# APPLICATION OF A MODEL FRAMEWORK FOR ASSESSING RISK AND ADAPTATION TO CLIMATE CHANGE ON THE SOUTH COAST OF NEW SOUTH WALES

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## ABSTRACT

Coastal land use planning and management need an indication of the degree of risk and vulnerability to climate change, particularly sea-level rise. Assessment of coastal behaviour needs to account for natural sources of variability and trends in shoreline behaviour occurring at timescales that are appropriate for planning and engineering. The framework involves determining the long-term behaviour trends, on the basis of sediment budgets and dominant barrier dynamics (i.e. progradation or recession); short-term process fluctuations associated with storm cut and recovery; and the trajectory of sea-level change. Best practice engineering approaches with geologically-informed assessments of sediment budget and past coastal behaviour provides an indication of the degree of climate change risk to which open coasts may be exposed. For example, a validation assessment undertaken on a data-rich coast of Narrabeen in NSW that integrated a probabilistic engineering-based model linking wave characteristics at the site (Joint Probability Method) and risk of coastal recession (Probabilistic Coastal Recession) within the context of a geomorphologically-based modelling framework (the Coastal Tract) adopting a sediment budget perspective. Managers and policy-makers can apply the information from this validated framework and assessment to incorporate estimated risk into future planning considerations. Further adaptation options have greater confidence as the underlying risk assessment is transparently evidence-based. The application of this approach is extended using GPR on Moruya, southern NSW coast.

## INTRODUCTION

Climate change is a significant threat facing the world, the effects of which make sandy coasts particularly vulnerable to the imminent hazards associated with rising sea level and increased storm erosion. In Australia more than 80% of the population lives along the coast, with most concentrated along the southeast coast. As a result, coastal settlements and infrastructure are disproportionately at risk as a consequence of these two hazards emphasising the importance of future climate change modelling and adaptation critical to managing these habitats. However, in order to best understand how increased sea level and storm erosion will impact the coast, better knowledge needs to be acquired about the history of these processes. This paper aims to explore how risk due to sea-level rise can be assessed along the Australian coast, with a focus on extending and expanding a model framework recently outlined and tested as part of a National Climate Change Adaption Research Facilities (NCCARF) project (Woodroffe et al., In Review).

Global mean sea levels have been, and are projected to continue, rising as a consequence of global warming and climate change (IPCC, 1992, Nicholls et al., 2011). In New South Wales it has been suggested that sea levels will rise as much as 0.40 m by 2050 and 0.90 m by 2100 (although these specific figures have recently been revoked). For decades it has been recognised that a rise in the sea will cause landward retreat of the shoreline, but quantifying the rate and exact impact of this sea-level rise on beaches and dunes is complicated. This complexity results in debate about not just how these coast will respond but the procedures used to forecast their responses, resulting in little guidance available for coastal managers and planners to determine sensible set-back lines where the landward construction of buildings and infrastructure is judicious.

The best known model relating shoreline retreat to an increase in sea level is the Bruun Rule (Bruun, 1962). This simplistic approach gives a measure of expected erosion related to the slope of the shoreface, such that as sea level rises the basic shape of the beach will be uniformly maintained (equilibrium profile). Based on a closed sediment budget and wave energy this morphology will simply be translated up and landwards as sand is eroded from the beachface and deposited in the nearshore. There has been widespread criticism of this rule (Pilkey et al., 1993, Cooper and Pilkey, 2004), particularly due to the lack of longshore transport consideration and the fact that it ignores perturbations such as seasonal/storm fluctuations. A modified version of the Bruun method incorporates circumstances where there is a net landward translation of sand, as opposed to the standard interpretation in which sand is moved seaward (Davidson-Arnott, 2005). Modelling of the southeatern Australian coast found that different substrate slopes resulted in various shoreline responses. The lowest gradient substrates (0.2˚) resulted in a sand barrier translating landwards by rollover, whereas on slopes of more than 1˚ the Bruun-type transfer prevails (Roy et al., 1994, Cowell et al., 2006). However, for slopes of 0.7˚, which is the common gradient along much of the southern NSW coast, the transfer of sediment is in both directions. It seems that the reason the Bruun Rule is the most widely used approach to determine the behaviour of sandy coastlines is its simplicity rather than its appropriateness.

The reality is that sandy beaches behave in complex ways in response to the dynamic nature of various wave and tidal conditions, with the greatest change resulting from storms. These high energy events erode sand from the beach transporting it either landward as washover deposits or offshore into nearshore bars, leaving dune scarps and flattened beach profiles consisting of coarse-grain and or/heavy mineral lag. When wave energy has subsided sediment that was transported offshore is reworked onshore rebuilding the beach (Komar, 1998). This post-storm recovery varies along the coast and is likely to vary depending on whether a beach is retreating seaward, accreting landward or remaining staionary. When sediment eroded from the beach during a storm does not return during recovery then long-term retreat or a recession of the shoreline occurs. Alternatively, sediment can be gradually added to the system causing shoreline accretion over time. Stable beaches are those that experience no overall sediment loss or gain through the storm and recovery cycle such that the coast appears stationary. These trends are difficult to determine and require careful documetnation of the beach morphology over long periods of time. The best method of aquiring such data is collecting a series of topographic profiles over the same cross-section of beach through time, such as that done at Narrabeen Beach and at Moruya (McLean and Shen, 2006). Superimposing these profiles defines a sweep zone over which the 'active beach' migrates.

The trend of a shoreline over the longer-term (past 6000 years) can be determined from the type of coastal landform that backs the beach. These accumulations of beach and dune sediments are referred to as coastal barriers. The evolution of these barriers, and the long-term behaviour of their associated beaches, is traditionally considered a function of the relationship between the pattern of sea-level change and the availability of sediment. Within the literature it is generally thought that there are three main types of barriers: 1) transgressive, 2) stationary (also termed aggradational) and 3) progradational (which is also described as regressive) (Roy et al., 1994, Woodroffe, 2003). Transgressive barriers gradually migrate landwards as a result of overwash usually in response to sea-level rise or a diminishing supply of sediment. Aggradational barriers occur along stable shorelines where sediment accretes vertically at a rate roughly equal to the gradual rate of relative sea-level rise. Progradational barriers occur when there is a relative fall of sea level or under stable sea-level conditions when there is a substantial supply of sediment to the coast. These regressive barrier systems are called strandplains, beach-ridge plains, or a plain of relict foredune ridges (Murray-Wallace et al., 2002). Figure 1 is a schematic representation of the interaction between sea-level tendency and sediment supply in terms of transgression (landward retreat) and regression (seaward advance), presented with respect to the associated barrier types.

