photogrammetric data at Boambee and downdrift beaches such as Park Beach, Campbells Beach and Sapphire Beach. The model results showed good agreement with the historical data. The model results suggested the impacts to Park Beach have slowed in recent years, while harbour impacts continue to migrate north and are beginning to impact upon Moonee Beach. The photogrammetry data confirmed these trends.

A key capability of the SEM is the ability to investigate the impacts of sea level rise in combination with the harbour structure. This is demonstrated in Figure 6. The rise in sea level tends to ‘re-initiate’ the harbour impact to the downdrift coastline. Thus, greater extents of erosion occur at Park Beach than can be predicted with the Bruun Rule alone. As such, The SEM provides a significant advance on the Bruun Rule

(1962) in predicting shoreline recession due to sea level rise and structural features, as it is able to account for the three dimensional nature of the coastline.

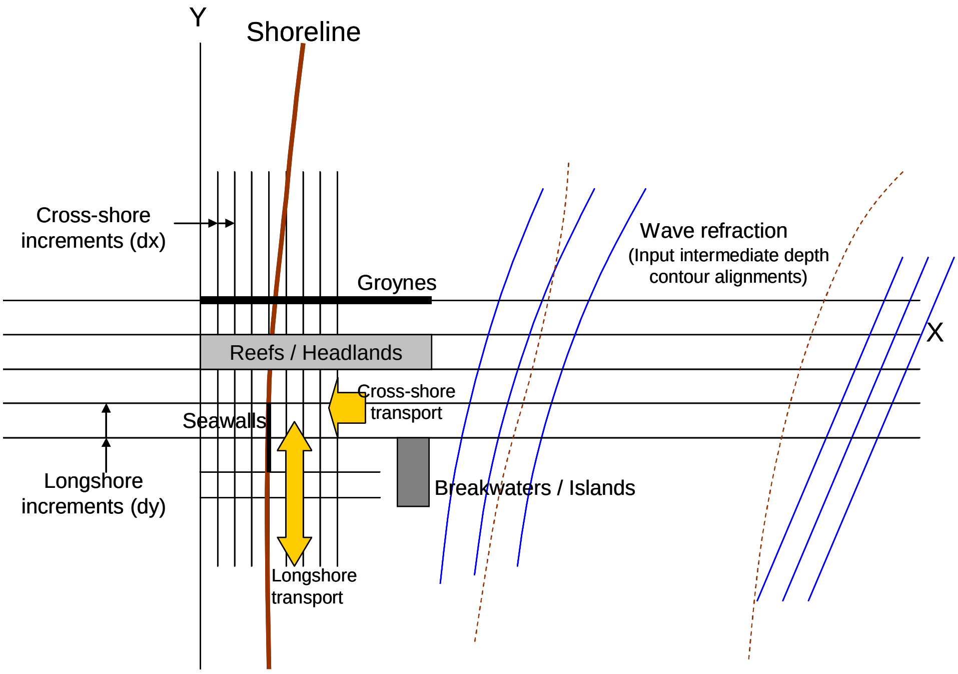

Figure 2 Plan View Schematisation of Shoreline Evolution Model Domain

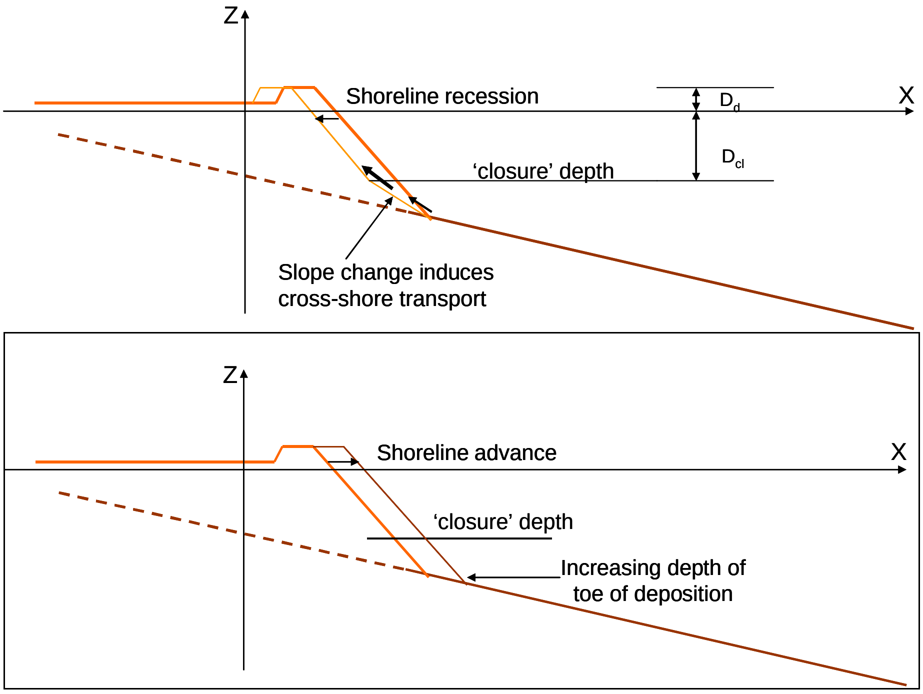

Figure 3 Cross-shore Profile View of Shoreline Evolution Model Domain for Erosion (top) and Accretion (bottom)

