



AN INNOVATIVE APPROACH TO DETERMINE ECONOMICALLY OPTIMAL COASTAL SETBACK LINES FOR RISK INFORMED COASTAL ZONE MANAGEMENT

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Abstract: Current methods used to determine Coastal setback lines have several limitations. Furthermore, the historical practice of defining setback lines based on a single deterministic estimate is also proving inadequate with the emergence of risk management style coastal planning frameworks which require probabilistic estimates of coastal recession. This paper describes an innovative approach for the determination of the economically optimal coastal setback line which combines an economic risk model and a process based, probabilistic coastal setback line model. It is anticipated that this new approach is highly suitable to provide vital information for risk informed coastal zone management.

Keywords: Coastal Risk assessment; Coastal zone management; Coastal setback line; Coastal recession; Narrbeen beach; Sea level rise.

INTRODUCTION

Accelerated coastal erosion due to climate change represents a major threat to coastal communities and assets worldwide. Consequently, the establishment of effective setback lines, which represents the 'retreat' and/or 'accommodate' adaptation philosophies, is now a delicate issue. Effective setback lines should not only ensure the safety of coastal communities/assets but also ensure that multi-million dollar land use opportunities are not forgone.

Coastal setback lines have historically been determined by separately estimating ephemeral erosion due to storms and long term recession trends (e.g. due to longshore sediment transport gradients and sea level rise (SLR)). Generally, the various components are estimated using a variety of methods such as aerial photogrammetry, numerical modelling, field data etc., and added up to obtain a single deterministic estimate of the setback line. Obviously this approach has several limitations. These include (but are not limited to): double counting (e.g. long term recession due to SLR and due to longshore transport gradients), data aliasing when using sparse field data (e.g. aerial photographs obtained every 3-5 years to determine long term recession), and the use of crude and inaccurate models (e.g. Bruun rule for SLR induced recession). Furthermore, the historical practice of defining setback lines based on a single deterministic estimate is also proving inadequate with the emergence of risk management style coastal planning frameworks which require probabilistic estimates of coastal recession. Recognising these issues, Jongejan et al. (2011) developed an innovative approach that combines an economic risk model and a process based, probabilistic coastal setback line model to determine the economically optimal coastal

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setback line at a given location. This paper provides a brief summary of the approach and outlines its application to a case study site in Australia: Narrabeen beach, Sydney.

The risk-informed approach presented in this paper requires probabilistic estimates of coastal erosion volumes. Callaghan et al. (2008) presented a probabilistic approach to determine the full range of dune erosion due to storms within a probabilistic framework (JPM model). This method makes use of marginal and conditional distributions fitted to long time series of wave and water level data in conjunction with a process based dune erosion model to calculate the exceedance probabilities of dune erosion. The model output can be used to directly determine, for example, the 1 in 10yr or 1 in 100yr dune erosion volume at a given site. Similarly Ranasinghe et al (2009) presented a process based, probabilistic model (PCR model) to determine the exceedance probabilities of coastline recession due to sea level rise. This model represents a marked shift from the historically adopted Bruun rule approach of determining coastline recession due to SLR. The PCR model (Ranasinghe et al., 2009), which is an extension of the JPM model, can be directly used to determine the exceedance probability of the coastline recession that maybe expected for a given planning horizon.

To effectively use probabilistic estimates of the various contributors to coastal erosion within a risk based framework, it is necessary to differentiate between uncertainties that develop differently over time in the various different contributors. For example the uncertainty associated with short term storm erosion develops differently to that associated with long term recession due to SLR and decadal oscillations in climate (forcing). This is due to different processes or forcings that govern or drive these phenomena and/or due to the difference in current predictive capabilities for the different phenomena. Furthermore, risk based coastal management also requires that the economic value and lifetime of property/infrastructure developments be taken into account in arriving at optimal management strategies. These are two important aspects that are seldom considered when establishing coastal setback lines. This paper aims to generically demonstrate the effects of ignoring these aspects and proposes simple rules that can assist coastal planners/managers to determine coastal setback lines that optimise the balance between risk and reward. The proposed risk informed approach is applied to Narrabeen beach, Sydney, Australia to illustrate its potential in rationalising decisions for land-use planning in coastal regions.

METHODS

Quantifying coastal recession risks:

Two inputs are needed for quantifying coastal recession: (i) an exceedance probability distribution of the extent of coastal recession, and (ii) a value density function that describes the spatial distribution of the value at risk (existing or planned) (Vrijling et al., 2002) (Fig. 1).

