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Moving from deterministic towards probabilistic coastal hazard and risk assessment: Development of a modelling framework and application to Narrabeen Beach, New South Wales, Australia

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ABSTRACT

Traditional methods for assessing coastal hazards have not typically incorporated a rigorous treatment of uncertainty. Such treatment is necessary to enable risk assessments which are now required by emerging risk based coastal zone management/planning frameworks. While unresolved issues remain, relating to the availability of sufficient data for comprehensive uncertainty assessments, this will hopefully improve in coming decades. Here, we present a modelling framework which integrates geological, engineering and economic approaches for assessing the climate change driven economic risk to coastal developments. The framework incorporates means for combining results from models that focus on the decadal to century time scales at which coasts evolve, and those that focus on the short term and seasonal time scales (storm bite and recovery). This paper demonstrates the functionality of the framework in deriving probabilistic coastal hazard lines and their subsequent use to establish an economically optimal setback line for development at a case study site; the Narrabeen–Collaroy embayment in Sydney, New South Wales.

1. Introduction

Intensification of human settlements along coastlines worldwide will mean that many will become increasingly vulnerable to the impact of sea-level rise in the coming century. In the state of New South Wales in eastern Australia, which contains the study site considered by this paper, it has recently been estimated that the contemporary replacement value of some 40,000 to 60,000 residential buildings exposed to storm inundation after a 1.1 m sea-level rise is between 12 and 19 billion dollars (DCC, 2009). Coastal development planning decisions made now have the capacity to either mitigate or exacerbate the severity of sea-level rise consequences to future generations.

Coastal engineers and scientists must use robust methods for assessing the exposure of land to coastal processes and their related hazards in order to provide sound advice relating to the setbacks that should be applied for different types of coastal developments and settings. Due to the considerable uncertainty inherent in our present understanding of coastal processes, it is vital that this uncertainty be acknowledged and incorporated into planning decisions. This paper introduces a framework for incorporating uncertainty associated with environmental forcing into coastal development decision making and demonstrates its application to our primary study site, the Narrabeen/Collaroy embayment on the northern beaches of Sydney, New South Wales, Australia.

2. Framework overview

Risk management approaches to coastal hazards have attracted significant attention for at least the past decade or so (Van Dongeren et al., 2008; Vrijling et al, 2003) and are becoming increasingly common and sophisticated (den Heijer et al, 2012; Penning-Rowsell et al, 2014; Zanuttigh et al., 2014). The present guidelines for Coastal Zone Management Plans in New South Wales (OEH, 2013) advocate a risk management approach. The present standard for formal risk management is contained in International Organisation for Standardisation ISO 31000, which contains features that are common to a wide array of historical

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risk assessment standards (ECHCPDG, 2000). The formal standard is flexible, allowing for the incorporation of uncertainty in a transparent manner. This is beneficial when balancing quantitative estimates of uncertain coastal hazards against, for example, the potential intangible losses (environmental losses, beach amenity etc.) in the coastal zone.

With reference to the international standard, our framework focuses on using models to quantitatively analyse risks, and deals with the “risk analysis” and “risk evaluation” phases of the overall risk management process. In our application, risk analysis requires determination of the likelihood and consequences of beach erosion reaching a location where it threatens development. Subsequently, our risk evaluation uses an economic model to determine an optimal development setback location, based on whether investment at a particular location is economically viable, given the amount of damage expected to be sustained through damage by coastal processes. The methods applied here are discussed in greater detail in Woodroffe et al. (2012).

3. Components of coastal hazard analysis

Essentially, the coastal *risk analysis* process comprises (i) determination of the extent or severity of identified hazards for a range of exceedance levels (i.e. the *probabilities or likelihoods*); and (ii) determination of the potential losses for the extents and/or severities identified in (i) (i.e. the *consequences*). By quantifying both of these, the overall risk can then be calculated.

Our study was limited to hazards associated with the location of a dune scarp on a sandy beach. Hazard definition becomes more complicated when it is applied to planning over long time frames with non-stationary boundary conditions, such as the expected sea-level rise over coming centuries. The discrimination of mean trend (e.g. recession) from fluctuating components (erosion and recovery) of shoreline location and their analysis can be summarised as:

$$d(t) = \overline{R}_V - \overline{R}_{SL} - E \tag{1}$$

where $d(t)$ is the distance from the present day scarp location at time t; $\overline{R}_V$ is the ongoing recession resulting from the time averaged sediment budget ($+ve =$ accretion); $\overline{R}_{SL}$ is the recession resulting from a rising sea level; and E is an allowance for storm erosion, representing movement of the shoreline from its pre-storm location to the base of the storm cut erosion scarp.

