HOW TO WEIGH COASTAL HAZARD AGAINST ECONOMIC CONSEQUENCE

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ABSTRACT

It is well recognised that sea level change over the coming century will have an extraordinary economic impact on coastal communities. To overcome the uncertainty that still surrounds the mechanics of shoreline recession and stochastic forcing, land-use planning and management decisions will require a robust and quantitative risk-based approach. A new approach is presented, which has been evaluated using field measurements and assessed in economic terms.

The paper discusses a framework for coastal risk analysis which combines four main components 1) the effects of non-stationary climate, including decade scale variability and anthropogenic change; 2) a full probabilistic assessment of incident wave and surge conditions; 3) determination of storm erosion extents; and 4) the economic impact of combined coastal erosion and recession. The framework is illustrated in **Figure 1**. The operation of this framework has been demonstrated, building upon previous work (Callaghan et al., 2008; Jongejan et al., 2011; Ranasinghe et al., 2011).

The first three components relate to physical hazards. Using stochastic simulation, we quantify the 'likelihood' side of risk. That likelihood is typically represented by lines indicating a projected extreme landward shoreline condition and an associated quantitative probability. For the first time, the effects of non-stationary climate (e.g. sea level rise) have been included. This can be extended to include decadal scale climate variation effects such as beach rotation.

The fourth component requires the determination of values associated with land threatened by coastal erosion during the time frame being considered. We assign a spatially varying value density relationship. The exceedance probability of erosion is combined with the value density to calculate the expected value of damage at a given point in time. In a non-stationary climate scenario, the exceedance probabilities change with time, and this is also considered.

Given a known rate of return on investment, the differentials in the rates of return (between coastal and inland property investments) are subsequently used to determine the efficient position of the setback line. The results are presented within a GIS framework to effectively feed into the coastal land use planning process. We demonstrate the framework by applying it to using real data (both physical and economic) for our subject site, Narrabeen Beach in Sydney.

A RISK AWARE APPROACH

Using standard definition (AS/NZS ISO, 2009) a risk is "an effect of uncertainty on objectives". A standard risk assessment comprises three steps, namely

- Risk identification
- Risk Analysis
- Risk Evaluation

The objective is to maintain economic viability, and the uncertainties associated with coastal processes such as the timing of and size of storms, and the amount of sea level rise are key. Complete identification and description of the risk considered here is:

"That, within an assigned planning time frame, the face of the dune at the back of a beach will move to a landward location as a result of ongoing recession, sea level rise and variability caused by storms and climate. Further, that landward location may be such that the total value of assets lost, or damage requiring repair, would make investment in those assets unviable over the specified planning time frame"

This poster paper deals primarily with risk analysis and evaluation:

- The likelihood of the dune position being at a particular location at a given point in time;
- The consequences of that dune position, represented by property value density landward of the present dune location; and
- evaluation on purely economic terms, using net present value analyses.

MEDIUM TO LONG TERM TRENDS: SEA LEVEL RISE AND RECESSION

The impact of long term recession is assessed stochastically. A variety of methods can be applied here, depending on the assumptions made and the time scale considered. For example, the Shoreface Translation Model (STM) (Cowell et al, 1995) is a two-dimensional cross-shore profile model which simulates large scale coastal behaviour based on geometric rules of shoreface and barrier morphology. That model tracks movement of the entire shoreface, a long term process that responds to sea level rise and can be run in a stochastic, Monte-Carlo mode. Alternatively, the PCR model (Ranasinghe et al, 2009) considers erosion of the dune, following the method of Larson et al. (2004) and subsequent recovery. That model can also be run in a stochastic manner, adopting randomly generated time series derived using the JPM method of Callaghan et al. (2008).

A key input is the amount of sea level rise (SLR) and, following standard practice, we consider here SLR between 1990 and 2010. Tabulated values for the 5 and 95 percentile SLR values for the A1FI emissions scenario (rapid economic growth with intensive fossil fuel use) at 2050 and 2100 were obtained from Hunter (2010). Based on advice from Nichols et al. (2011), the probability density variation between these values is assumed Gaussian (**Figure 2**). Through random sampling and subsequent fitting of a second order polynomial, a SLR trajectory can be sampled for use in stochastic simulation. Additional SLR components can be added for local gravitational and isostatic adjustments, depending on available information.