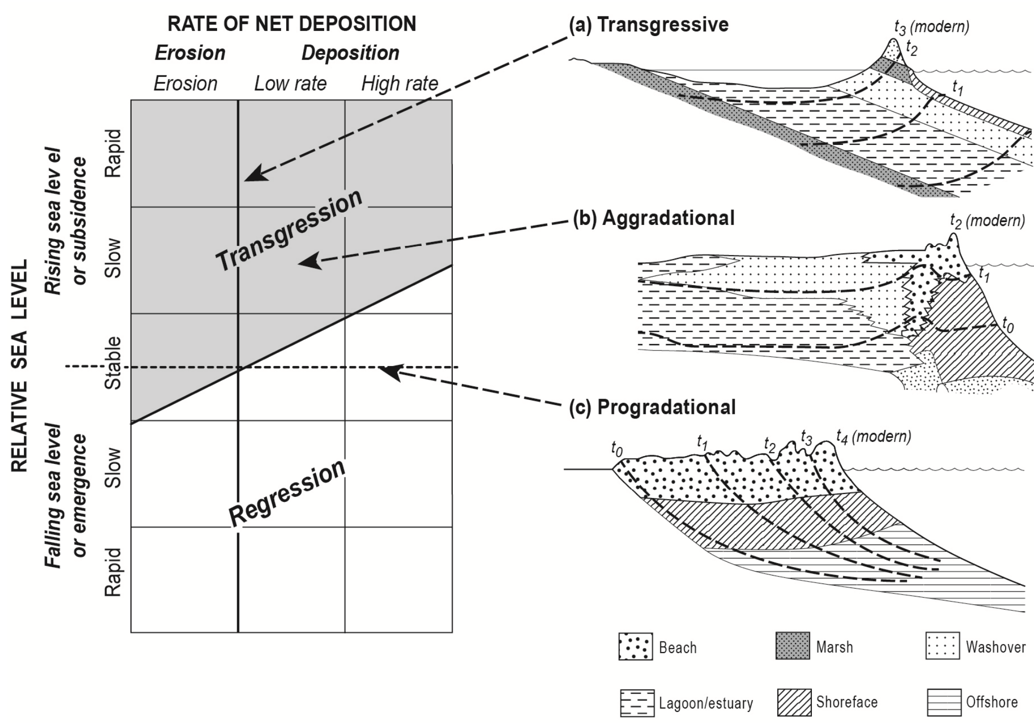


**Figure 1: A representation of the Curray-Swift diagram in which the morphology and stratigraphy of coastal barriers is represented as a function of sea-level trajectory (which influences accommodation space) and the relative sediment budget (modified from Curray, 1964, Swift, 1976, Cowell et al., 2003, Galloway et al., 1984).**

Coastal barriers have been extensivly studied in NSW providing some of the best models (Figure 2) with respect to their morphology, composition, stability, geologic setting and energy environment (Chapman et al., 1982, Roy and Thom, 1981, Thom, 1984). These detailed studies show that barriers have transitioned through different evolutionary types at differnt times in the past. All barriers were likely trangressional as sea level rose, but since sea level stabilised at a level close to present around 6000-7000 years their evolution has varied from place to place based on sediment supply. Since that time barriers with continuous sediment supply have progaded seaward while those experincing a loss of sediment over time result in the shoreline continuing to transgress landward or recede. Receded barriers extend the definition of these erosional features to those where loss of sediment is to the offshore as opposed to onshore resulting in barrier rollover. Barriers that have not moved laterally, likely due to a closed sediment system, are termed stationary; these differ from aggradational barriers in that they do not appear to have experienced continued vertical addition (aggradation) of sand. The only vertical accretion documented was through formation of large dunes, classified as a dunefield barrier type. Adjacent sandy coastal barriers need not have evolved similarly in the past, nor will they erode at the same rate and style in the future.

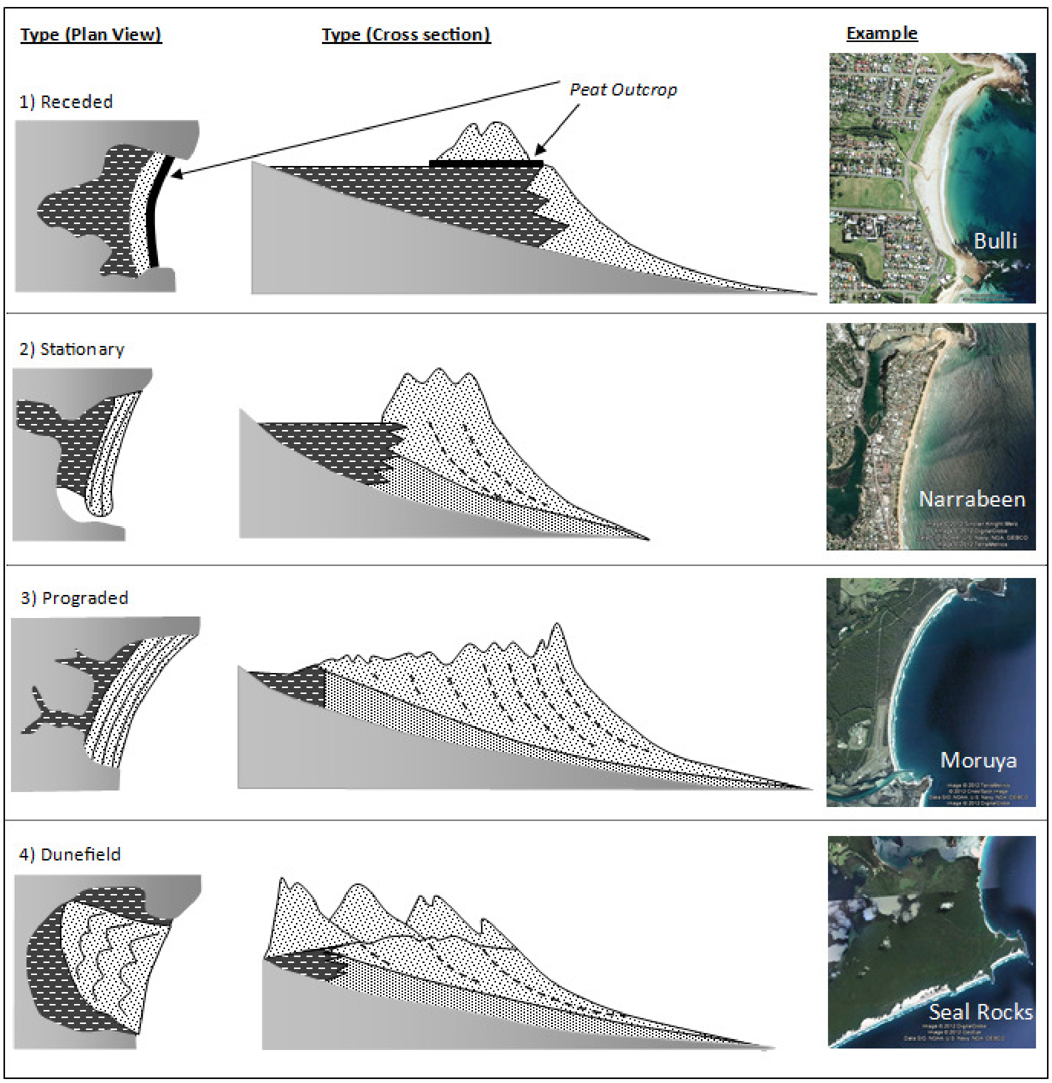


**Figure 2: Classification, morphology and evolutionary history of barrier types, with representative NSW examples of each shown in the Google Earth images.**