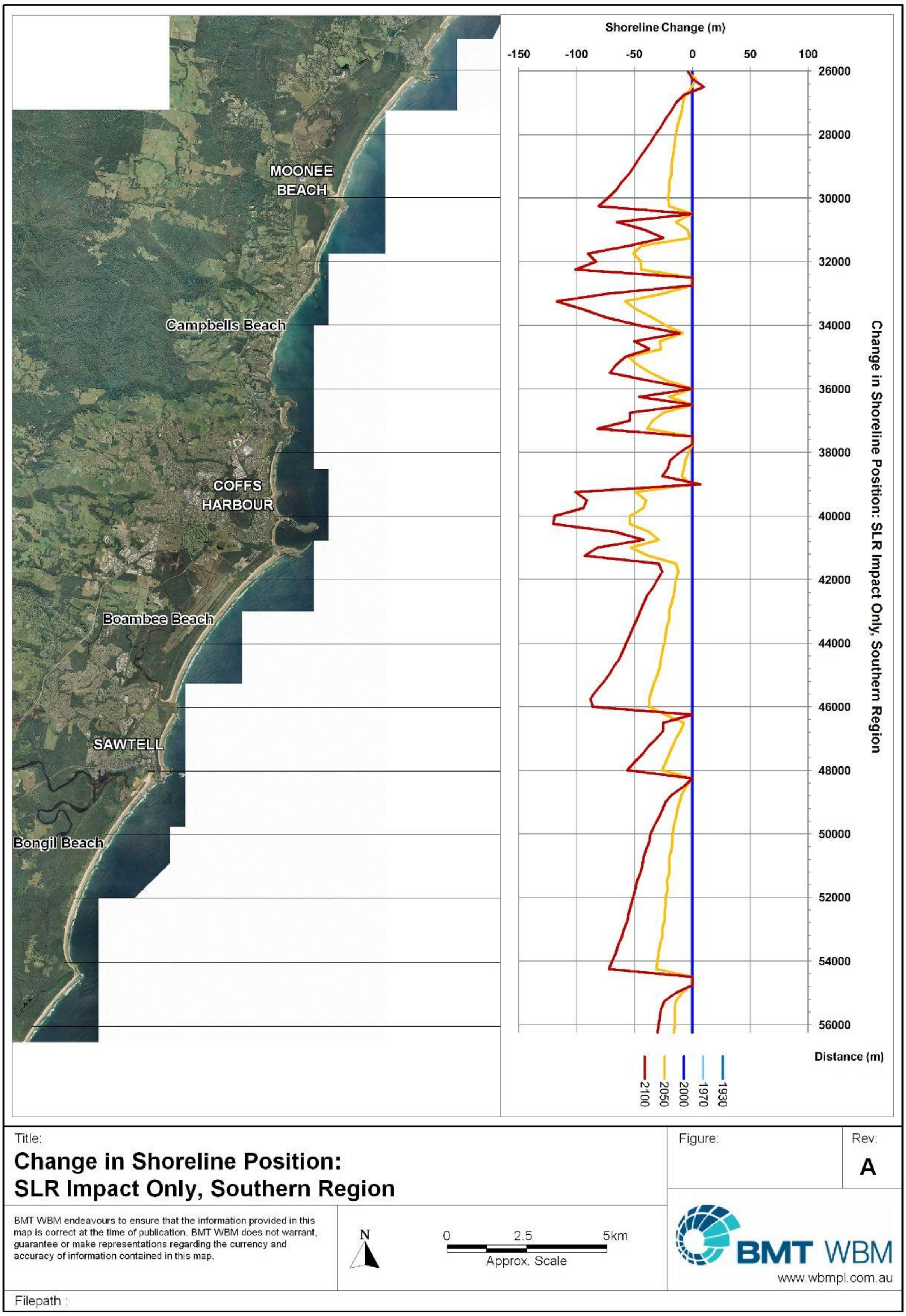

Figure 4 Recession due to Sea Level Rise Only with the Shoreline Evolution Model, Southern Coffs Coastline