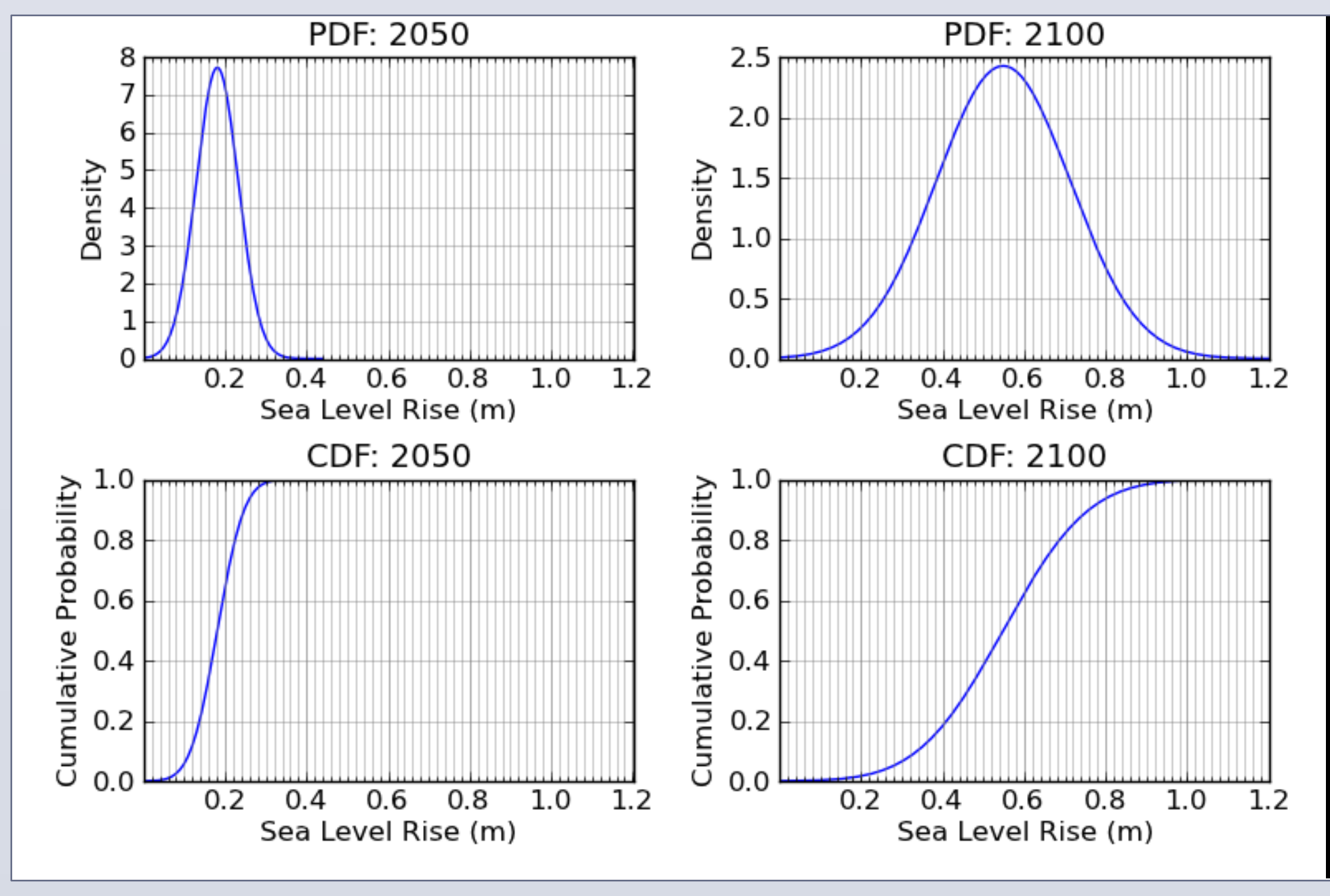


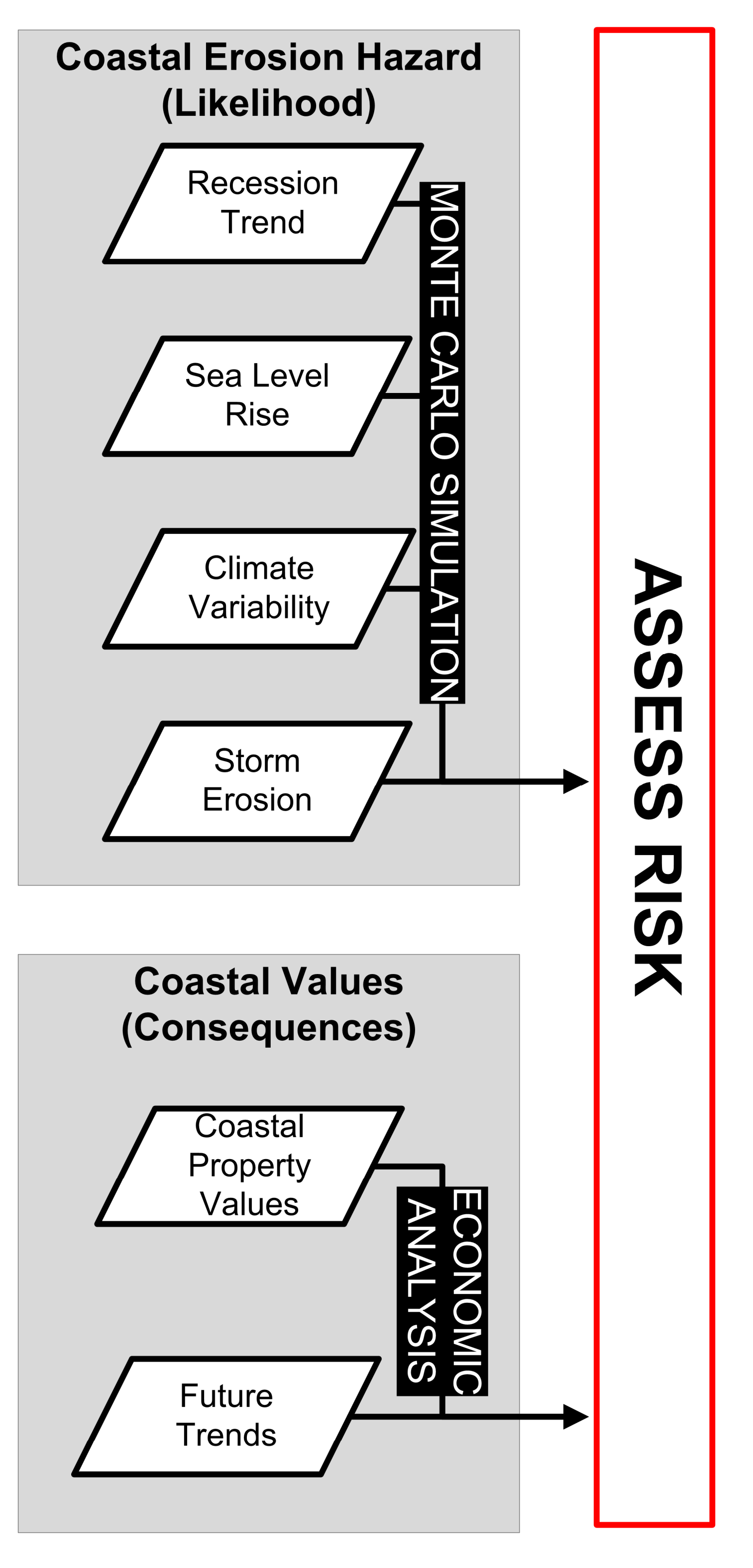
Figure 2: Probability distributions were derived for SLR at 2050 and 2100, based on published values and the assumption of Gaussian variation. Corresponding random samples are subsequently extracted for 2050 and 2100 and second order polynomial fitted to generate a random SLR trajectory for all 110 year simulations within the stochastic modelling framework

VARIABILITY: STORM EROSION AND CLIMATE

Stochastic modelling of storm erosion and recovery processes is required to determine probability distributions of shoreline location. The Joint Probability Method approach (JPM, Callaghan et al. 2008a) uses recent developments in extreme value modelling to include allowances for joint probability between all basic erosion variates including; maximum wave height during the event, representative wave period and direction, event duration, tidal anomaly and event spacing. Event grouping, where significantly more erosion can occur from two closely spaced storms is handled by temporally simulating the synthetic wave climate and the resulting beach erosion and accretion. Using stochastic modelling, numerous (50,000 to 100,000) 110 year long time series of storm and inter-storm recovery periods are generated and the resulting nearshore conditions provided to a cross-shore profile model.