The probability of damage at a specific distance from shore ($P(x)$) equals the probability that erosion causes the shoreline to retreat beyond x :

$$P(x) = 1 - F_e(x) \quad (1)$$

The expected value of damage ($d(x)$) at a specific distance from shore ($E(d(x))$) equals the product of the probability of damage and the value at risk at that location:

$$E(d(x)) = (1 - F_e(x)) \cdot v(x) = P(x) \cdot v(x) \quad (2)$$

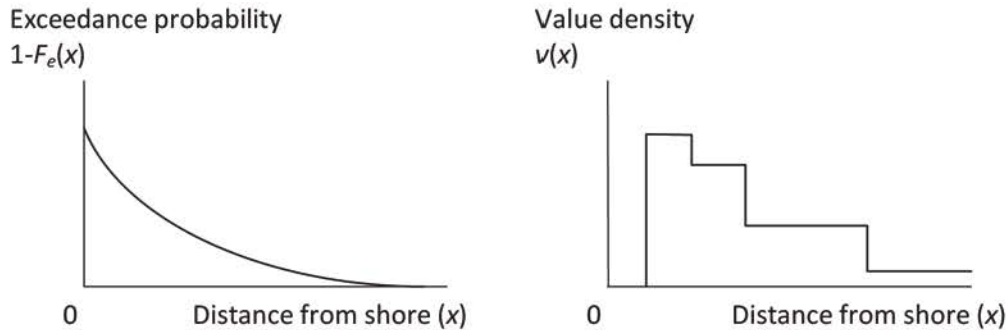


Fig. 1. The exceedance probabilities of setback in yr⁻¹m⁻¹ (left) and value density in cost/m² (right).

The expected value of damage per meter shoreline thus equals:

$$E(d) = \int_{x=0}^{\infty} (1 - F_e(x)) \cdot v(x) \cdot dx \quad (3)$$

The exceedance probabilities of the extent of erosion (1-F_e(x)) could be time-dependent due to sea level rise, changes in forcing and/or ambient long term trends in shoreline evolution. Because properties cannot be moved, this would cause loss probabilities to become time dependent (see Fig. 2a and 2b).

Case 1: efficient setback lines under stationary morphological conditions:

To analyse the efficiency of land-use decisions by private investors, we follow a cash-flow approach (hence, no depreciation) and assume that each investment is followed by a constant stream of net cash-inflows:

$$c(x) = I(x) \cdot r(x) \quad (4)$$

where: c(x) = net cash inflow per m² at distance x from shore (cost/yr/m²); I(x) = initial investment per m² at distance x from shore (cost/m²); r(x) = rate of return at distance x from shore, defined as a percentage of the initial investment (yr⁻¹).

Under stationary morphological conditions, loss probabilities are constant over time. The net present value of an investment at a specific distance from shore then equals:

$$NPV(x) = -I(x) + \int_0^{\infty} r(x) \cdot I(x) \cdot e^{-\gamma t} \cdot dt - \int_0^{\infty} P(x) \cdot I(x) \cdot e^{-\gamma t} \cdot dt \quad (5)$$

where NPV(x) = Net present value per m² at distance x from shore (cost/m²); r(x) = rate of return at distance x from shore (yr⁻¹); I(x) = initial investment per m² at distance x from shore (cost/m²); P(x) = loss probability at distance x from shore (yr⁻¹); γ = discount rate (yr⁻¹); t = time (yr).

As long as the net present value is positive, the investment outperforms alternative investments with a similar risk profile (here, risk refers to market risk, not storm erosion risk). When it equals zero, an investor will be indifferent to the investment in the coastal zone or the alternative investment. When it is negative, an investor will (should) not invest in the coastal zone. The net present value is negative when:

$$\int_0^{\infty} r(x) \cdot I(x) \cdot e^{-\gamma t} \cdot dt < \int_0^{\infty} P(x) \cdot I(x) \cdot e^{-\gamma t} \cdot dt + I(x) \quad (6)$$