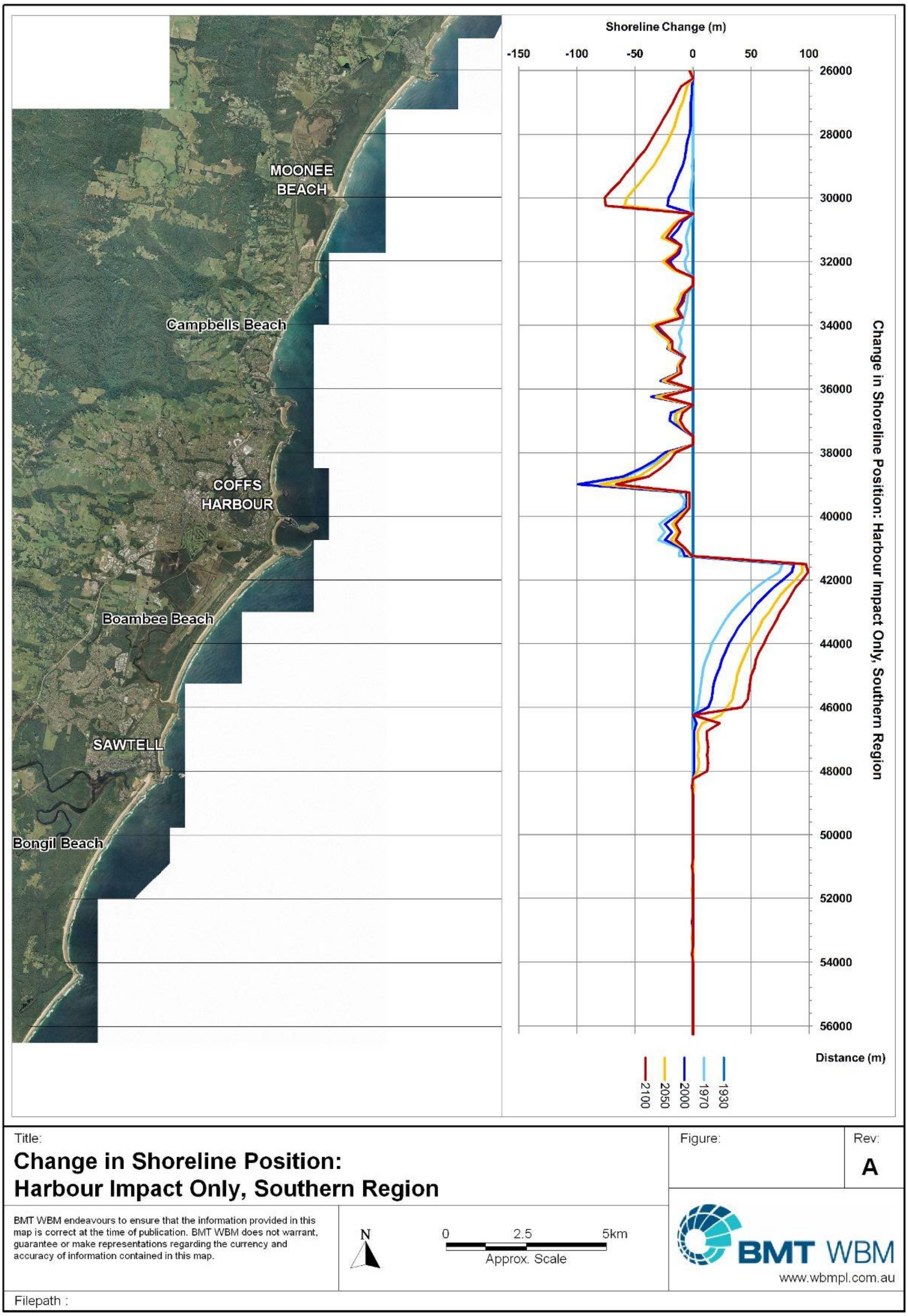

Figure 5 Recession due to the Coffs Harbour Structure (without Sea Level Rise) with the Shoreline Evolution Model, Southern Coffs Coastline.