In Australia a well-established protocol exists for coastal geomorphic hazard assessment to determine setback limits from beaches and foredunes. The approach involves a fundamental distinction between mean-trend and fluctuating constituents of coastal change, and requires consideration of three components necessary for future predictions: 1) long-term sediment budget, 2) short-term variability 3) sea-level trend. The protocol constitutes a *de facto* framework that is incorporated in policy and guidelines developed by most State agencies and applied routinely by consultants advising local government and commercial clients. While the demarcation of coastal hazard lines has traditionally involved deterministic estimates that put a single 'line in the sand' (and are often perceived as 'predictions'), as a part of a National Climate Change Research Facilities (NCCARF) we have examined extending this existing protocol to examine the likely retreat of shorelines in terms of probabilistic estimates of coastal recession ('forecasts') with implications in terms of setback lines (Woodroffe et al., In Review). The resulting framework can be summarised as a protocol to define a future shore-stability hazard zone, $d_{shz}$, ignoring uncertainty:

$$d_{shz}(t) = \overline{R}_V(t) + \overline{R}_{SL}(t) + E_D + B \tag{1}$$

where

$d_{shz}$ is the distance inland from a foreshore reference line encompassing land subject to risk of geotechnical impact from coastal-marine processes,

$R$ terms denote constituents of mean-trend recession distance by a future time, $t$,

the subscripts $V$ and $SL$ denote constituents associated with time-averaged sediment budget and future sea-level rise respectively,

$E_D$ is design erosion distance, relating to fluctuations in the location of the beach through time, and

$B$ is the inland extent of land remaining intact but suffering a reduced foundation-load bearing capacity adjacent to land undermined due to $R$ and $E_D$ (Nielsen et al., 1992).

The strength of this conceptual framework is the integration of best practice engineering approaches with geologically-informed assessments of past coastal behaviour to enable managers and policy-makers to incorporate estimated risk into considerations of adaptation options with greater confidence that the underlying risk assessment is transparently evidence-based. The temporal and spatial scales relevant to this framework are nicely linked within Figure 3. Detailed empirical studies at the shorter timescales feed into the process-based models and even provide valuable data with which to test models through hindcasting. The evidence based morphostratigraphic studies produce insight into coastal evolution over longer timescales which is crucial to constructing behaviour models. The upscaling of these short-term process-based models combined with downscaling the longer-term behaviour models is what ultimately guides predictions of coastal behaviour over decades and centuries relevant to coastal planners and managers.

The framework is not model-specific and a range of models exist that can be used to address each of these components. In our NCCARF project we examined how four different models might be incorporated into the process, i) the Joint Probability Method (JPM) which involves Monte Carlo simulation of a 110-year time series of storms derived from joint probability distributions of storm characteristics enabling the effects of clustering of more than one storm to be incorporated into estimates of beach erosion (Callaghan et al., 2008, Callaghan et al., 2009); ii) the Probabilistic Coastline Recession (PCR) model which adopts the JPM to generate probabilistic estimates of shoreline retreat in response to storms, using a process-based dune impact model (Ranasinghe et al., 2012); iii) the Shoreface Translation Model (STM), which is a two-dimensional cross-shore profile model that simulates large-scale coastal behaviour based on geometric rules of shoreface and barrier morphology, in order to quantify horizontal and vertical translation of the shoreface under different sea-level conditions (Cowell et al., 2006); and the Probabilistic Coastal Setback Line (PCSL) model which is an economic model that determines which setback lines would be optimal from an economic perspective (Jongejan et al., 2011). The integration of these four different models was demonstrated at Narrabeen Beach in northern Sydney. This case study site was chosen because beach morphology has been surveyed at regular intervals for over 30 years providing field evidence that enabled calibration and testing of the models. The results derived probabilistic estimates of erosion hazard for 2050 and 2100 in relation to the 1974 scarp position.

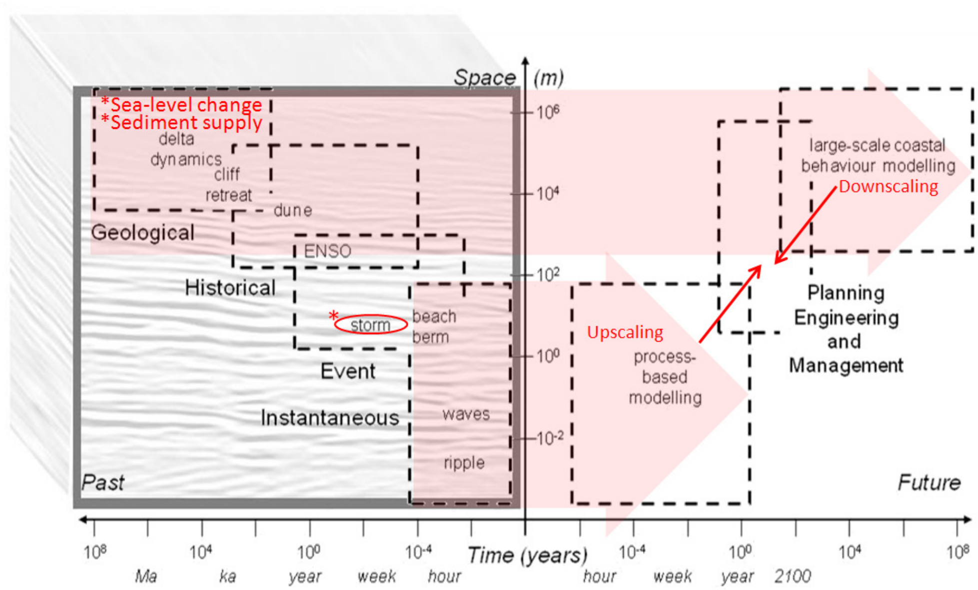


**Figure 3: Representation of the temporal and spatial scales relevant to coastal systems (modified from Gelfenbaum and Kaminsky, 2010, Woodroffe and Murray-Wallace, 2012). The left hand side of the diagram shows the scales at which coastal researchers have focused their investigations and developed conceptual understanding of past coastal evolution, with an underlay of GPR data to demonstrate its ability to span the space and time scales. On the right hand side of the diagram explores the scales relevant to a consideration of the future. The red arrows demonstrate how empirical studies of past behaviour on short and long timescales feed into process-based modelling and behaviour models that are upscaled and downscaled respectively to predict future shoreline evolution within time scales crucial to coastal planning and management.**

This integrated framework, using these or other independently verified models, in theory can be readily applied to the full range of coastlines around Australia. The report outlines constraints on modelling, gaps in knowledge, and areas where further research is required to better understand and predict coastal behaviour (Woodroffe et al., In Review). Some limitations to this comprehensive methodology exist with respect to the key constituents of short-term variability of storms and long-term trends in sediment budget. The short-term engineering models of storms are based on a limited period of wave climate data and the understanding of beach response from profile measurements, both of which do not exist for many coastlines. While the barriers of

NSW are some of the most studied, understanding of their long-term trend in sediment budget is still difficult to quantify. In this paper, the gaps in storm and sediment supply knowledge are considered in more depth. A geophyscially-based approach is presented to expand and bridge gap between short and long-term coastal behaviour. Data from the Narrabeen case study is examined and potential to extend this framework to Moruya is explored.