A further allowance can be made for post-storm slumping and/or reduced foundation capacity although, with adequate site investigation, this component can be treated deterministically and has been set aside for the purposes of this paper. All three components on the right side of Eq. (1) are subject to significant uncertainty and here we address and incorporate an understanding of that uncertainty into our analysis.

4. Study site: Narrabeen Beach

At 3.6 km, the Narrabeen–Collaroy embayment is the longest sandy system in the Sydney region. It is located 20 km north of Sydney CBD (Fig. 1). The embayment fronts a prograded coastal barrier with a tidal inlet at the northern end that maintains a well-developed flood tide delta (Fig. 1). This inlet leads to a back barrier estuary (Narrabeen Lagoon) behind the northern portion of the barrier. The Narrabeen–Collaroy compartment is a relatively closed system bound in the north by Narrabeen Headland and in the south by the prominent headland known as Long Reef Point. Rip cells, with their type and spacing varying

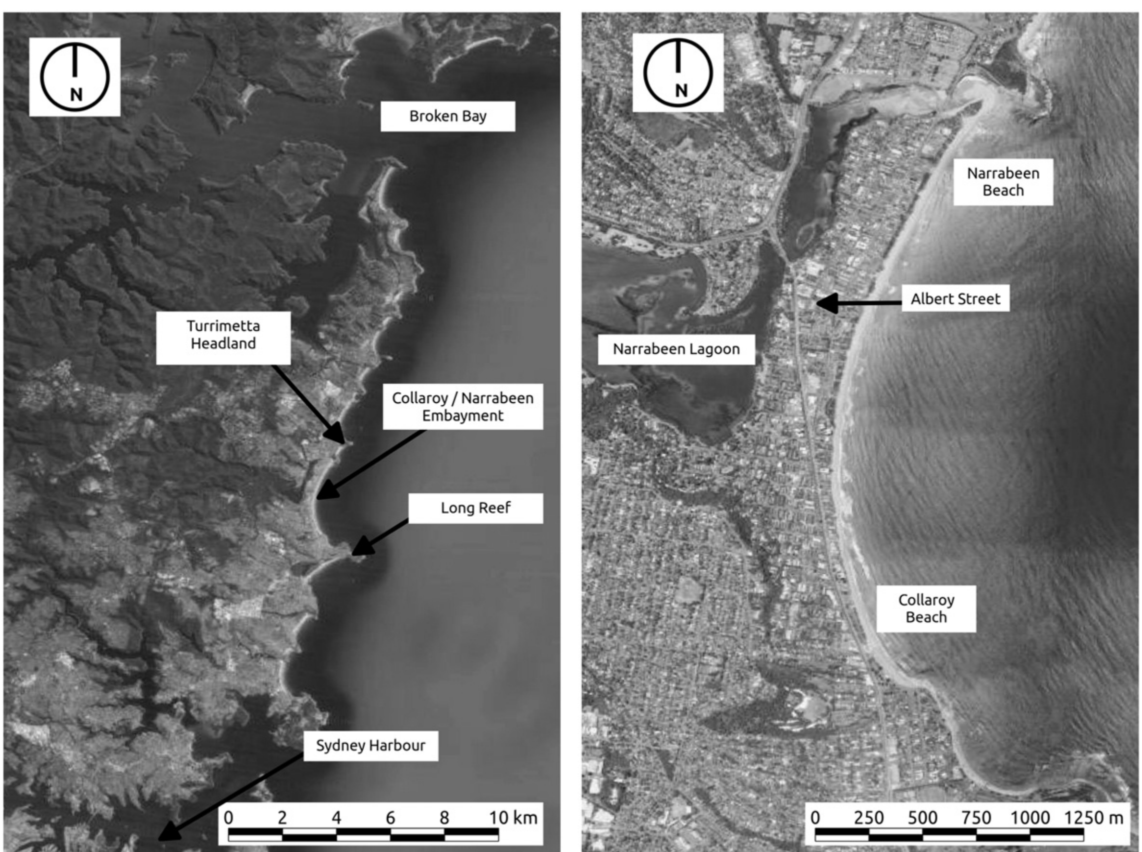

Fig. 1. Left frame shows Narrabeen–Collaroy Beach with respect to the Sydney coastline. Right frame shows Narrabeen Beach and Collaroy Beach. Imagery © 2014 CNES/SPOT Image, Digital Globe, Sinclair Knight Merz, Terrametrics, Map Data © 2014 Google.

in time, are a common feature along this beach and drive offshore sediment transport during high wave events (Short, 1985). Narrabeen's tides are microtidal, semidiurnal and have only minor tidal anomalies due to surge processes (Harley et al., 2011).