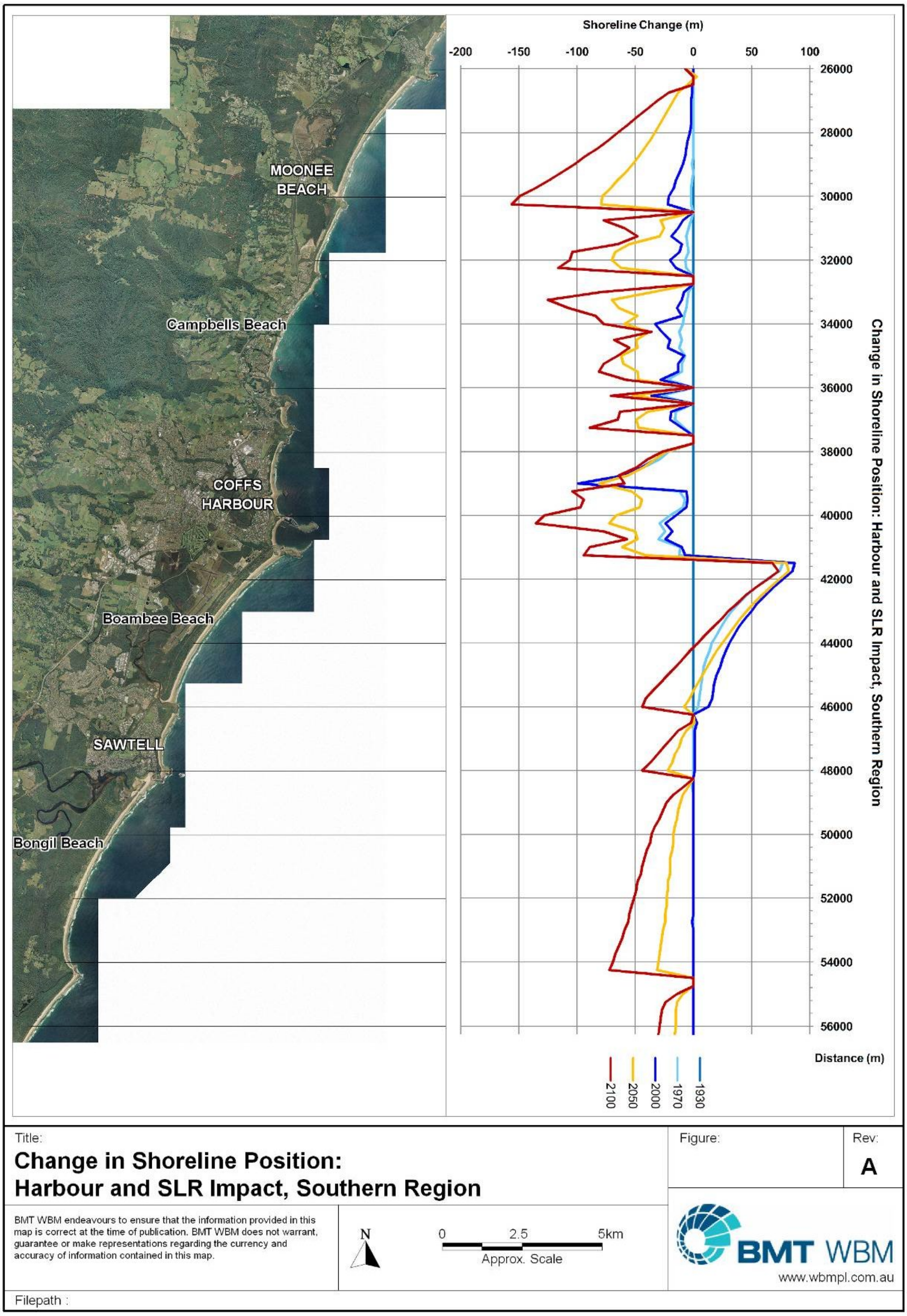

Figure 6 Recession due to the combined impact of Sea Level Rise and Coffs Harbour, Southern Coffs Coastline

The Shoreline Response Model (SRM) – A New Technique to Predict Recession and Erosion due to Wave Climate Change and Sea Level Rise

BMT WBM's Chris Huxley, in association with DECCW developed the Shoreline Response Model (SRM) (Huxley, 2010), which predicts shoreline response to the combined impact of wave climate variability (height, direction) and sea level rise under a future climate. This model is able to estimate the change in shoreline width and orientation, by calculating both the longshore and cross shore sediment transport in response to wave height, wave direction and water level, including sea level rise.

The SRM is the first model of its kind to combine both longshore and cross shore sediment transport processes to estimate the response of the beach (erosion and rotation) to the combined impact of short term storm events, long term wave height and direction change and sea level rise. The model is able to simulate shoreline response for hourly events (storms) as well as shoreline evolution over 100 years. Figure 7 and Figure 8 show schematic representations of the cross-shore and longshore model domains which form the basis of the SRM model.