### *Extending the short-term storm record*

There is comprehensive understating of beach processes with respect to storm erosion, but little is known about the subsequent recovery. While most of the understanding about storm cut and recovery is from beaches along the NSW coast during the erosive events of the 1970s, however only one site (Moruya) has continuous profiling data to measure shoreline behaviour. Additionally, while the 1970s storms are considered 1 in 100 year events, there is no context for this since recurrence intervals of large-magnitude erosional events are poorly understood due to limited documentation and instrumental records constrained to a historical timeframe. The ability to study the series of older post-storm beachfaces preserved within a progradational barrier affords the opportunity to extend the detailed process-based knowledge of beach erosion recorded during an individual and/or a sequence of storms (such as in the 1970s) over the past several thousand years. Ground penetrating radar (GPR) offers an ideal technique for remotely sensing the distinct storm cut shape of older beaches within the stratigraphic record (Dougherty et al., 2004). In addition, strength of the geophysical signature and increased concentration of coarse-grained/heavy mineral sand can provide insight into storm intensity. Augmenting existing radiocarbon dating with Optically Stimulated Luminescence (OSL) chronology may resolve ages associated with the paleo-beachfaces. Mapping and dating these distinct erosional storm-profile beaches over thousands of years could reveal periodicity and strength of the most extreme erosive events.

### *Detailing long-term sediment supply*

The geomorphological history of a particular barrier type is one of the key indicators of its likely future sedimentary dynamics. The size and type of a barrier with respect to its embayment can indicate the amount of sediment available in a compartment. While the rapid postglacial sea-level rise resulted in the landward retreat of all barriers, the interactions of sediment supply and varying space to accommodate it along the coast controlled gross evolution under a stationary sea level. Deciphering this more subtle relationship between sediment budget and accommodation space over the past millennia is difficult. It is not clear at what stage effects of a more rapidly rising sea level in future will become apparent and distinguishable, but it is clear that response will differ for different barriers. This is an important challenge, because when the relative role of these factors can be deciphered then the influence of future sea-level rise can be more effectively forecast. Geophysics can contribute a more accurate account of the sediment budget by providing detailed subsurface volumes that coupled with existing radiocarbon dates can quantify rates of sediment accumulation over time. Additionally, this remote sensing technique can help reconstruct the initial accommodation space available by imaging the underlying basin.

## GROUND PENETRATING RADAR (GPR)

GPR is a high-resolution geophysical technique that can be thought of like an x-ray, only instead of imaging bones it can detect paleo-beach, dune and nearshore surfaces (stratigraphy) preserved underground. GPR provides an image of barrier stratigraphy by emitting short pulses of electromagnetic energy into the ground (Figure 4). The transmitted pulses are limited in their depth by such variables as mineralogy, grain size, water content and saline concentrations (Jol, 2009). These factors control the electrical conduction properties (dielectric permittivity) of the material being penetrated and cause energy pulses to reflect back to the receiver, therefore recording facies changes by travel-time within the waveform (Figure 4). This time measurement is converted into depth by entering the dielectric constant of the material that it is travelling through. The result is individual waveforms display changes within the subsurface by recording an wave-amplitude spike at a stratigraphic boundary surface, such that low wave-amplitude represents homogenous sediments and any increase in amplitude is associated with greater contrast in sediment characteristics (e.g. change in water content, mineralogy, grain-size, sorting, etc.). By collecting GPR data in continuous mode along a transect, individual wave traces stack laterally and peaks of high-amplitude merge to form reflections of stratigraphic boundaries (Figure 4 and

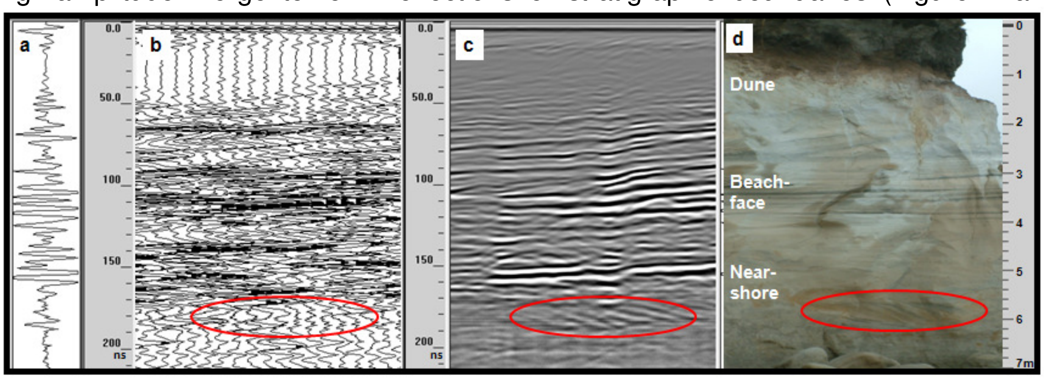


Figure 5). These strong or high-amplitude reflections show up as prominent coupled lines of black and white, for example beachfaces resulting from heavy mineral layers concentrated during a storm

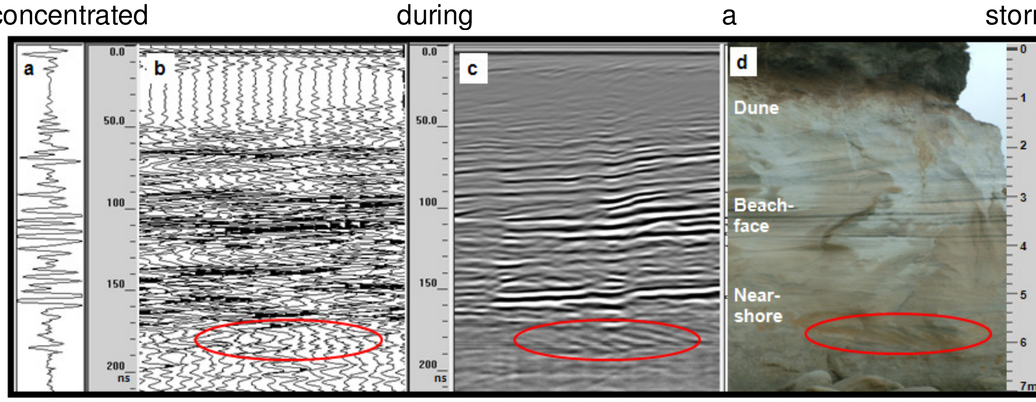


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Figure 5). Alternately, areas where the substrate is similar in composition produce low-amplitude frequencies resulting in weak reflections or reflection-free areas, such as the opaque grey at the top of