The approach was validated against ~30 years of beach profile data from Narrabeen Beach and found to replicate the statistical response of the shoreline with reasonable reliability (Callaghan et al. 2008a). To date, a variety of cross-shore profile methods have been tested within this framework, including that of Kriebel and Dean (1993), Larson et al (2004), SBeach and XBeach (Callaghan et al, 2008a,2008b; Ranasinghe et al, 2009; Riesenkamp,2011). Overall, it was found that the more computationally intensive numerical models do not add certainty to the resulting estimates of extreme erosion when compared to the simpler profile models. Considering the computational demand, simpler profile models make a sensible choice at the present time.

A sample of the type of output acquired for a single profile is provided as **Figure 3**. The results obtained do not presently incorporate an allowance for beach rotation, known to occur at Narrabeen (Short and Trembanis, 2004) and are representative of conditions at the 'fulcrum' of the beach rotation process.



Coastal Erosion Hazard (Likelihood)

Recession Trend

Sea Level Rise

Climate Variability

Storm Erosion

MONTE CARLO SIMULATION

Coastal Values (Consequences)

Coastal Property Values

Future Trends

ECONOMIC ANALYSIS

ASSESS RISK

Figure 1: In this risk assessment process, the likelihood of the beach eroding landward to a given location is quantitatively modeled. The consequences of that erosion are represented by the existing coastal property values and estimated future trends. These are combined to assess the risk using net present values, with an overall economic loss considered an undesirable risk