The model uses a time-stepping approach to predict shoreline change resulting from changes in both the cross shore and longshore sediment transport. On an hourly timestep, the model uses water level (tide, surge and sea level rise) and wave input (significant wave height, period and direction) to calculate shoreline response due to both cross shore and longshore sediment transport processes (Huxley, 2009). The dynamic linking of the cross shore and longshore sediment transport processes results in a useful modelling tool, well suited to the assessment of climate change impacts resulting from the combined impact of both sea level rise and wave climate.

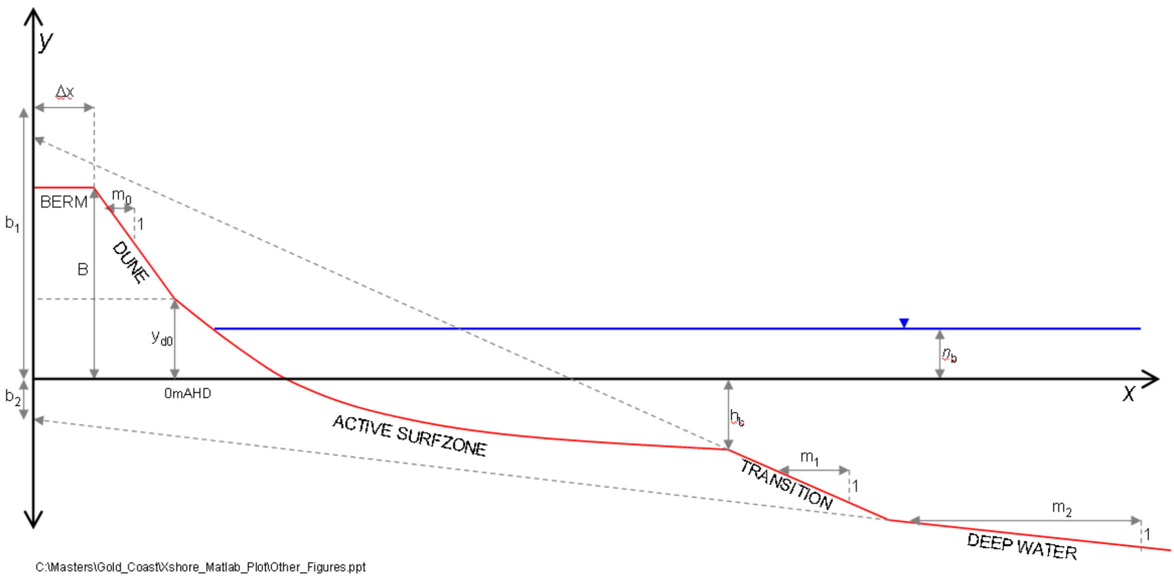

Figure 7 Cross-shore Profile View of Shoreline Response Model Domain

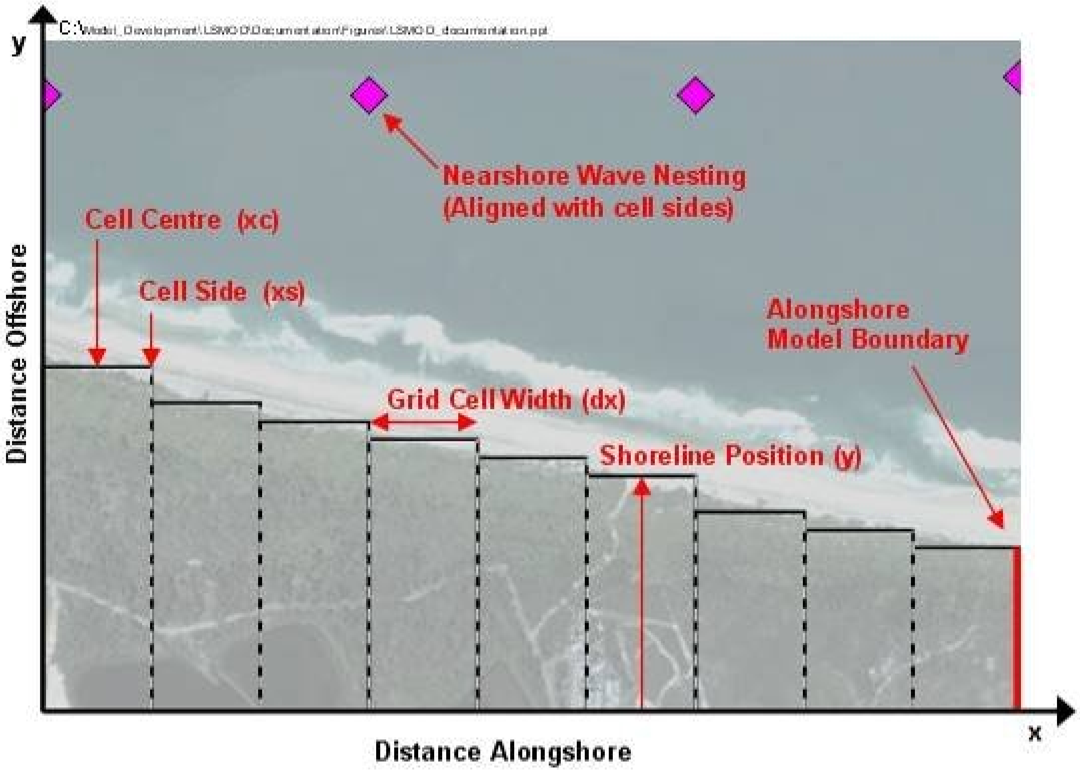

Figure 8 Plan View Schematisation of Shoreline Response Model Domain

The SRM is capable of predicting shoreline response (particularly beach erosion and shoreline recession) to climate change driven forcings, most importantly (Huxley, 2009):

- Sea level rise;
- Changes in wave direction;
- Changes in swell wave height; and
- Changes in storm wave height and occurrence.