The coastline of this region is classified as wave-dominated (Short and Trenaman, 1992). The wave climate at Narrabeen is typically moderate (average significant wave height H_s and peak spectral wave period T_p of 1.6 m and 10 s, respectively) but occasionally high-energy, dominated by east coast swell waves propagating from mid-latitude cyclones to the south of Australia (Davies, 1980). The dominance of these swell waves is illustrated with approximately 50% of all waves coming from the southerly and south-south-easterly direction (Harley et al., 2011). Collaroy is at the southern end of the compartment and is partially sheltered from the dominant south-easterly waves by Long Reef Point.

The Beach comprises uniform sediments of fine to medium quartz sand (medium grain diameter $D_{50} \approx 0.3$ mm) with approximately 30% carbonate fraction (Short, 2007). Typical beach gradients for the intertidal and nearshore zones are 0.12 and 0.02 respectively (Harley et al., 2011). Nine survey lines were established in April 1976 and five of those cross-shore profile lines have been surveyed monthly up to April 2010, amounting to a total of 376 surveys. All profile line surveys are measured at 10 m cross-shore intervals from fixed benchmarks at the back of the beach and continue until about 1–1.5 m below mean sea level (MSL). In recent times, both ARGUS and more detailed RTK GPS survey techniques have also been applied to the beach (Harley, 2009).

5. The geomorphological setting

To move beyond simplified rule-of-thumb assessments such as the Bruun Rule, it is important to understand the geomorphological processes leading to the present coastal form, spanning from years to millennia, of the site in question. Examining coastal evolution in response to the post-glacial marine transgression and Holocene still-stand can provide an indication of the sediment budget and contextualise future shoreline response to changes in sea level and the impacts of coastal works.

Evolution of the barrier is a complex outcome of geographically variable changes over time. It continues to be constrained by subtle boundary conditions, such as the onshore rate of sediment supply from the continental shelf. Such changes cannot be measured over short time scales, but may be deciphered through a combination of geomorphological studies with shorter term information, such as survey or modelling studies. At Narrabeen Beach, a combination of data collected using ground penetrating radar (GPR) and a review of background geomorphological studies, including historical photogrammetric analyses of the beach, has informed our assessment. Outputs from a GPR survey along Albert Street are reproduced in Fig. 2. Geological evidence (Gordon and Hoffman, 1986; Hudson and Roy, 1989; Roy and Lean, 1980) and historical evidence (Patterson Britton and Partners, 1993; Public Works Department, 1987) were also interpreted to gain quantitative understanding of the different sediment budget components contributing to historical trends.

The GPR was interpreted temporally by utilising pre-existing stratigraphic data from Narrabeen (Roy and Lean, 1980). Overall, GPR records indicate that progradation of the barrier was punctuated by at least four major erosion events between 7000 and 3000 years before present (Fig. 2b). A fifth erosional signature and seawall associated with a documented series of storms in 1974, were detected within the seaward most portion of the GPR trace (Fig. 2c). The rigour of the interpretations could be improved with further surveys, and the chronology of deposition could be constrained by dating, particularly optical stimulated luminescence (OSL) dating of sand samples from these post-storm signatures. Such analysis could be used to estimate major storm recurrence intervals as well as progradation rates related to sediment supply.