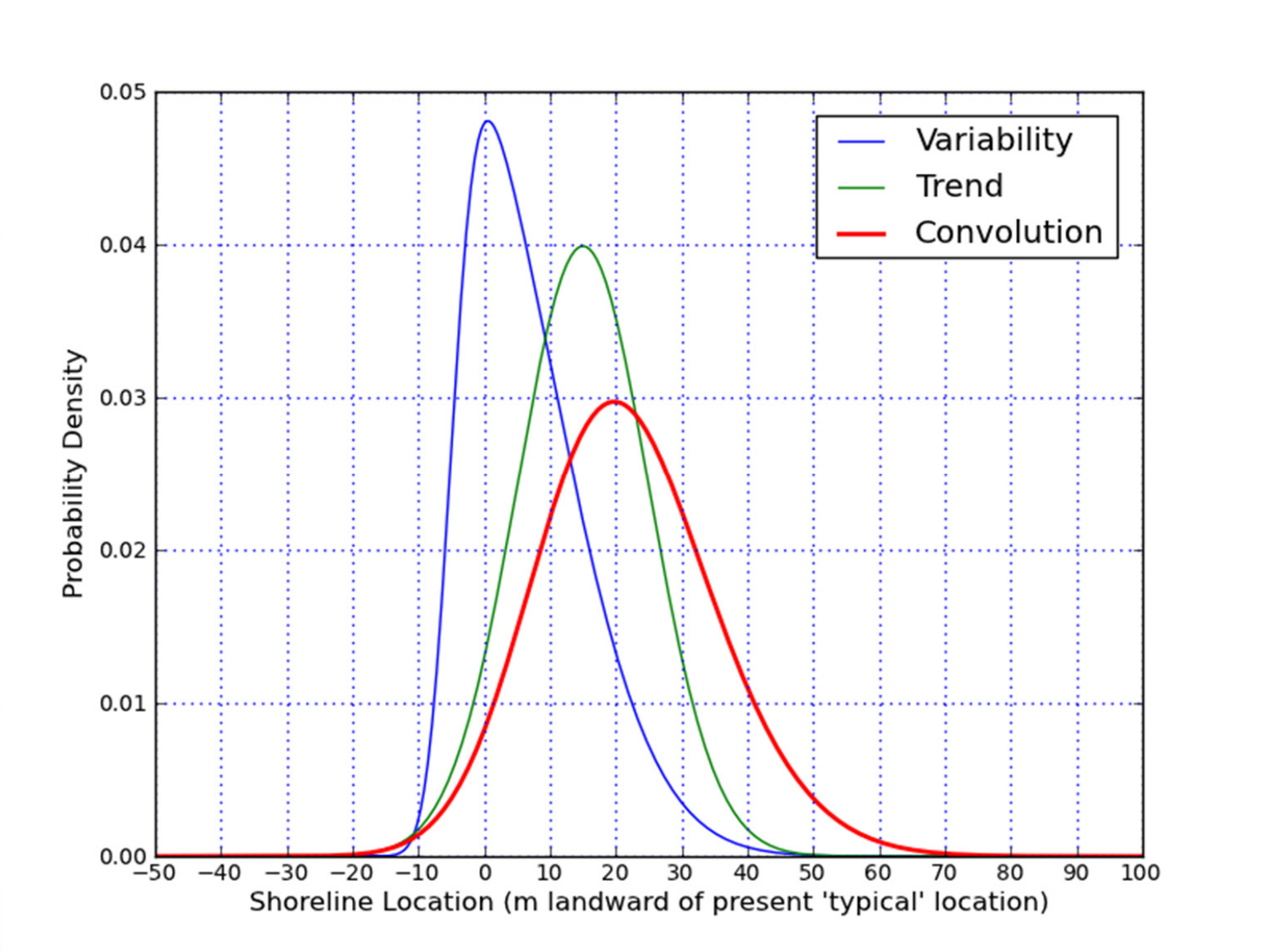


Figure 4: Example combination (convolution) of short term variability and medium- long term trends in shoreline location.

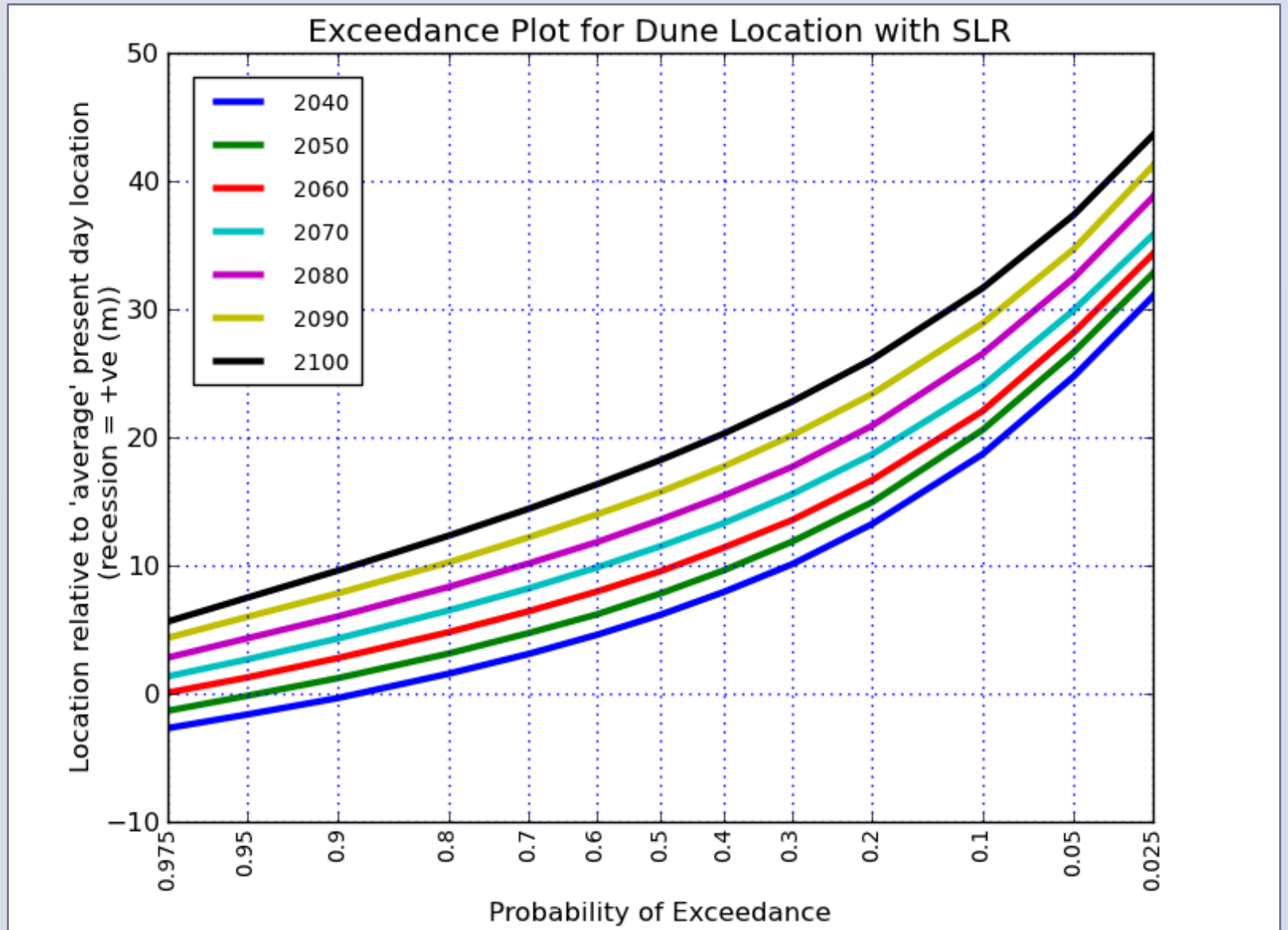


Figure 5: Combined exceedance curves incorporating both variability and recession due to SLR. Results are for a single shore normal profile