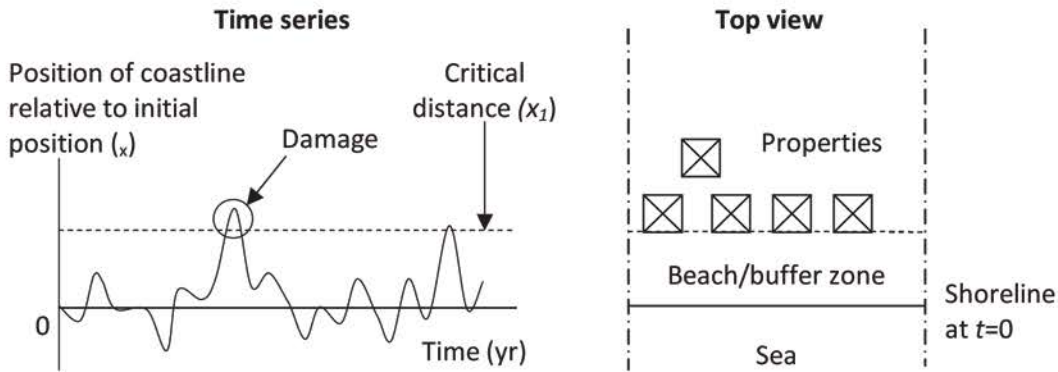


Fig. 2a. A fictitious time series of coastal erosion for uncertain ephemeral storm erosion only (left) and a top view of the corresponding beach section including a setback line at a distance x_1 from shoreline beyond which the probability of damage is considered acceptable (right).

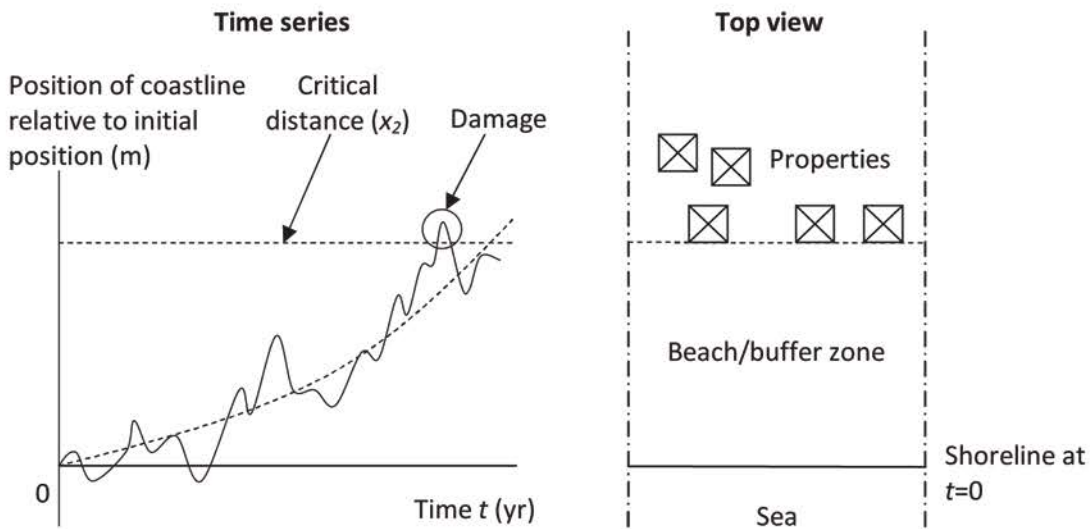


Fig. 2b. A fictitious time series of coastal erosion for uncertain ephemeral storm erosion plus an exponential chronic erosion trend (left) and a top view of the corresponding beach section including a setback line at a distance x_2 from shoreline beyond which the probability of damage is considered acceptable (right). Note that the setback line is positioned further inland ($x_2 > x_1$) to implement a safe margin between today's and future conditions during the lifetime of the property development.

or

$$\frac{r(x) \cdot I(x)}{\gamma} < \frac{P(x) \cdot I(x)}{\gamma} + I(x) \tag{7}$$

or

$$r(x) - \gamma < P(x) \tag{8}$$

Hence, without market imperfections, no rational investor would invest in the zone between the shoreline and the setback line with an exceedance probability that equals the difference between the rate of return on investment and the cost of capital. If the investments in a coastal zone yield a constant 2.5% rate of return in excess of the rate of return offered by similar investments at inland locations ($r(x) - \gamma = 0.025$ per year), the exceedance probability of the setback line that marks the contour of the buffer zone should equal 0.025 per year.

Case 2: Efficient setback lines under non-stationary morphological conditions:

The probability of damage might increase over time due to long term trends in coastline evolution and forcing (Fig. 2b). Let us assume that the probability of damage increases annually by the same factor, i.e. exponentially. This assumption, which simplifies the mathematics of this paper that only addresses the basic principles of a risk-informed approach, is not supported by measurements. Note that, for loss probabilities to change exponentially, physical processes need not change exponentially as well.