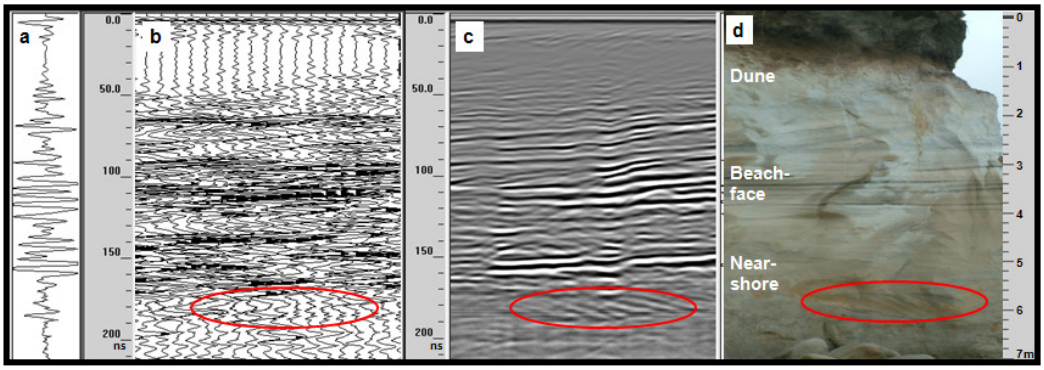


Figure 5c, indicating massive well-sorted dune sands in

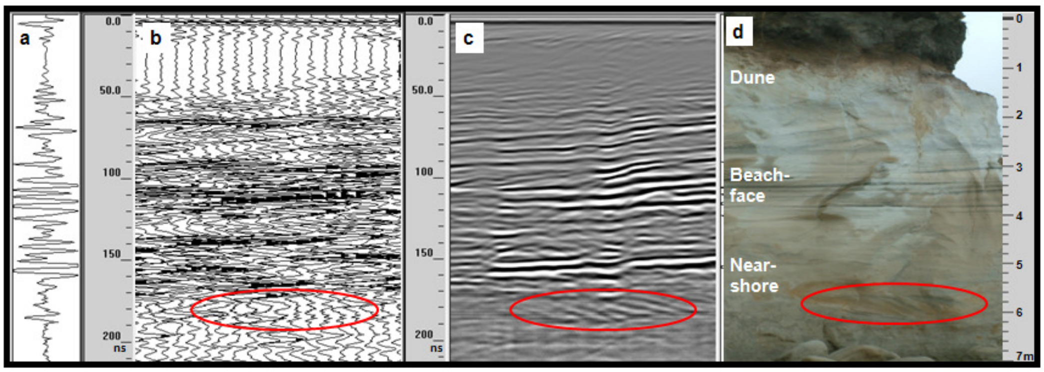


Figure 5d.

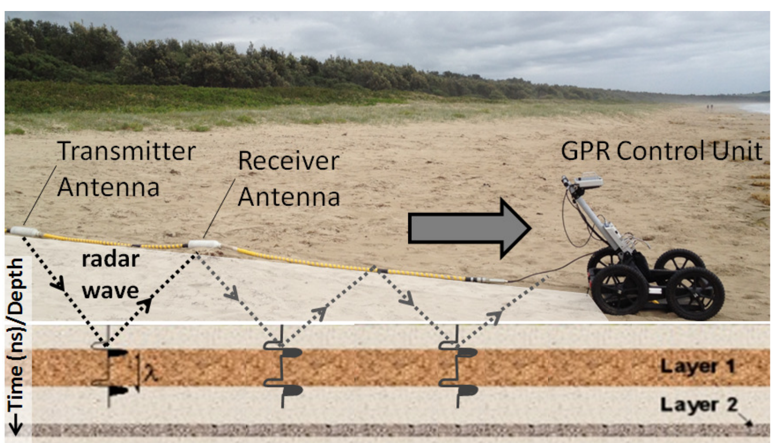


**Figure 4: A cart-mounted Mala Ground Penetrating Radar (GPR) system with key components annotated. Radar waves emitted from the transmitter antenna penetrate the subsurface interacting with a stratigraphic layer at depth and the reflected wave is recorded by the receiver antenna as it returns to the surface, providing an indication of stratigraphy, such that the greater the change in the layer the larger the amplitude within the wavelet.**

In the late-1980s and 1990s, the application of GPR to coastal research revolutionized understanding of barrier architecture; it is now an accepted tool among coastal researchers (Jol, 2009). GPR has allowed for actual sedimentary layers within barriers to be continuously imaged in detail at decimetre resolution over kilometres of coast**Error! Reference source not found.**, enabling detection of large-scale facies boundaries across prograding barriers, previously unrecognisable by coring alone.

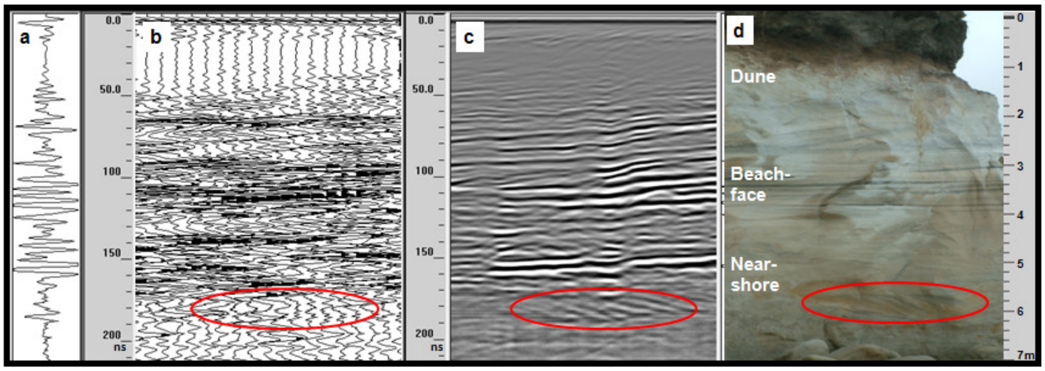

**Figure 5: Sample of GPR data. a) a record of a single radar waveform, similar to that in Figure 4; b) a series of waveforms staked laterally to produce a GPR record; c) the same GPR record shown in what is called 'Linescan Greyscale Mode' which is preferred data display due to its ability to show small-scale structures (e.g. steeply dipping beds in the red oval); and d) a photograph of an outcrop of the three barrier facies imaged in the geophysical record (dune, beachface and nearshore).**

## STRATIGRAPHY OF THE NARRABEEN BARRIER FROM GPR

Narrabeen is a popular destination within the Sydney region. This narrow stationary barrier is covered with a dense residential infrastructure. Six GPR transects were collected across Narrabeen Barrier with two each from the north, south and central portions. All of the records contained evidence of the 1974 storm in the seawardmost portion of the profiles. Strong low-angle radar reflections record the post-storm flattened lower-beachface that terminates landward in a series of hyperbolic reflections, interpreted as signal diffractions from a buried seawall in the south and central transects (Figure 6). Post-storm recovery deposits are recorded, first with the higher angle berm deposits and then the dune facies (Figure 6c). This post-storm signature was identified in the geophysical record of the landward stratigraphy at least four times, indicating four other episodes of erosion preserved at Narrabeen (Figure 6b); with the potential of one more that may be obscured by signal interference crossing Ocean Road. While the morphology of the barrier has been leveled during development, four filled shallow swales are identified within the GPR which are interpreted as recording the original dune morphology pre-construction. Utilising pre-existing stratigraphic data from Narrabeen (Roy and Lean, 1980) and the stacked GPR records collected for this study, an idealised three-dimensional morphostratigraphic model of Narrabeen was constructed (Figure 6**Error! Reference source not found.**d). This model indicates an evolution where the progradation between 7000 and 3000 years was punctuated by at least five major erosional events. Further research is necessary to determine the frequency and intensity of these events.