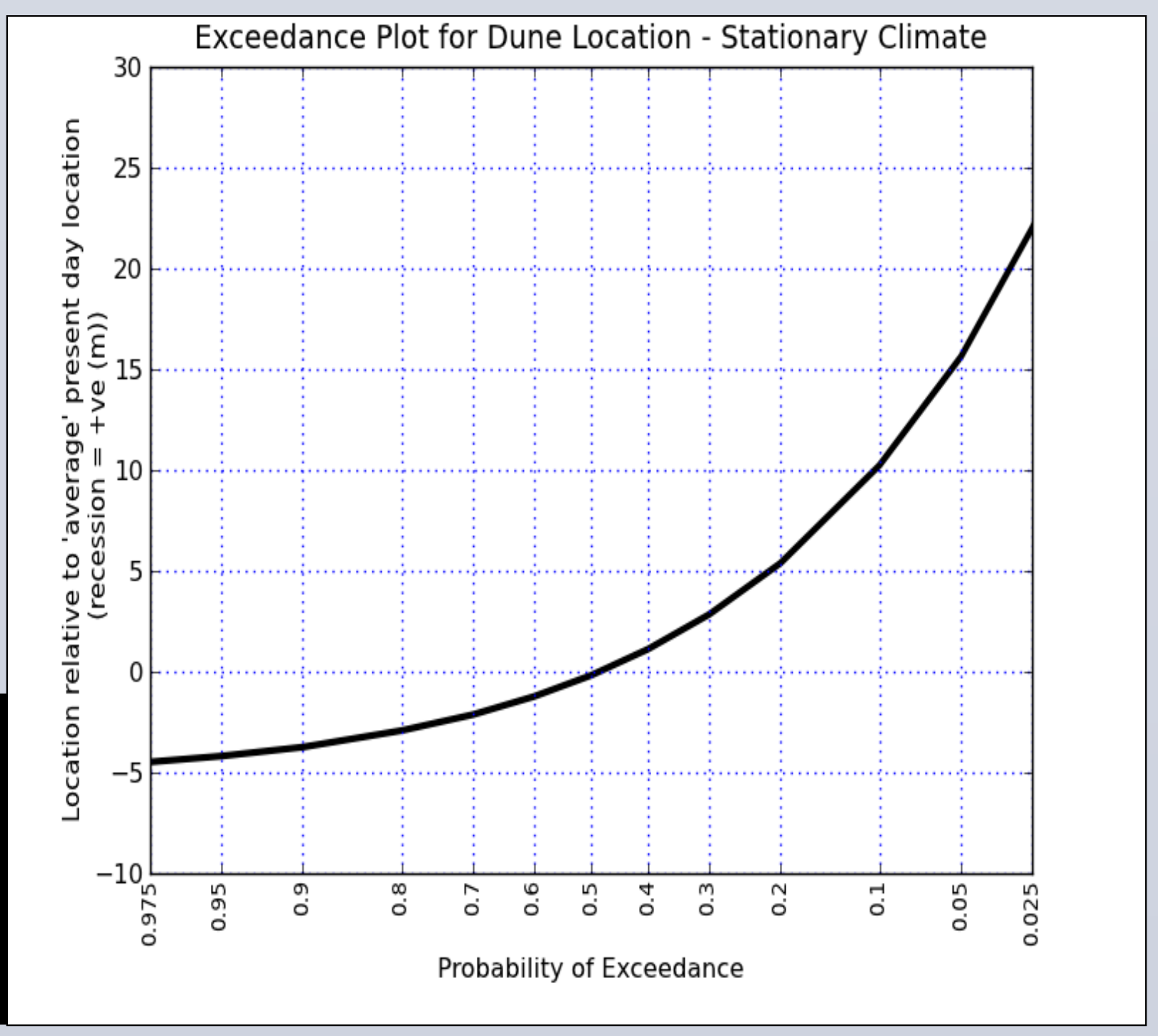


Figure 3: A Dune location exceedance probability curve for a single beach profile under present day conditions. A value of zero represents the median 'most landward' location during a given year of analysis. Positive values indicate a more landward (i.e. eroded) dune and negative values more seaward (i.e. accreted) dune. The nature of this curve varies along the beach, and will also vary in accordance with a change in mean sea level or wave climate, both expected to result from climate change.