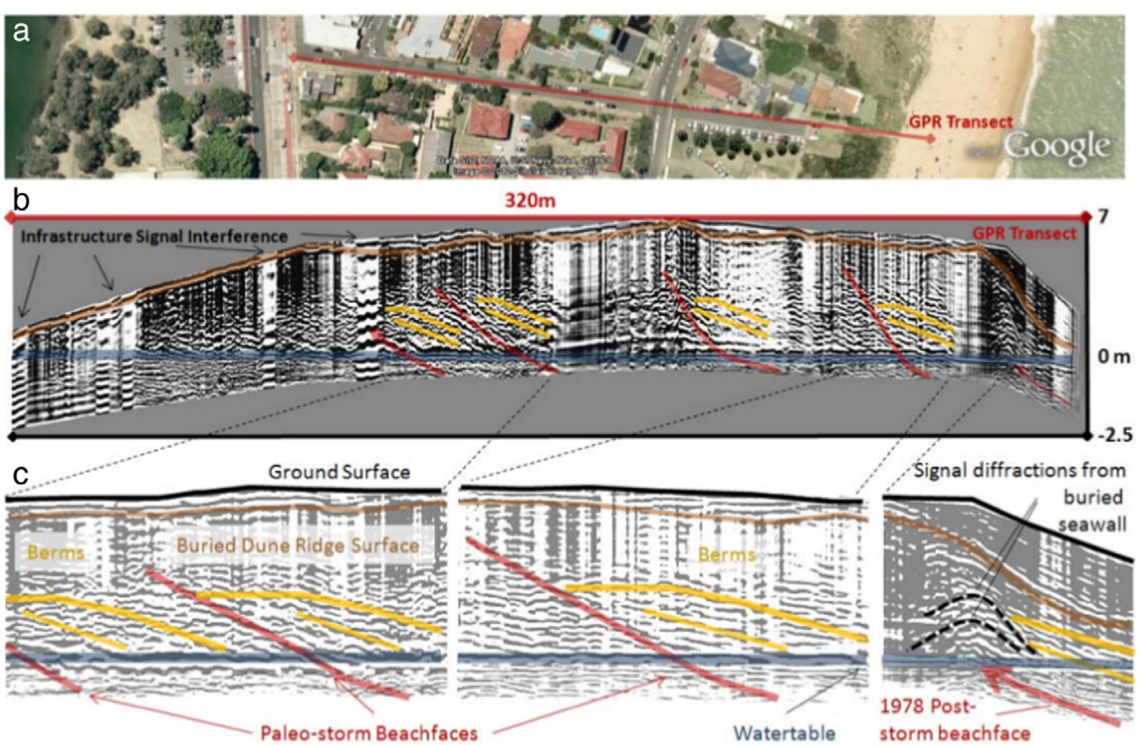

Fig. 2. Representative ground penetrating radar (GPR) data from Narrabeen. This geophysical transect was collected across the central barrier along Albert St. (a) (see Fig. 1 for location). The data from the entire profile shows 5 paleo-beachfaces with a distinct post-storm morphology highlighted in red and the subsequent beach recovery and berm accretion in yellow (b). These features, as well as those of the existing dune (brown) and a buried seawall (black), are displayed in more detail within the cropped and annotated GPR (c). Imagery © 2012 Sinclair Knight Mertz.

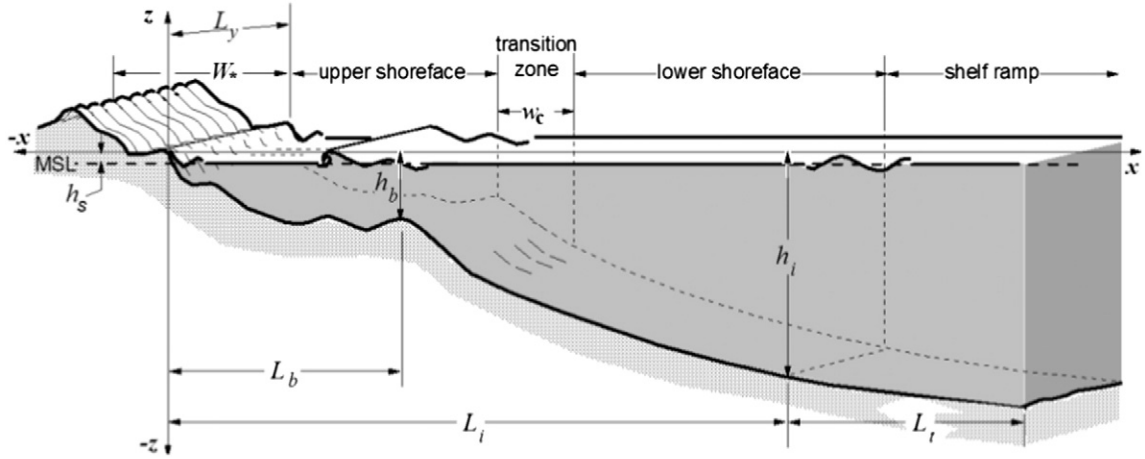

Fig. 3. Cross-shore parameters considered in constructing cross-shore geometry. The cross-shore profile of the inner continental shelf varies in time through constrained geometrical relationships containing a number of parameters. These parameters are assigned for repeated Monte Carlo simulations by sampling from imposed probability density functions of their possible values.

6. Assessing long term trend hazards

For long term trends, including those relating to present day sediment budget and those relating to sea-level rise, the Coastal Tract approach (Cowell et al., 2003, 2006) and Shoreface Translation Model (STM, Cowell et al., 1995) were adopted. The domain over which key parameters vary has been defined in a similar way to that previously undertaken for Manly Beach just to the south of Narrabeen (Cowell et al., 2006).

At Narrabeen the approach utilised Monte Carlo techniques upon a single, laterally averaged cell spanning the coast between Long Reef (southern boundary), and Turrimetta Headland (northern boundary). The cell extended seawards to a depth of 100 m.

The STM solves the conservation of mass equation,

$$V_s - \int h(x-R, t+\delta t) - h(x,t) + S)dx = 0 \tag{2}$$

where V_s is the gross sediment supply from outside the coastal cell summed across all cell boundaries (m^3/m); h is the alongshore averaged bed elevation, t is time and δt is the numerical time increment; R is the shoreline recession distance; and S is the sea-level rise. Eq. (2) balances changes in sand volume along the bed profiles with Vs, with an allowance for sea level rise and recession.

