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Drawing the line on coastline recession risk

Ruben Jongejan [a, b, *], Roshanka Ranasinghe [a, c, d, e], David Wainwright [f, g], David P. Callaghan [f], Johan Reyns [c]

[a] Civil Engineering and Geosciences, Delft University of Technology, PO Box 5048, 2600 GA Delft, The Netherlands
[b] Jongejan RMC, Schoolstraat 4, 2611 HS Delft, The Netherlands
[c] Department of Water Engineering, UNESCO-IHE, PO Box 3015, 2610 DA Delft, The Netherlands
[d] Harbour, Coastal and Offshore Engineering, Deltares, PO Box 177, 2600 MH Delft, The Netherlands
[e] Research School of Earth Sciences, The Australian National University, 42 Mills Road Acton, Canberra, 6200 ACT, Australia
[f] School of Civil Engineering, The University of Queensland, Brisbane, QLD 4072, Australia
[g] Whitehead and Associates, 197 Main Road, Cardiff, NSW 2285, Australia

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ABSTRACT

Climate change and the growth of coastal communities will significantly increase the socio-economic risks associated with coastline recession (i.e. the net long term landward movement of the coastline). Coastal setback lines are a commonly adopted management/planning tool to mitigate these risks. While it is widely recognized that planning decisions should be risk-informed, setback lines are presently determined using deterministic methods that cannot easily be related to considerations regarding the tolerability of risks. Here, we present a model for quantifying the risks posed by coastline recession and show how it can be used for deriving economically optimal setback lines. A demonstration at Narrabeen beach, Sydney, Australia illustrates that the proposed risk-informed approach to coastal zone management can significantly improve the transparency and efficiency of land-use planning decisions.

1. Introduction

The 20th century has witnessed unprecedented economic and population pressures on coastal zones. Small and Nicholls (2003) estimated that, for 1990, 23% of the global population lived within 100 km and less than 100 m above sea level. In relatively flat, low-lying areas, that are protected from flooding by dunes or flood defences, elevated water levels, for example due to slow sea level rise (SLR) or episodic storm surges, can affect vast areas, causing $ billions worth of damages and displacing tens of thousands from their homes (Hallegatte et al., 2013). Along sloping coasts with elevated hinterlands, while flood damage might be limited, significant damage could occur near the coastline due to chronic and/or episodic landward movement of the coastline (i.e. coastal recession) driven by erosion.

Up to 70% of the world's sandy coastlines are eroding, resulting in gradual and continuous coastline recession (Bird, 1985) This is driven by chronic processes such as Sea level rise (SLR) and episodic processes such as storm erosion (Brown et al., 2013; Hinkel et al., 2013; Nicholls and Cazenave, 2010; Ranasinghe et al., 2012a; Stive et al., 2010). The rate of coastline recession is likely to increase due to the projected impacts of climate change on mean sea level (IPCC, 2007a), offshore wave climate (Hemer et al., 2013a) and storm surge (Colberg and McInnes, 2012; Sterl et al., 2009). At the same time, rapid development in the world's coastal zones continues to increase potential damages, while often reducing the resilience of coastal systems (Nicholls et al., 2007). The risks associated with coastline recession are thus likely to increase over the coming decades, unless effective risk mitigation strategies are developed and implemented (Penning-Rowsell et al., 2014).

Recession risks in coastal zones can be mitigated through coastal protection structures (e.g. breakwaters, groynes, seawalls) or periodic beach nourishments (Ranasinghe and Stive, 2009). They can also be proactively managed through the implementation of land-use restriction policies which are a key component of coastal

* Corresponding author. Jongejan RMC, Schoolstraat 4, 2611 HS Delft, The Netherlands.

E-mail addresses: Ruben.Jongejan@JongejanRMC.com (R. Jongejan), R.Ranasinghe@unesco-ihe.org (R. Ranasinghe), d.wainwright2@uq.edu.au (D. Wainwright), Dave.Callaghan@uq.edu.au (D.P. Callaghan), J.Reyns@unesco-ihe.org (J. Reyns).