LIKELIHOOD

To combine the probability density functions for variability and medium to long term trends a numerical convolution procedure is adopted following:

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

where:

$x =$ distance from present day location
$f(x) =$ first probability density function (e.g. variability)
$g(x) =$ second probability density function (e.g. long term trend)
$(f \times g)(x) =$ convolution of $f(x)$ and $g(x)$ (i.e. pdf resulting from combination of $f(x)$ and $g(x)$)

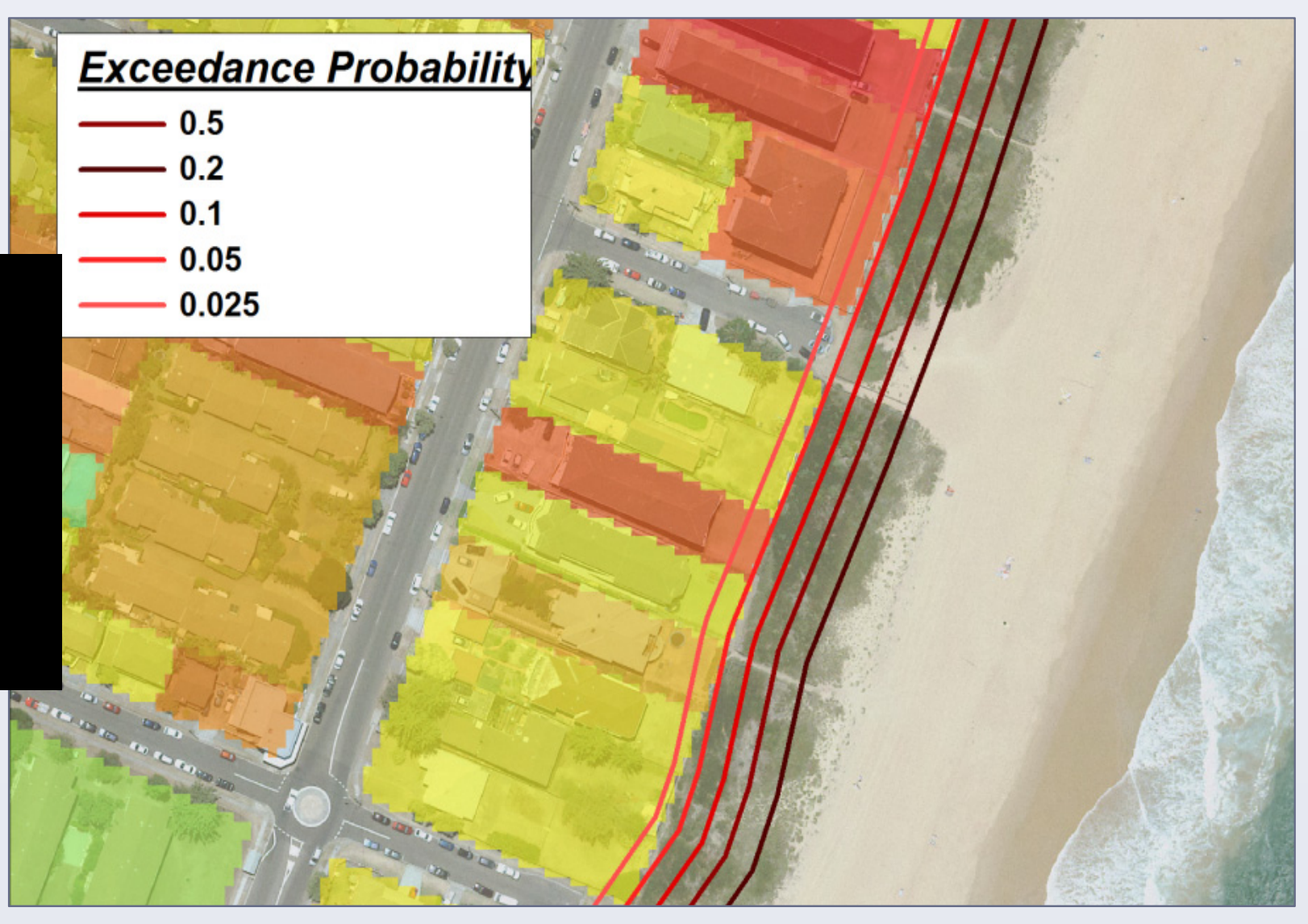
Figure 4 demonstrates the process assuming idealised probability distributions. Again, for each profile, the exceedance probabilities of particular dune locations are determined for a variety of future times (as shown in **Figure 5**). By connecting corresponding results for a number of shore normal profiles along the beach, areas at risk can be defined geographically, as described in the next section.