An assessment of the shoreline response to changes in the above forcings at Wooli Wooli Beach (NSW North Coast) and Batemans Bay (NSW South Coast) has been completed using the SRM model as part of the DECCW funded NSW Coastal Zone Climate Change Impact Study. Figure 9 to Figure 11 present some of the historic and climate change shoreline response assessment results from the Wooli Wooli Beach Assessment.

Further validating the shoreline response trends shown in Figure 6 for the Coffs Harbour coastline using the SEM, the Wooli Wooli Beach assessment indicates that shoreline response to sea level rise for littoral drift dominated coasts (northern NSW) is non-uniform alongshore. The results indicate that beach sections immediately downdrift from major headland/groyne controls are likely to experience the greatest shoreline recession due to climate change induced sea level rise. For Wooli Wooli beach this results in increased shoreline recession at the southern end of the beach unit. These results highlight the need for detailed assessment of the impact of climate change accounting for combined cross-shore/longshore sediment transport processes.

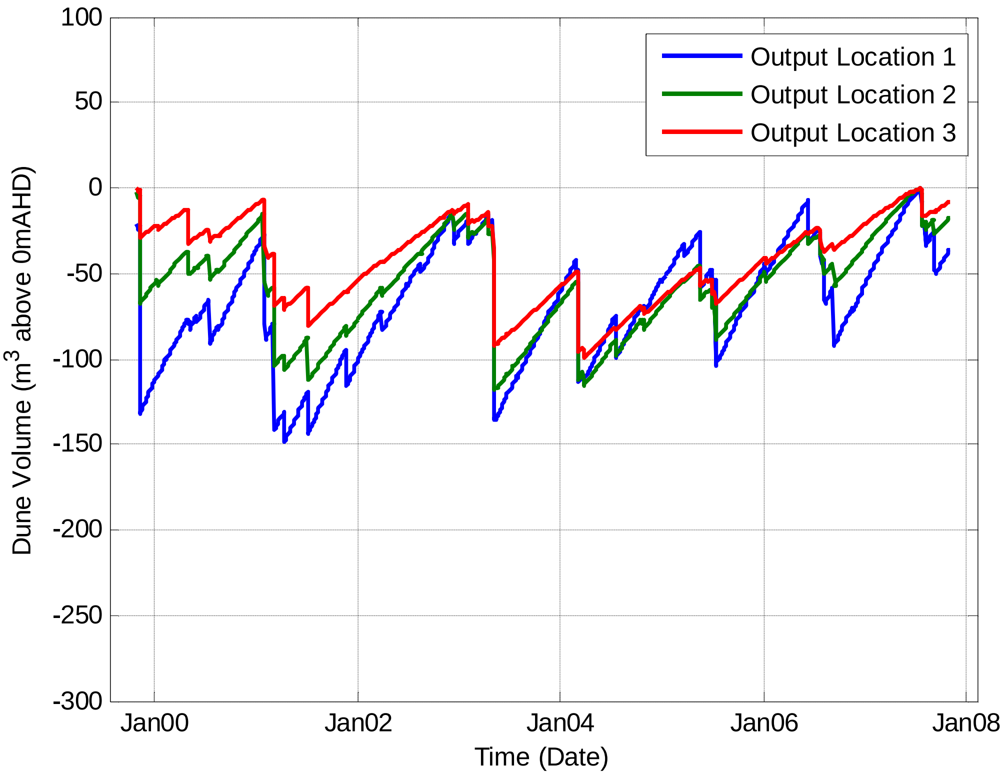

Figure 9 **Historic Shoreline Responce Assessment Results: Dune Volume – Wooli Wooli**