Eq. (2) is solved numerically to obtain quantitative estimates of the change in bathymetry over time. There are numerous uncertainties relating to (i) the amount of sea-level rise; (ii) the external sediment budget components; and (iii) the expected future cross-shore shape $h(x,t)$ which, importantly, may not exhibit geometric similarity to the shape at $t = 0$. Representation of the cross-shore profile is via a function with variable parameters, calibrated through alongshore averaging of terrain and bathymetric data, resulting in the generic geometry illustrated in Fig. 3.

In general, there are six components of long term sediment budget that may need to be considered: (i) littoral supply; (ii) in-situ production, especially biogenic carbonate; (iii) anthropogenic (e.g. sand mining, nourishment); (iv) beach/dune exchanges; (v) beach/tidal inlet exchanges; and (vi) exchange with the continental shelf.

Monte Carlo analysis was used to incorporate key uncertainties into the resulting estimates of shoreline recession. To incorporate uncertainty, probability distributions for all input parameters were imposed. In the case of estimates based on geological evidence, it is generally easier to identify feasible limits for various parameters, meaning that a triangular distribution, bound by those limits is a simple and reasonable representation of probabilities (Cowell et al, 2006). It is also possible to construct sea-level rise trajectories using a normal probability density function. However, given the common practice of IPCC reports (AR4 from 2007 was applied here) to present ranges of likely sea-level rise, a triangular distribution was applied here.

For Narrabeen, an erosion scarp from 1974 was adopted as a base reference line for movement. To enable calibration of the model against historical behaviour, coastal recession estimates from photogrammetric analyses spanning the period 1941 through 1986 (Public Works Department, 1987) were considered. Preliminary model simulations were then undertaken with the probability density functions (PDFs) of minor time-dependent variations in lower-shore geometry fine-tuned until the model generated results that were consistent with coastal recession range estimated from the photogrammetry. These “calibrated” PDFs were then used to simulate future scenarios. In defining the sediment budget, various components were considered including the following:

1) There is a likely northward transport along the inner shelf, offshore from the prominent headlands, and this may represent a net loss of sand to the north of the Narrabeen embayment.
2) A possible range of $-10{,}000 < V_s < 0$ m^3/year sand loss was adopted for the compartment, based on previous photogrammetric analyses.
3) Based on the proportion of carbonate in the total late Holocene sand barrier, an estimate of the carbonate production rate was derived.
4) The rates of accumulation of the sediment volumes over time were assessed using ^{14}C dating and previous analyses (Roy and Lean, 1980). These analyses ultimately indicated that progradation of the Holocene barrier began around 7000 BP, but ceased at some stage after 3000 BP, with subsequent recession.
5) It is estimated that sand is lost to the Narrabeen Lagoon flood tide delta at a rate of 6500 m^3/year. Much of this sand is presently removed through a clearance operation and used to replenish the southern end of the beach (i.e. at Collaroy).
6) It is possible that eroded sand from the upper profile will be sequestered within accommodation space on the lower shelf, particularly under the effects of sea-level rise. The degree to which the lower shoreface dilates with rising sea level is also treated as uncertain, and modelled by adjusting the probability distributions representing some of the parameters in Fig. 3.

7. Assessing short term variability

Sandy beaches are inherently dynamic, undergoing gradual changes in response to incident waves and tidal variations. The most apparent changes occur as a result of increased wave energy during a storm event or a series of storms. Storms erode the beach causing flattened beach profiles, erosional dune scarps and, on occasion, wash-over deposits. During storms, sand is transported offshore (either by 2DV processes such as undertow or 2DH processes such as rips), typically forming nearshore bars which are later reworked onshore by lower-energy swell waves. Post-storm recovery of the sub-aerial beach face has been well documented, although the rate of recovery can vary substantially from beach to beach.

At Narrabeen, the probabilistic storm erosion model (JPM) of Callaghan et al. (2008) was adopted. The previous storm response analysis presented by Callaghan et al. (2008) for a central profile at Narrabeen Beach was expanded here to include five profiles along the entire beach. The model incorporates analysis of five variables: (i) storm duration (D); (ii) peak significant wave height (H); (iii) storm maximum tidal anomaly (R); (iv) significant storm wave period (T); (v) wave direction (Dir); and (vi) inter-storm period (dt).

Generalised Pareto distributions were fitted to H, D and R and logistics joint probability distributions between H and D (relatively strong) and H and R (relatively weak). T is related to H via a distribution derived from the standard log-normal distribution with additional parameters included to reflect physical constraints to the relationship between T and H (Callaghan et al, 2008). Wave direction is empirically distributed, based on measured storm data. Inter-storm arrival time is assumed to be a Poisson process, with an expected arrival frequency that varies annually. It is noted that alternative statistical modelling is possible particularly with respect to joint probability, where alternative methods such as copula functions could be adopted (Li et al., 2014).