The infrastructure at Narrabeen has necessitated adaptation measures such as beach replenishment and nourishment as well as physical defences such as seawalls. As a result beach behaviour over historical times has been altered. Natural patterns of erosion are inhibited by partial seawalls and other manmade structures. The sediment supply from longshore drift is modified by beach replenishment using sand from the Narrabeen Lagoon. This inhibits the understanding of short-term coastal change with respect to storms and recovery patterns. Additionally, beach profile and wave data collection started after 1974 and therefore does not include information from a large storm event that occurred that year. GPR imaged 1978 post-storm beachface, but the full profile was truncated by the existence of the seawall. The limited sediment supply that has resulted in Narrabeen being stationary, means that there is a low preservation potential of storm events within the stratigraphy as compared to a progradational barrier with ample sediment accumulation between episodes of erosion.

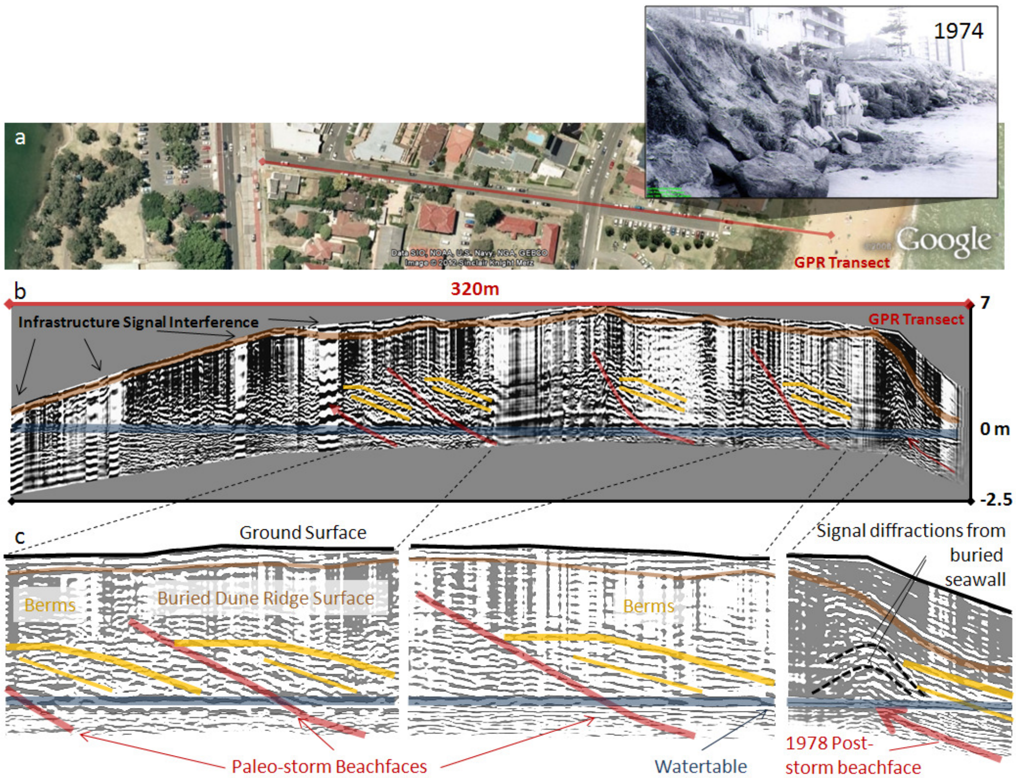


**Figure 6. Representative GPR data from Narrabeen. This central transect was collected along Albert Street (a). The raw data from the entire transect line (b) shows displays 5 paleo-storm beachfaces highlighted in red and subsequent berm accretion in yellow. The processed sections of the GPR (c) detail these beach and berm features as well as those of the dune (brown) and seawall (black) exposed in 1974 as pictured by inset (a).**

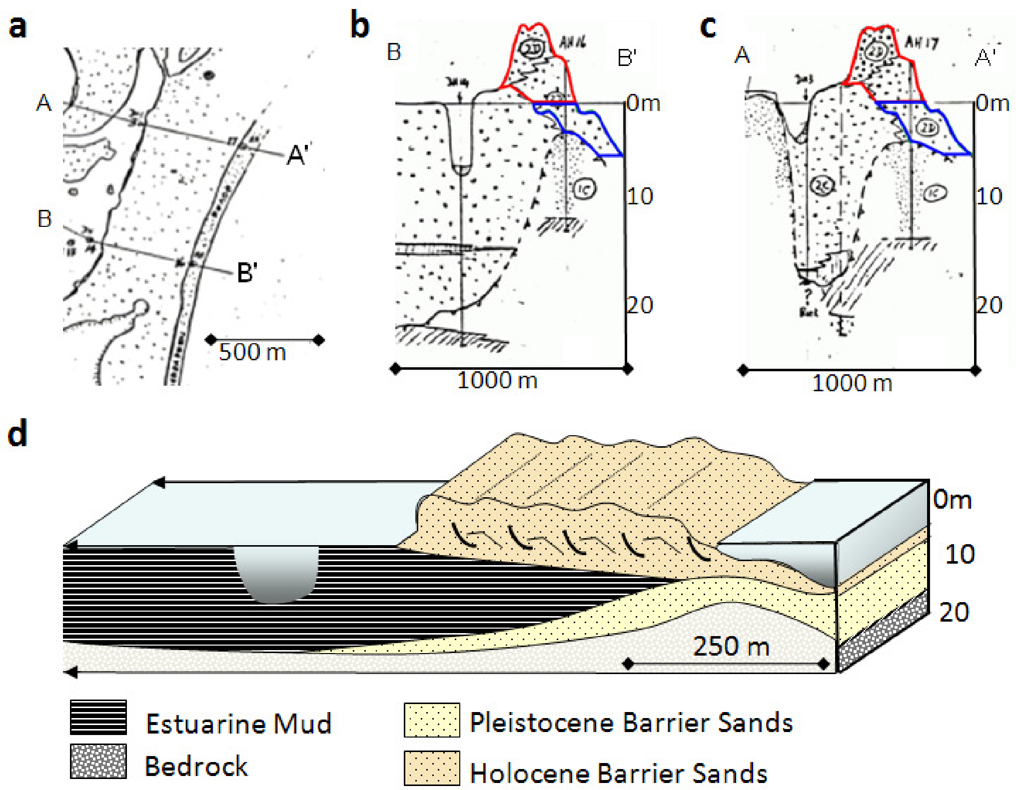


**Figure 7. Existing stratigraphic data (a, b and c) from Roy and Lean (1980) was augmented with the GPR profiles to construct a detailed morphostratigraphic model of Narrabeen Barrier.**