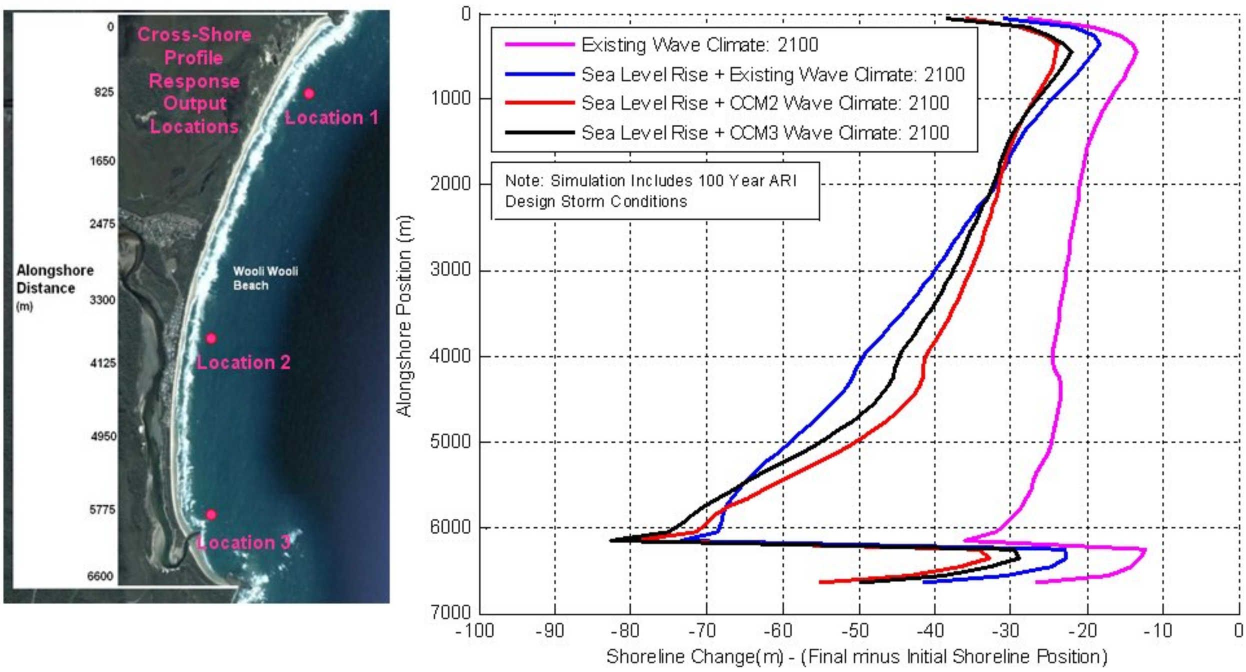

Figure 10 **Varied Wave Climate/ Sea Level Rise Shoreline Response Results – Wooli Wooli Beach**