The JPM was based on the analysis of available storm data from Sydney. A site-specific analysis would be required to justify appropriate interrelationships and probability distributions at other sites, but it is suggested that similar relationships to those described above may apply to similarly sited beaches. Some variation is expected to result from differences in the weather conditions that cause storms along any given coast (e.g. Corbella and Stretch, 2012).

The statistical model enables rapid sampling of realistic storm → inter-storm sequences. For planning periods (say ~100 years) sampling of the sequence of storms and periods of relative calm can be repeated thousands of times, for subsequent Monte Carlo analysis. The resulting progression of storm and inter-storm arrival periods enable simulation of storm erosion and subsequent recovery sequences.

A significant point regarding this method is that it doesn't rely on a "design" storm specification. The "design" storm concept is problematic when considering the erosion of sandy coastlines, as multiple closely spaced storms, where recovery may be incomplete, may have a cumulative effect of the same magnitude as a single large storm. The effect of antecedent morphology is very important, as demonstrated by the May–June 1974 storm events in Sydney, a sequence of storms that is often used as a benchmark for design purposes in New South Wales.

Specification of the beach recovery rate is also difficult, and at this stage does require the availability of suitable site-specific data to estimate the rate of that process. In the case of Narrabeen, an exponentially decreasing recovery rate was adopted, based on the findings of Ranasinghe et al. (2004).

For calculating erosion, the time series of storm waves was converted to equivalent conditions at 20 m water depth (i.e. outside the surf zone) using pre-calculated wave transformation tables from the wave model SWAN (Callaghan and Wainwright, 2013), and surf zone transformations using linear wave theory, assuming parallel contours.

Subsequently, the dune erosion model of Larson et al. (2004) was applied to determine erosion volumes. Larson et al.'s (2004) model relates the volume of eroded sand to the impact force caused by bores running up the beach and striking the eroding dune face. Geometrical relationships are then adopted to transfer eroded volume to a line at the top of the eroding scarp. The location of that scarp as it erodes and accretes is tracked during simulations and the results of many simulations can thereafter be analysed statistically to provide quantitative estimates of dune scarp recession for risk assessment. The most landward scarp location in each simulated year was recorded for use in subsequent statistical analyses. More detail on this probabilistic coastline recession approach (the PCR method), including the allowance for sea-level rise, is presented in Ranasinghe et al. (2012).

In summary, the Monte Carlo model approach used here adopts the following steps:

1. Generate a 110-year (1990–2100) storm time series using Callaghan et al.'s (2008) joint probability model;
2. If sea-level rise is to be incorporated, estimate the sea-level rise at the time each storm occurs using IPCC projections of sea level rise;
3. For each storm, estimate dune recession using the physics-based dune impact model of Larson et al. (2004), while allowing for dune recovery in-between storms;
4. Determine the most landward position of the dune during every year of the 110-year simulation;
5. Repeat steps 1–4 until convergence is obtained for exceedance probabilities greater than 0.01% (i.e. bootstrapping).

8. Probabilistic combination of the hazards

Different approaches to combining long and short term hazards were considered. Firstly, the PCR method can incorporate a deterministic sea-level rise projection as input, if such a projection is stipulated by local government regulations or policy. Secondly, the PCR method can be executed with the input of statistically sampled sea-level rise projections based, for example, on the range of projections published by the IPCC. Thirdly the STM, which incorporates statistical sampling of sea level rise as an input to its Monte Carlo simulations, can be used to derive a probability distribution of long-term recession. This was combined with a corresponding probability distribution of short term change from the PCR method executed without sea-level rise.

Combination of the long-term and short-term coastal hazard distributions for a selected future time is achieved via the convolution operation shown as Eq. (3). The concept is demonstrated visually in Fig. 4.

$$(f \times g)(x) = \int_{-\infty}^{\infty} f(x-\tau) \times g(x) d\tau \tag{3}$$

where x is the scarp location relative to present; $f(x)$ is the probability density function (pdf) of setback due to short term hazard; $g(x)$ is the

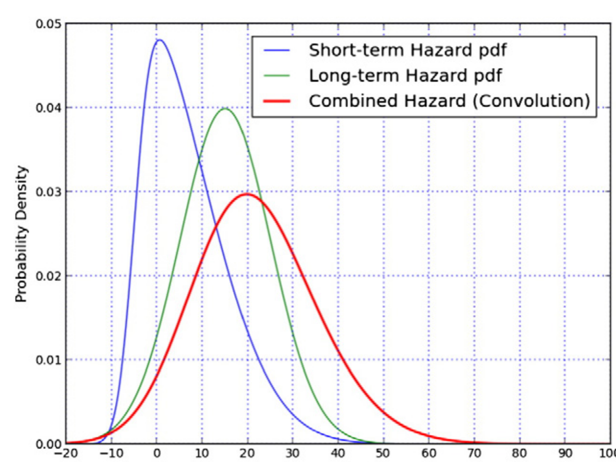

Fig. 4. Combination of long term and short term coastal hazard probability density functions. A convolution is performed to derive the combined hazard. The short term hazard pdf is considered to be invariant with future projection, whereas the long term hazard pdf varies depending on the future time frame being considered.

pdf of setback due to long term hazard; and $(f \times g)(x)$ is the pdf resulting from convolution of $f(x)$ and $g(x)$.