CONSEQUENCES

The consequences of the recession line reaching a particular location are assessed in terms of economic value. Values represented here were acquired for individual land parcels from historical figures provided by the New South Wales State Government, and recent sales data.

The value density of each land parcel (value / area) is calculated and converted to a gridded data set to enable spatial calculation. Economic data on the trends of prices are also required to project the value density grid into the future. A sample value density grid, along with projected dune location lines and assigned probabilities is illustrated in **Figure 6**.

Figure 6: Dune location exceedance lines overlain on a sample value density grid. Areal Integration of the value density landward of the exceedance line results in the representative loss of value, should the dune reach that location.



RISK EVALUATION

From an economic perspective, the aim is to derive a setback line (buffer zone) for development. To be economically efficient, the cost of risk bearing must be weighed against the cost of foregone land-use opportunities. In a non-stationary climate scenario, the economic viability varies over time. With shoreline recession, the expected value of damage at a location will exceed the annual return on investment at a certain time T^*. Beyond that time, it is assumed that the investment is no longer viable, and no cash flow (neither positive, nor negative) is associated with that particular location. A Net Present Value (NPV) calculation at each location which incorporates a non-stationary climate is:

$$NPV(x) = \int_0^{T^*} r(x).I(x).e^{-\gamma t}.dt - I(x) - \int_0^{T^*} P(x).I(x).e^{-\gamma t}.dt$$

$t =$ time in years
$\gamma =$ adopted discount rate (/yr)
$I(x) =$ initial investment ($\$/\mathrm{m}^2$)
$r(x) =$ rate of return of investment at distance x from the coastline ($\$/\mathrm{m}^2/yr$)
$P(x) = 1 - F_x(x) =$ probability of damage at a distance x from the coastline ($/yr$)
$F_x(x) = \int_{\infty}^{x} f_x(x)\,dx =$ cumulative distribution function of dune location
$I(x).e^{-\gamma t} =$ future discounted value of initial investment ($\$/m^2$)

The three terms comprise 1) an ongoing positive cash flow representing returns from the initial investment; 2) the initial investment; and 3) an ongoing negative cash flow resulting from intermittent damage from coastal storms. This risk assessment asserts that the economically optimal setback line should be located such that the net present value equals zero. The technique described above forms the basis of the Probabilistic Coastal Setback Line (PCSL) model, which is described in more detail in Jongejan et al. (2011).

The PCSL was used at Narrabeen to investigate two scenarios with spatially constant rates of return, one of low returns ($\gamma = 2.5\%, r = 3.4\%$) and one of high returns **(**$\gamma = 3.4\%, r = 5.4\%$**)**. Both scenarios were executed both with and without sea level rise. The present day dune location exceedance level for efficient setback lines was determined using the PCSL for the four resulting scenarios:

- Without Sea Level Rise, Low Returns: 0.009
- Without Sea Level Rise, High Returns: 0.014
- With Sea Level Rise, Low Returns: 0.0015
- Without Sea Level Rise, High Returns: 0.0045

In other words, for a stationary climate, the setback line adopted would sit at a location where there is presently a 0.9 to 1.4% chance of the beach eroding to that location in a given year (i.e. around once every 100 years on average) . For the sea level rise scenario, that line is shifted further back, where there is a corresponding 0.15 to 0.45% chance of exceedance.

CONCLUSIONS

A framework for determining an economically optimal and risk based set back line for coastal development has been presented. The method is underpinned by fully stochastic and physically based models of hazard over both short and medium-long term time scales. Using economic viability as the criteria, it has been demonstrated that future climate change and sea level rise in particular, can reasonably affect present day planning decisions. The assumptions made regarding the magnitude of the effects of climate change are of key importance.

A risk assessment which goes beyond economic viability would also consider the effects of beach amenity, business interruption and other social and environmental criteria. Some of these have been outlined for Narrabeen Beach by Anning et al.(2009). The acceptance of risk is essentially a moral judgment which economics can only inform. The assessment made herein needs to be combined with broader analyses that provide a more rounded basis to support decision making.

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