## STRATIGRAPHY AND PROGRADATION AT MORUYA FROM GPR

Moruya, southern NSW, is an ideal study site to extend this research and utilise GPR to bridge between sedimentary evolution and beachface dynamics time scales, capitalising on a unique set of data. Extensive coring of this 1.5 km wide progrdational barrier (Figure 8) has resulted in a general stratigrpahic model with detailed morphology and chronology. Additionally, the beach is one of the longest monitored sites in Australia with regular surveys collected at four locations over the past 40 years (Thom and Hall, 1991, McLean and Shen, 2006, McLean et al., 2010). Unlike at Narrabeen, the Moruya beach profile surveys captured the major erosion by a series of storms in 1974, with the greatest retreat being recorded after subsequent storms in 1978 (Thom and Hall, 1991). The erosion resulted in a loss of sediment volume of more than 150 $m^3$/m of linear beach (Figure 8). It then took close to a decade after the storm cut for the sand to return back to the beach and foredune. Since the mid-1980's the beach has displayed a relatively stable period with minor fluctuations (additional data to that reported in Thom and Hall, 1991 from published and unpublished data from R.F. McLean). This unique dataset enables the comparison between the short-term patterns of variation recorded during the period of beach surveys and the longer-term record of evolution derived from the geomorphological reconstruction of progradation over the past 7000 years.

GPR acquired a geophysical image of the eroded beachface resulting from the 1978 storm and subsequent progradation to present. A transect was collected across the foredune and over the incipient dunes ending at the high tide line (Figure 9a). The data recorded a strong feature extending from the known dune scarp displaying a flattened geometry similar to a beach profile collected nearby just after the storm in 1978 (Figure 9b). In addition to imaging the post-storm beachface accurately, the GPR recorded a similar recovery volume above AHD (160 $m^3$/m) to that measured by repeat profiles (150 $m^3$/m). This geophysical methodology offers the opportunity to retroactively record the beach sweep zone since the 1978 storm where no profile records exist. Variations in recovery volumes of different barrier types can be assessed using these techniques.

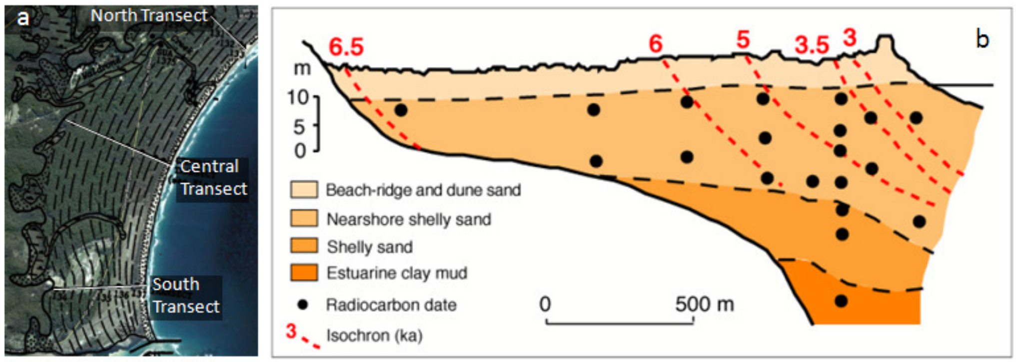


**Figure 8: (a) Aerial photograph of Bengello Beach, Moruya, New South Wales, with a generalised overlay of the strandplain ridges and transects mapped by Thom et al. 1981. (b) Stratigraphy and chronology of this prograded barrier based upon drilling and radiocarbon dating (after Thom et al., 1981).**

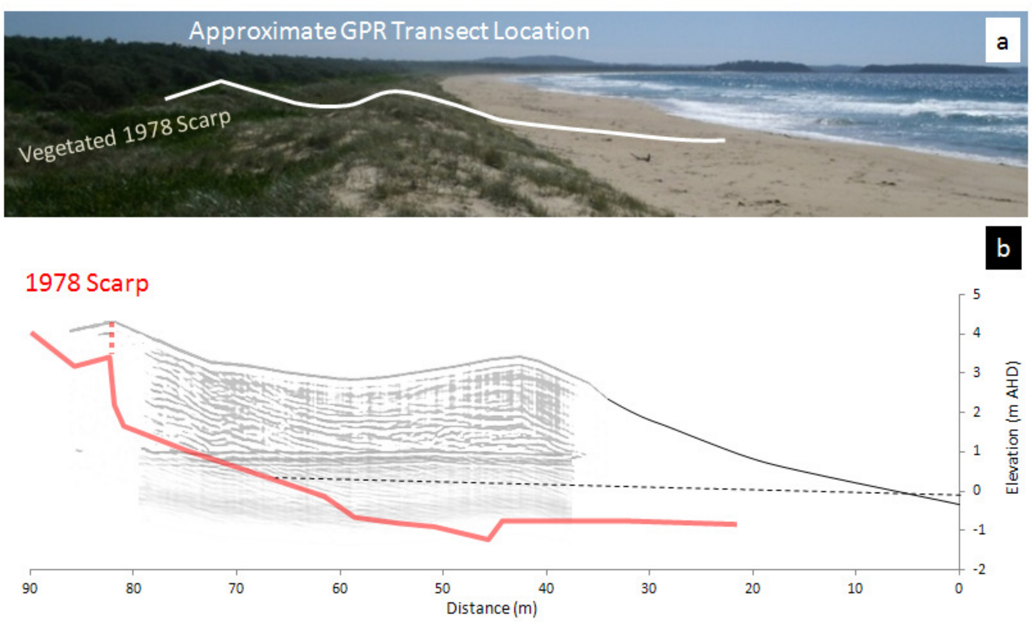


**Figure 9: A photograph of the erosional scarp form the 1978 storm (above), and subsequent accretion which have become vegetated (a). Below is a GPR profile collected across the 1978 scarp imaging the associated erosional beachface matching the geometry of topographic profile collected after the storm overlain in red (b). Volumetric calculation from this geophysical record resulted in a**