There are a number of disadvantages associated with each of the three approaches outlined above. The first approach does not acknowledge the uncertainty inherent in sea-level rise projections. The input of sea-level rise into the PCR (for the first and second approaches) and subsequent use of that approach in the dune impact model of Larson et al. (2004) does not consider more broad scale changes to the beach profile, occurring in areas away from the immediate beach face. Use of the STM (third approach) necessitates longshore averaging of the long term hazard signal, meaning that alongshore variations to wave exposure are not considered.

For all approaches, the combined coastal hazards are determined at a series of shore normal profiles and interpolated along the beach. Clearly, this does not fully include longshore processes (rip cells and longshore drift) that are important in the evolution of the beach across both short and long time frames. The convolution operation, while probabilistic, comprises a linear combination of the long-term and short-term coastal hazards without consideration of the non-linear interactions between these.

At present, limitations such as these need to be accepted due to an incomplete understanding of the processes driving coastal evolution, and the need to make sure that the large number of Monte Carlo computations remain feasible using available computing facilities.

9. Determining the economically "optimal" setback line

In this application, the PCR model was applied along 5 cross-shore profiles at Narrabeen beach with a deterministic sea level rise of 0.9 m by 2100 (relative to 1990). A typical PCR model output for Profile 4 is shown as Fig. 5.

By longshore averaging the model results obtained at the more or less equally spaced 5 cross-shore profiles along Narrabeen Beach, a series of longshore aligned percentage exceedance curves were constructed. Together, these represented the "hazard" likelihood side of risk analysis. These help to derive the most likely "cost" when combined with the value of development in the coastal zone.

Risk management often includes an assessment of costs and benefits. Here, an economically optimal setback line (EOSL), following the methodology of Jongejan et al. (2012) was derived. Importantly, that method assumes a world without "market imperfections", such as a lack of perfect information, or moral imperatives for decision makers to provide safety to the public. It is argued that, in a perfect market, individuals behave to maximise profit and would only invest in coastal zones if the balance between risk and reward was positive. In reality, there are legal, moral, policy and regulatory constraints which mean that a "perfect market" is not achieved. Accordingly, the analyses undertaken here should be considered as one part of a more comprehensive assessment. The analysis is useful as it considers the cost of opportunities that would otherwise be foregone, if development is prevented on coastal land.

The probability of damage increases seawards. This indicates that a point exists where risk starts to outweigh reward. Without market imperfections, an undeveloped zone along the coastline would naturally arise. The EOSL could be interpreted as the line which would separate undeveloped and developed zones, where the balance between risk and reward is negative and positive, respectively.

At Narrabeen, we have divided property investments into infinitesimally small geographical units, each with their own independent return on investment. Each unit is assumed to be completely damaged when impacted by coastline recession, requiring full replacement. Furthermore, we assume the cost of risk bearing equals expected loss. This is reasonable where efficient insurance markets or other mechanisms exist for risk transfer.

The net present value of an investment $NPV(x)$ at a distance x from today's coastline becomes:

$$NPV(x) = -I_0(x) + \int_0^{T(x)} \left(I_0(x) \times r(x,t) \times e^{-\gamma t}\right)dt - \int_0^{T(x)} \left(I_0(x) \times P(x,t) \times e^{-\gamma t}\right)dt \tag{4}$$

where $I_0(x)$ is the investment at distance x at $t = 0$, $r(x,t)$ the rate of return on the investment at time t, γ the discount rate, $T(x)$ the lifetime of an investment at distance x from today's shoreline, and $P(x,t)$ the probability of damage at distance x at time t.

At Narrabeen, both property values and the rate of return on investment generally increase towards the coastline. The EOSL can be found where the net present value $NPV(x)$, as defined by Eq. (4), drops below zero (Fig. 6). When the rate of return and the probability of damage are time-invariant, the optimal setback line is therefore found where:

$$P(x) = r(x) - \gamma. \tag{5}$$

Hence, in case of time-invariance, the economically optimal exceedance probability equals the difference between the rate of return on investment and the discount rate.