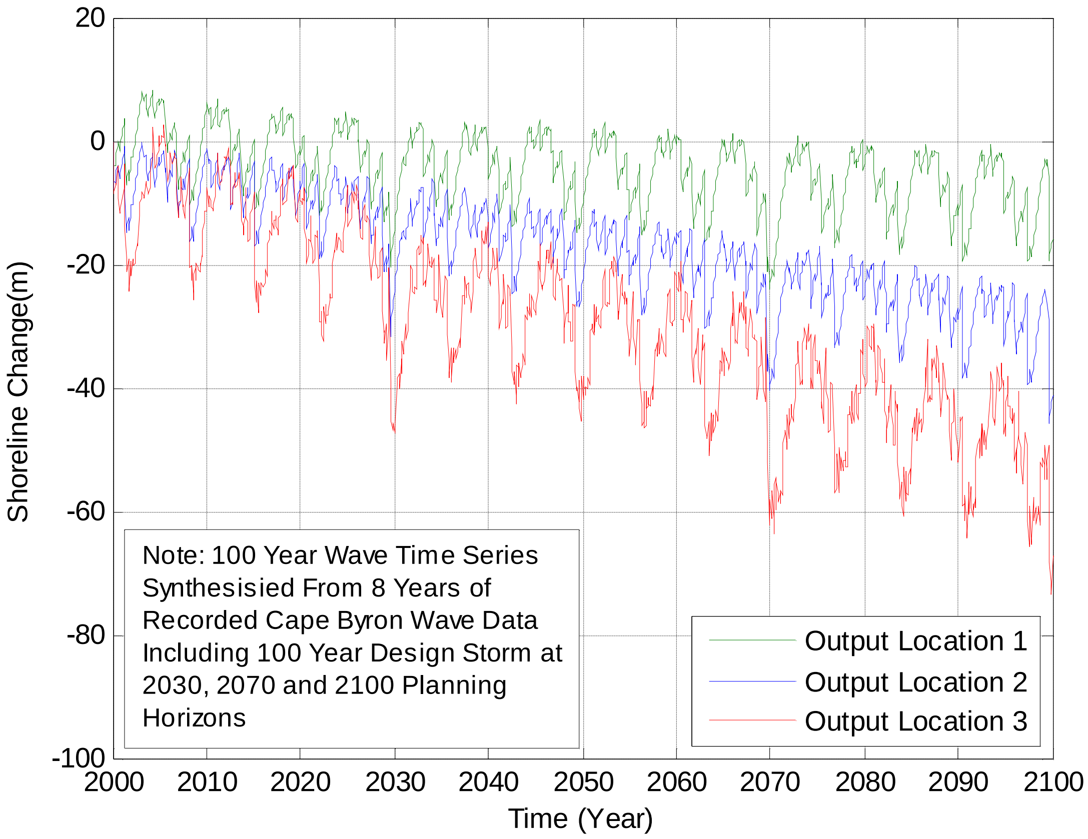

Figure 11 Sea Level Rise Scenario Only Assessment Results: Shoreline Position – Wooli Wooli

Accounting for Uncertainty in Shoreline Change Assessments

The coastal zone is highly complex with many processes interacting independently and dependently to various extents. Science is improving, but not yet able to represent all of these processes. Climate change adds further to the uncertainty in assessing coastal hazards, with uncertainty not only in projections for sea level and wave climate, but in the extent and timeframe of impacts this may have in the coastal zone.

Given this complexity, assumptions are made and variables excluded in order to develop models, or to assess empirical data. Therefore, the results from any assessment technique are an estimate, not an absolute outcome. Modelling is a tool to assist in our understanding of coastal processes, and should be used to augment rather than replace real data. Model results need to be consistent and verifiable against measured data that describes the physical constraints of coastal processes and geomorphology.

While councils are urged to use the best available information and techniques, there must be transparency as to the assumptions, accuracy and certainty of predictions made, in order to support sound decision making.

Within a risk-based approach to coastal management, the certainty of hazards estimates should be described in terms of the likelihood of the hazard impact. Description of likelihood of hazard impact should indicate the limitations of the data (e.g. accounting for storm periods not captured by the data) and assumptions used to estimate the hazard (e.g. accounting for model assumptions regarding cross-shore or longshore transport). The likelihood of hazards forms one component of assessing the risk from coastal hazards. Consequences from hazards are not dependent upon the assessment techniques used for hazards, but rather, the people / land affected when the hazard does occur.

The risk assessment framework has now been endorsed for use in coastal management with the CZMP Guidelines and various other NSW coastal management guideline documents.

Conclusions

There are a number of assessment techniques available for conducting beach erosion and recession estimates for use in coastal planning. Councils are given exemptions from liability where coastal management actions are undertaken in 'good faith', under the *Coastal Protection Act 1979*. Councils need to be cognisant of the latest techniques available for assessing coastal hazards, in order to provide the best available information on which to base management responses and thereby limit their future liability.

A review of techniques commonly used in the past in NSW indicates that fundamental assumptions limit the predictive capacity of such techniques for coastal hazard definition. In particular, the Bruun Rule is not able to account for regional longshore transport and wave climate interactions with headlands, breakwaters and other structural features of the coastline in predicting recession due to sea level rise. SBEACH ignores longshore sediment transport and coastal structures, resulting in a reduced or incomplete estimate of storm erosion. Empirical approaches with photogrammetry are typically limited by data availability over time and along a beach, and are limited to predict impacts from events that have not been recorded in the past, such as sea level rise and climate change induced wave climate change.

Two new modelling tools have been developed that provide superior predictive capacity over previous techniques.

The Shoreline Evolution Model of Patterson (2009) provides a powerful tool with which to investigate the likely response of regional coastlines to sea level rise where structural features such as headlands and reefs interact with wave climate driven longshore processes. In particular, the model demonstrates that as the sea level rises, existing headland features increasingly act as a barrier to northerly sediment transport, which starves the southern ends of the beaches in lee of the headlands. The result is enhanced recession at the southern end and reduced recession at the northern end of beaches, compared with Bruun Rule estimates.

The Shoreline Response Model of Huxley (2010) is capable of estimating recession due to sea level rise and wave climate change (e.g. due to climate change) together with erosion during storms and subsequent beach re-accretion, over a 100 year period. The SRM calculates combined longshore and surfzone cross shore transport, providing a much improved estimate of beach response to storms. For individual beach units this offers a powerful tool to investigate shoreline change under a future climate.

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