**similar amount of sediment accumulation since the storm as that recorded in detailed profile data.**

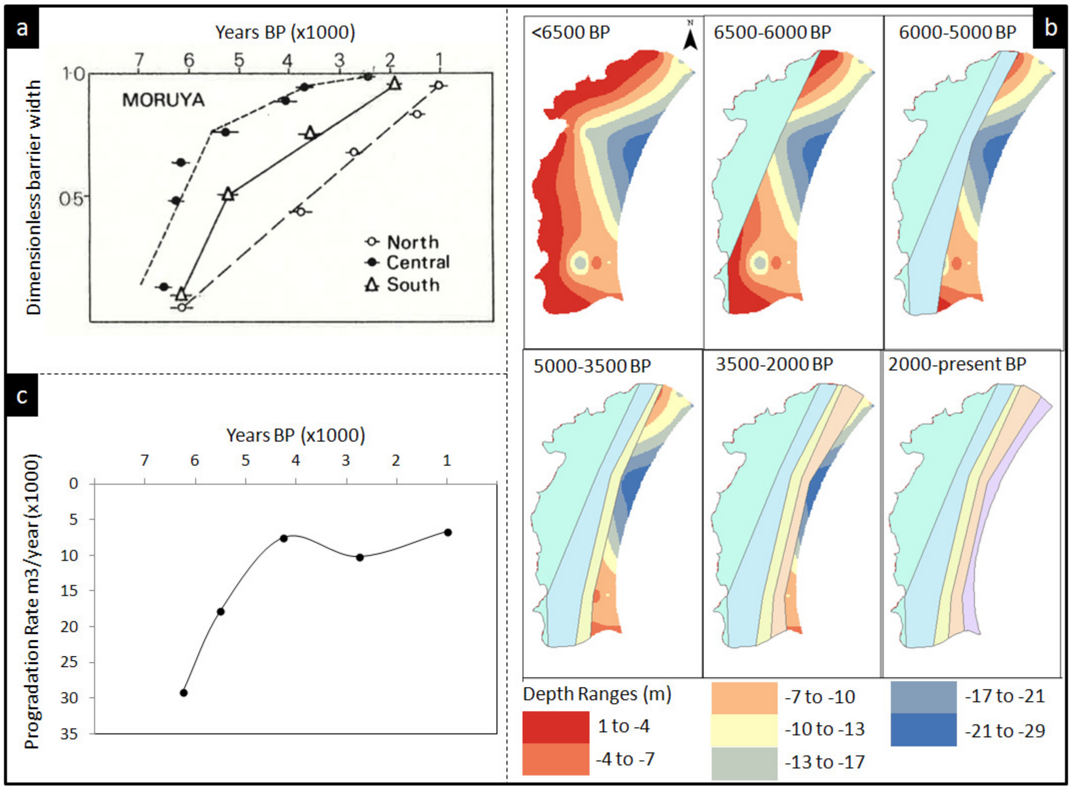


**Figure 10: (a) progradation through time of the north, central and southern transects (Thom et al. 1981); (b) preliminary schematic visualisation of progradation through time overlayed on a elevation model of the transgressive sand sheet surface underlying the present day barrier; (c) preliminary volumetric progradation rate in m$^3$/yr calculated from the time series shown in (b).**

A preliminary study is under way to develop a methodology for recording past long-term sediment supply to coastal barriers that incorporates the influence of accommodation space. Moruya is the ideal study site to trial this methodology because of the large amount of subsurface data available from multiple cores collected along three transect lines spanning the northern, central and southern portions of the barrier (Figure 8a). Additionally, progradation rates have already been calculated using barrier width divided by distance prograded at any given time, termed dimensionless barrier width (Figure 10a). This data shows that progradation slowed gradually over time in the central and southern parts of the barrier while the north maintained a linear trend. Using the existing historical core data from Thom et al. (1981) a digital elevation model was created in GIS. Volumetric slices were determined based on isochrons on cross-sections of the three transects (Figure 8b). A time series of these volumetric slices shows similar longshore variations in progradation to that observed by Thom et al. (1981), but this visualisation demonstrates how they are linked to differences in depth to the underlying surface from north to south (Figure 10b). The volumetric progradation rates determined for the entire barrier resulted in a more complicated history with the addition of sediment slowing and then speeding up (Figure 10c). Further investigations are under way to incorporate volumes above 0m AHD using GPR, similar to that demonstrated for volume of storm recovery but over the entire width of the barrier at a couple locations. Interpolation between these GPR transects, augmented with LiDAR data to detail the lateral extent, will discern the subaerial volume component in three dimensions. The addition of OSL dates associated with this detailed stratigraphy should refine the radiocarbon chronology and resolve any ambiguity about sediment volume associated with using isochrons.

## SUMMARY

Sandy coastal systems in NSW are vulnerable to sea-level rise and storm erosion as a consequence of climate change. Different types of coasts will respond differently, just as evolution has varied in the past. It has been the practice in NSW to predict deterministic setback lines based on three constituents within geomorphic hazard assessments: 1) long-term sediment budget, 2) short-term variability 3) sea-level trend. As part of a recent NCCARF study, we have formalised this protocol, examining the likely retreat of shorelines in terms of probabilistic estimates of coastal recession ('forecasts') with respect to setback limits. The NCCARF research used a modelling approach that incorporates geomorphic, engineering and economic techniques. Application of four selected models (JPM, PCR, PCSL, and CT) demonstrated the integration of these probabilistic approaches producing erosion hazard estimates and their probabilities for 2050 and 2100 at Narrabeen Beach in northern Sydney. This theoretical framework can be applied to coasts around Australia, using a range of existing models to address each of these components. Such medium-term forecasts of coastal behaviour use upscaling and downscaling of models to bridge the gap that exists between the short-term studies and long-term geomorphological research. Ground penetrating radar (GPR) data collected on a decimetre scale offers the scope of spanning hundreds of kilometres, providing the potential to fill some of these knowledge gaps by extending the understanding of present day coastal dynamics over the past few thousand years. GPR data from Narrabeen demonstrated its utility; however the modified nature of this stationary barrier inhibits the full potential of this geophysical technique. Preliminary extension of this approach to Moruya, capitalised on a unique set of beach profile data and a large cache of sediment cores, radiocarbon dates and detailed topographic profiles of the barrier. Results show that GPR can image storm cut and recovery of the known 1974 and 1978 storms with accuracy similar to that of repeated beach profiles. This geophysical signature can then be identified throughout the stratigraphy of barriers that have prograded over the past several thousand years, contextualising these 1970s events within a longer storm reoccurrence interval. Additionally, a preliminary outcome is developing a method to improve the understanding of long-term sediment supply with respect to accommodation space using existing sediment cores and dates. Future studies utilising GPR, LiDAR and OSL chronology can augment these preliminary sediment budget findings and extend the knowledge of storm history resulting in a detailed evolution of the Moruya, and subsequently other, coasts that can be fed into models to better predict sandy coast response to climate change.

## ACKNOWLEDGMENTS

Funded with assistance of the Australian Government Department of Climate Change and Energy Efficiency's Climate Change Adaptation Research Grants program. This research is an extension of the National Climate Change Research Facility (NCCARF project SI1008). This is one component of the broader study and we are grateful to the other researchers, steering committee and stakeholders for the opportunity to collaborate in this integrated project, particularly David P. Callaghan and David J. Wainwright at the University of Queensland, Roshanka Ranasinghe and Ruben Jongejan from UNESCO-IHE, Delft, Stephen J. Barry of University of Sydney and Kerrylee Rogers from University of Wollongong.

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