When risks gradually increase due to climate change (time varying probability of damage), it becomes economically optimal to introduce a safety margin by lowering the exceedance probability of the setback

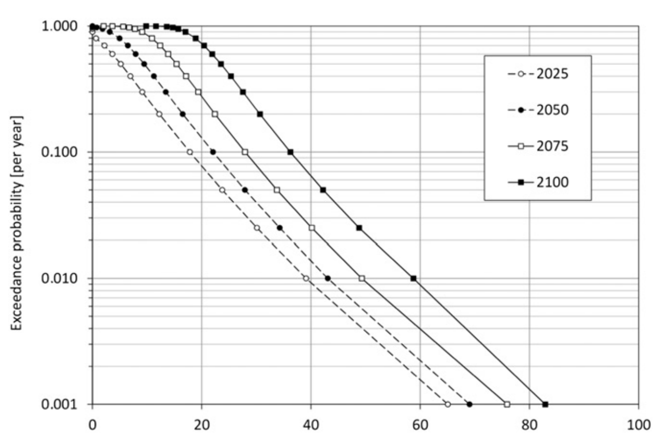

Fig. 5. Cumulative probability distribution functions for maximum over various future planning horizons. Values for "Profile 4", near the middle of Narrabeen Beach.

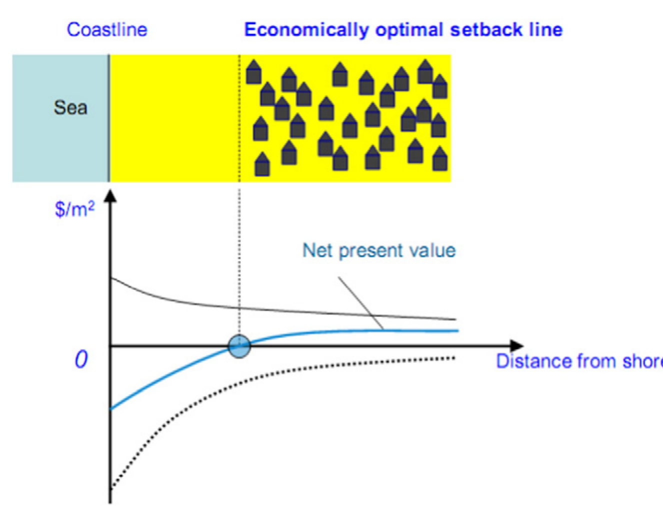

Fig. 6. Location of the Economically Optimal Setback Line. The line exists at the landward extent where the return on investment exceeds the cost of damages.

line that is used for guiding today's land-use planning decisions. This margin is highly dependent on the intensity of climate change impacts.

Site specific property value data for the Collaroy–Narrabeen embayment were obtained from the office of the NSW Valuer General, which assesses and publishes the value of unimproved land, and from real estate agents in the Narrabeen Area. These data were processed spatially, using exceedance curves established from the hazard analyses, and a spatial application of the economic model outlined above. From these calculations, an EOSL for the Collaroy–Narrabeen embayment was determined as shown in Fig. 7.

10. Conclusions

The risk assessment framework developed here represents an extension of the deterministic methods that are commonly applied in locations such as New South Wales, by the inclusion of stochastic methods.

The types of models available and computational capacity to undertake such assessments will improve over time. The models used here were intentionally simplified to make them computationally efficient.

The adoption of a range of estimates of different probabilities represents a more transparent means of communicating the uncertainty

Fig. 7. A segment of an EOSL (~2010 development) derived for Collaroy Beach. For this example, the PCR model was used with deterministic mean sea-level rise increases of 0.4 m at 2050 and 0.9 m at 2100 (relative to 1990). The EOSL (black line in Fig. 5) has an approximate exceedance value of around 0.3% per year. Economic risk seaward of the EOSL is notably higher. The line derived here is further seaward than that obtained by more traditional deterministic methods.
Aerial Photograph courtesy of Warringah Council.

with which coastal engineers and scientists may view coastal processes and hazards, particularly when projecting future scenarios.

The derivation of an Economically Optical Setback Line (EOSL) provides an illustration of how probabilistic hazards can be integrated to a likely damage value in a way which provides an indication of where to best place development without unnecessarily precluding development which would otherwise be of significant benefit to society. However, it needs to be considered in context of the "perfect market" assumption, which is generally not realised in the real world.

While a single EOSL might be derived using the approach presented herein, the limitations of the analyses need to be made clear to decision makers, the public and other stakeholders, so that these limitations can be taken into account during ensuing discussions and the final decision making process. This is a difficult yet rewarding task and involves early, clear and consistent communication during the process so that well informed and socio-economically acceptable decisions can be made. While a particular setback line may be recommended on the basis of a pure, risk based, economic assessment, the discretion of decision makers during their consideration of other factors may result in the adoption of a different setback line or even an entirely different approach to planning.

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