Under the assumed time dependency, the probability of damage at some location x and time t , $P(x,t)$, depends on today's probability of damage, $P_0(x)$, according to.

$$\begin{cases} P(x,t) = p_0(x) \cdot e^{at} & \text{for } a \cdot t < -\ln(P_0(x)) \\ P(x,t) = 1 & \text{for } a \cdot t \geq -\ln(P_0(x)) \end{cases} \tag{9}$$

where $P_0(x)$ = probability of damage at distance x from the shoreline at time $t=0$ (yr^{-1}); a = constant (yr^{-1}); t = time (yr).

When loss probabilities increase over time, so will expected losses. Expected loss will start to exceed the annual return for a property (an investment) that is located at some distance x from today's shoreline, when:

$$t = T^* = \begin{cases} \frac{1}{a} \ln \frac{r(x)}{P_0(x)} & \text{for } r(x) \geq P_0(x) \\ 0 & \text{for } r(x) < P_0(x) \end{cases} \tag{10}$$

Note that T^* will be a function of both long term forcing (eg. SLR) and morphological evolution.

The lower the intensity of the annual increase of the probability of damage, the longer it will take before the expected cost of risk bearing will exceed the return on investment. The time it takes for the expected cost of risk bearing to exceed the return on investment also depends on the ratio of the rate of return and the probability of damage. This is illustrated by Fig. 3. The figure shows the number of years it takes before risk exceeds return (vertical axis) for different values of the initial loss probability (horizontal axis). Each curve corresponds to a different intensity of the long term trend, defined by the number of years it takes for the probability of damage to increase by a factor 10 or $T_{10} (T_{10} = 1/a \cdot \ln(10))$.

When probabilities of damage increase over time (e.g. due to climate change), the cost of risk bearing also increases with time. When morphological conditions are non-stationary, the economic lifetimes of investments in coastal zones thus have to be considered. For non-stationary conditions, the net present value of an investment at some distance x from today's shoreline can be computed according to:

$$NPV(x) = \int_0^{T^*} r(x) \cdot I(x) \cdot e^{-\gamma t} \cdot dt - I(x) - \int_0^{T^*} P(x,t) \cdot I(x) \cdot e^{-\gamma t} \cdot dt \tag{11}$$

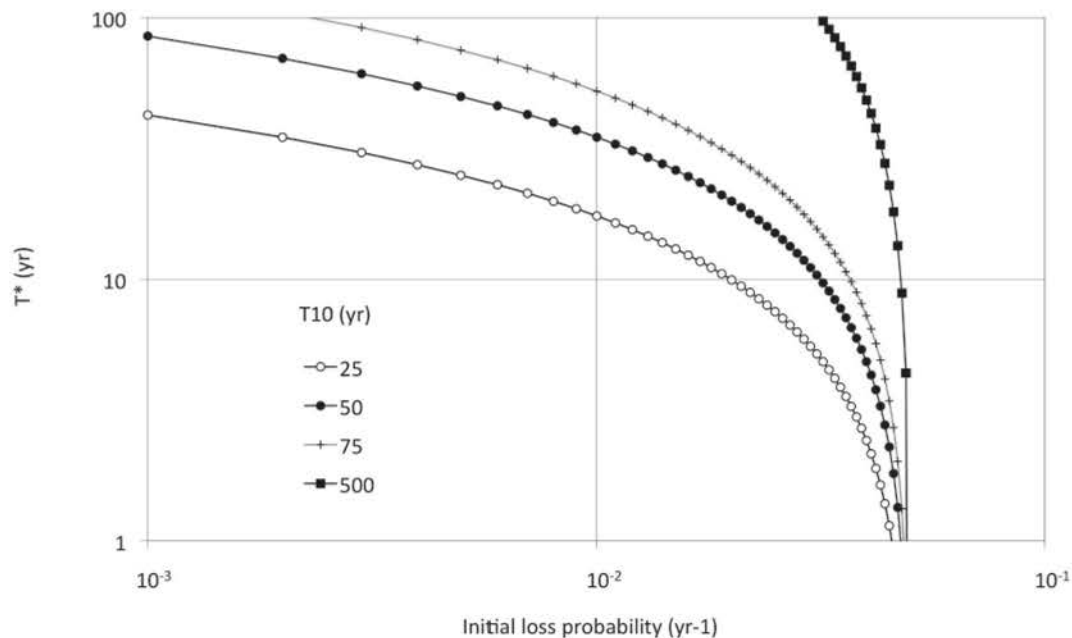


Figure 3. The expected number of years (T^*) it takes for the expected cost of risk bearing to exceed the return on investment as a function of the initial loss probability, for different intensities of the long-term trend.

where $NPV(x)$ = Net present value per m^2 at distance x from shore $cost/m^2$; $r(x)$ = rate of return on investment at distance x from shore (yr^{-1}); $I(x)$ = initial investment per m^2 at distance x from shore ($cost/m^2$); $P(x,t)$ = Loss probability at distance x from shore at time t (yr^{-1}); γ = discount rate (yr^{-1}); t = time (yr); T^* = expected economic lifetime (yr).

When computing the optimal exceedance probability of today's setback line for land-use planning, only the period in which gains exceed costs of risk bearing (T^*) should be considered. After all, when costs start to exceed gains, the economic activity will (should) be discontinued. When the probability of damage increases strongly, by e.g. a factor 10 every 50 years, and today's loss probability of a specific distance from shore equals 1/1000 per year., the expected economic lifetime equals 85 years (in Fig. 5: the intersection of the y-axis and the line with solid circle).

The optimal initial loss probability as a function of the number of years it takes for the probability of damage to increase by a factor 10 (T_{10}) is shown in Fig. 4. For weak long term trends ($T_{10} \rightarrow \infty$), the optimal initial loss probability asymptotically approaches $r(x) - \gamma(x)$ (see also eq. 8).

As illustrated by Fig. 4, the exceedance probability of the economically optimal setback line (or: today's optimal probability of damage) only drops by a factor 5-10 when the intensity of the long-term trend is relatively strong (e.g. $20 < T_{10} < 100$). This drop even less pronounced in case of higher discount rates. Only when the probability of damage increases by a factor 10 every 20-50 years, should a setback line with a significantly lower exceedance probability be selected for land-use planning purposes. Only strong

long-term trends significantly influence the optimal exceedance probability of the setback line because the present value of money earned today is greater than the present value of money earned in say 20 or 50 years (money earned today can be reinvested)

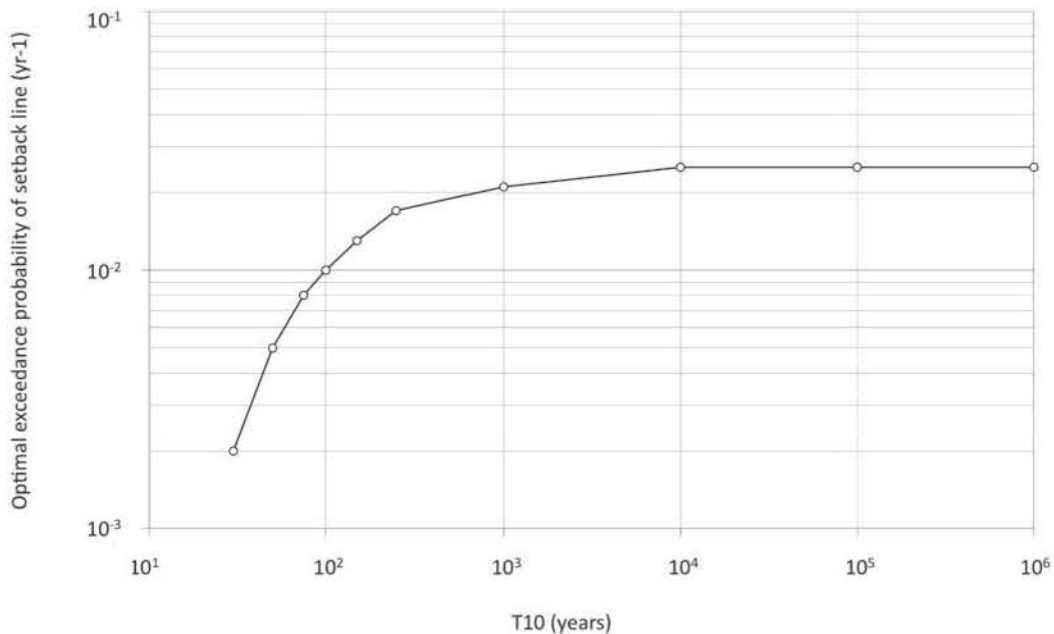


Figure 4. Optimal loss probability (or: optimal exceedance probability of the setback line that is used to define a buffer zone along a coast in case of e.g. moral hazard) as a function of the number of years it takes for this probability to increase by a factor 10 ($\gamma = 0.025 \text{ yr}^{-1}$; $r(x) = 0.05 \text{ yr}^{-1}$).

Establishing setback lines: basic rules:

Based on the results of the preceding sections, relatively simple rules can be derived to assist coastal zone managers in dealing with land-use issues. The rules presented in Table 1 depend entirely on the costs and benefits of foregoing land-use opportunities. Considerations regarding, e.g. public safety, might lead to more stringent land-use regulations. It is emphasised that all parameter values mentioned in Table 1 are crude estimates that may vary depending on local circumstances. Moreover, it is emphasised that the implementation of buffer zones should only be considered in case of market imperfections that would otherwise lead to excessive risk-taking behaviour on the part of individuals and firms. It should also be noted that there might sometimes be more cost-effective alternatives to the implementation of land-use planning restrictions, such as the introduction of a mandatory insurance program.

The probabilistic estimation of the position of setback lines:

Recognising the need for probabilistic estimates of storm erosion and coastline recession due to SLR, Callaghan et al. (2008) and Ranasinghe et al. (2009) developed the JPM and PCR models respectively. Jongejan et al. (2011) combined these two models to develop a model (Probabilistic Coastal Setback Line (PCSL)) that is capable of providing reliable, probabilistic estimates of the coastal setback line. The physical process of coastal recession due to SLR as considered in the PCSL (and PCR) model is summarised below.

Following common practice, the quantity of coastal recession (R) due to SLR is defined as the horizontal displacement of the dune position (toe of the dune) over a long time period. The basic physical philosophy

underpinning the method used in the PCR model is that any net long-term recession of the coastal dune is due to the successive occurrence of higher return interval storms while the mean water level is slowly increasing due to SLR. In simpler terms, assume the mean water level (MWL) is zero at present and the dune is at $x=0$ (horizontal axis). Now say a 1 in 10 year storm occurs. The associated storm erosion would then result in a dune retreat of, say, 10m. Now assume that the next 1 in 10 year storm occurs in another 10 years when the MWL is elevated at $0+10x(\text{SLR}/\text{yr})$. As dune recovery is an extremely slow process, it is very likely that the dune has not completely recovered to its original position in the 10 year period that has elapsed during the two 1 in 10 year storms. Therefore, say in the 10 year elapsed period the dune only advanced 5 m seawards from its eroded position. Then, due to the second storm an additional 10 m of dune retreat can be reasonably expected, which would result in a net dune retreat of 15m ($10-5+10$) over the 10 year period. As time progresses and the MWL keeps increasing due to SLR this process will recur resulting in a gradual retreat of the coastline. If climate change results in more intense storms occurring more frequently, this rate of coastal retreat will accelerate.

Table 1. Rules for land-use planning	
Stationary morphological conditions	Non-stationary morphological conditions
Implement a buffer zone up to the point where the probability of damage exceeds the rate of return on investment minus the cost of capital, e.g. 0.025 yr^{-1} .	<p>In case of small increases in the probabilities of damage (e.g. by a factor 10 every >100 years):</p> <ul style="list-style-type: none"> Implement a buffer zone up to the point where the probability of damage exceeds the rate of return on investment minus the cost of capital, e.g. 0.025 yr^{-1} (base case) <p>In case of moderate increases in the probabilities of damage (e.g. by a factor 10 every 50-100 years):</p> <ul style="list-style-type: none"> Reduce the exceedance probability of the setback line (the base case defined above) by a factor 2 (crude estimate). Select property types with technical lifetimes of 50-100 years (crude estimate). <p>In case of very strong increases in the probabilities of damage (e.g. by a factor 10 every 20-50 years):</p> <ul style="list-style-type: none"> Reduce the exceedance probability of the setback line (the base case) by a factor 10 (crude estimate). Select property types with technical lifetimes of 25 to 50 years (crude estimate).

The PCSL model essentially performs multiple 110 year Monte Carlo simulations. In each simulation, the most landward position of the dune in a given year represents the setback line for that year. The multiple

estimates of the setback line given by the Monte Carlo simulation can thus be used to obtain exceedance probabilities for every year.

The modelling approach (for the determination of the time-dependent exceedance probability distribution of the setback line) thus consists of the following steps:

1. Generate a 110-year (1990-2100) storm time series using Callaghan et al.'s (2008) JPM model,
2. Using IPCC projections, estimate the sea-level rise, S , at the time each storm occurs,
3. For each storm, estimate dune recession using the process based dune impact model developed by 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 1-4 until convergence is obtained for exceedance probabilities greater than 0.01% (i.e. bootstrapping).

This Probabilistic Coastal Setback Line (PCSL) model requires minimal computing effort and primarily requires as input long term water level and wave data which are now available via widespread tide gauges and global hind cast models, such as WW3 (Uppala, 2005) and ERA40 (Tolman, 1997, 1999, 2009), respectively. Therefore, it is anticipated that the model should be widely and relatively easily applicable, albeit requiring skilled operators that are familiar with wave transformation analysis and the analysis of tidal information.

RESULTS

Case study: Narrabeen beach, Sydney, Australia:

The EOSL model which combines the above described economic model and the PCSL model, was applied at Narrabeen beach (Fig. 5), Sydney, Australia where over 30 years of concurrent wave, water level, and importantly, monthly beach profile data exist (Profile 4). The wave climate is predominately from weather systems located to the east or south east leading to wave directions from the south-east.

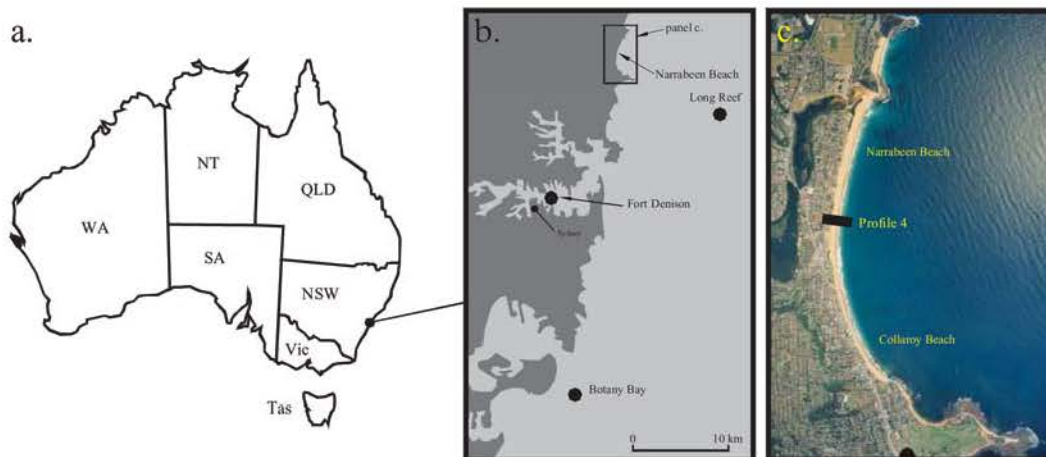


Figure 5. Narrabeen Beach and measurement location maps: a. location of Sydney within Australia; b. the Botany Bay and Long Reef wave buoy locations and the Fort Denison tidal recording station; and c. the location of long term beach profile surveys at Narrabeen Beach profile 4.

Narrabeen beach is subjected to beach rotations caused by a slowly varying imbalance between northerly and southerly longshore sediment transport. The results presented here focus on the beach rotation

fulcrum (Profile 4), where longshore processes are thought to be insignificant (Short and Trembanis (2004).

The extent of sea level rise in the Sydney region is uncertain, with an upper bound of about 0.9m by 2100 compared to 1990 (Solomon et al., 2007; McInnes et al., 2007). While this uncertainty could be included in the PCR-model (with the probabilities for alternative sea level rise scenarios based on e.g. expert judgments), the case study presented here assumes the absence of sea level rise for reasons of simplicity. When morphological conditions are stationary, the exceedance probability distribution of coastal retreat stays the same from year to year. Illustrating the link between the outcomes of the economic model and the PCSL-model is then relatively straightforward. The computed (time-invariant) exceedance probability curve for the selected profile at Narrabeen beach is shown in Fig. 6.

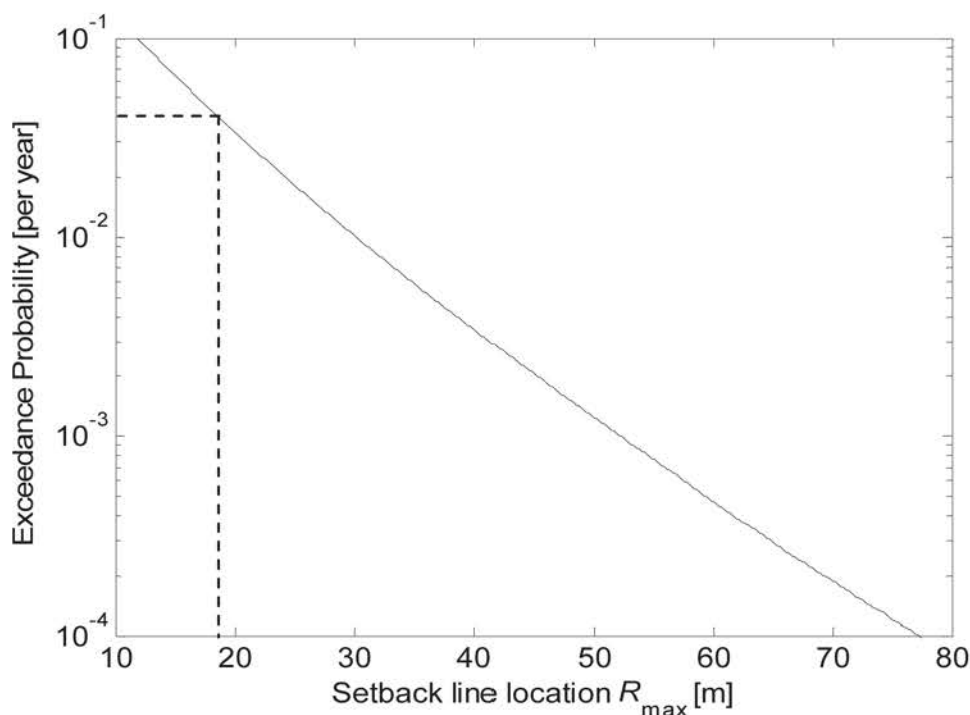


Figure 6. Exceedance probability curve of the extent of coastal retreat at Narrabeen Beach (at the beach rotation fulcrum; results obtained by the PCSL-model without decadal oscillations, long term changes and sea level rise). The dotted line shows the setback associated with an exceedance probability of 0.04 per year.

To find the position of the economically optimal setback line for land-use planning purposes, economic data is required about potential rates of returns on investment in the coastal zone. The residential area next to the beach consists mostly of mansions and luxury apartment buildings. Since no economic data were available for this case study, we assumed property values in a 250m-wide stretch along the beach to be 4% higher than those further inland (all other things being equal). In that case, the optimal setback line has an exceedance probability of 0.04 per year. The associated position of this setback line is defined by $R_{max}=19m$, or about 20m (Fig. 6).

Fig. 6 also implies that the uncertainty related to e.g. the discount rate is of little practical importance: if the discount rate were 0.02 per year higher, and thus the optimal exceedance probability a factor 2 lower (i.e. 0.02 per year), this would cause the optimal setback line to shift inland by only 6m to $R_{max}=25m$. This

illustrates that it is the orders of magnitude of the optimal exceedance probabilities that matter, not their exact values.

CONCLUSIONS

An innovative approach that combines an economic risk model and a process based, probabilistic coastal setback line model to determine the economically optimal coastal setback line is described. The generic results obtained in this study indicate that the level of safety implied by current approaches could easily be too high or too low from an economic perspective. While setback lines are typically defined by their distance from shore or elevation, this study shows that it is more useful to define setback lines in terms of their exceedance probabilities.

The exceedance probabilities of economically optimal setback lines will typically be in the order of 1/100 per year, with minor corrections depending on local circumstances. The results obtained herein emphasise that it is the order of magnitude of the exceedance probability that matters, not its exact value. A variation of the optimal exceedance probability by a factor 2 will typically have a limited impact on the optimal setback line position.

To develop economically optimal setback lines for specific locations, further work is needed to quantify the uncertainties related to short term storm erosion volumes, long term recession due to longshore transport gradients, decadal oscillations, and climate change impacts. However, while probability density functions of annual extremes (short-term) are a prerequisite for the implementation of the risk-informed approach, estimates of average long-term trends are likely to suffice in most cases. This suggests that it might be feasible to develop economically optimal setback lines for broad types of coastlines and coastal developments, which will greatly simplify this task especially in regional scale (100s of kilometres of coastline) applications.

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