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zone risk management plans (Wainwright et al., 2014). These involve the use of coastal setback lines to define an area along the coastline where development is prohibited or restricted (Wainwright et al., 2014; Vrijling et al., 2002). While the exact methods used to determine coastal setback lines differ among countries, regions and even local governance units (Wainwright et al., 2014; Gibb, 1983; Komar et al., 2002) the general approach is to first separately estimate (a) the long term (or chronic) recession for a particular longshore sediment transport gradient and sea level rise scenario, and (b) the episodic coastline recession for a particular storm event. These individual recession estimates are then linearly added to establish the position of the setback line. This approach has several limitations (Wainwright et al., 2014; Jongejan et al., 2012), such as failing to take the non-linear interactions among the different processes into account (e.g. extreme storm erosion and long term coastline recession trends), double counting (e.g. long term recession due to SLR and that due to longshore transport gradients), data aliasing when using sparse field data (e.g. aerial photographs obtained every few years to determine long term recession), and the use of crude models (e.g. Bruun rule for SLR induced recession (Bruun, 1962)). While detailed descriptions of coastal setback line definition approaches are difficult to find in the published literature, an exception can be found in the exhaustive review by Wainwright et al. (Wainwright et al., 2014) of the evolution of coastal setback line definition in the state of New South Wales, Australia (the most populated state in the country) since the 1960s.

A setback line that is positioned farther inland will always lead to lower loss probabilities. But foregoing land-use opportunities is costly, making the establishment of setback lines a balancing act (Vrijling et al., 2002). For balancing risk and reward, probabilistic estimates of coastline recession are a pre-requisite. Yet the presently adopted deterministic methods for establishing setback lines, as outlined above, are unable to provide such estimates. While these methods rely on notions such as $1/100\ \mathrm{yr}^{-1}$ storm events, it would be erroneous to assume that their outcomes can be interpreted along similar lines. Combining, for instance, the effect of a $1/100\ \mathrm{yr}^{-1}$ storm event in today's environment with the effect of 100 years of future sea level rise is unlikely to yield a physically meaningful result for either the present or the future.

Although quantitative risk assessments (QRA), underpinned by fully probabilistic hazard estimation, has been common practice in flood risk management for decades (Vrijling, 2001; Van Manen and Brinkhuis, 2005; USACE, 2011; Jongejan and Maaskant, 2015), this way of thinking has only recently emerged in coastal zone management (Ranasinghe et al., 2012a; Cowell et al., 2006; Woodroffe et al., 2012). Despite the growing recognition of the need for QRA informed coastal zone management, to date, a modelling approach that adequately meets this need has not been developed for the assessment of risk due to coastal recession (Wainwright et al., 2014). The present study was undertaken to specifically address this knowledge gap via the development of an innovative quantitative risk analysis (QRA) approach that is capable of providing time-dependent coastal recession risk estimates. The approach presented here recognises that insight into time-dependencies is essential for the design of adaptive land-use planning policies (Nicholls et al., 2007), rather than static policies that may well be unnecessarily stringent in today's environment. It enables the determination of setback lines in terms of exceedance probabilities of coastal recession, a quantity that directly feeds into risk evaluations and economic optimizations (Vrijling et al., 2002). As a demonstration, the risk-informed approach is applied to Narrabeen beach, Sydney, Australia.

2. Quantifying the risk associated with coastline recession

Risk can be defined in myriad ways. In quantitative risk analyses, risk is commonly defined as a set of probabilities and consequences associated with mutually exclusive accident scenarios (Kaplan and Garrick, 1981). The associated joint probability density function of potential consequences allows for a direct link with the theory of rational decision making under uncertainty (Von Neumann and Morgenstern, 1944; Savage, 1954). Risk (R) is therefore represented here by the joint probability density function of a vector of adverse consequences:

$$R = f_{\underline{U}}(\underline{u}) \tag{1}$$

where $\underline{u}$ is a vector comprising a particular realization of the uncertain consequences of coastline recession $\underline{U}$. These consequences could be measured in terms of e.g. economic loss, environmental damage, injury and/or loss of life.

Risk, as defined above, rests on a subjective interpretation of probability in which all uncertainties are dealt with by assigning probabilities to particular realisations (e.g. Apostolakis, 1990; Bedford and Cooke, 2001). In literature, distinctions are sometimes made between aleatory uncertainties, stemming from true randomness, and epistemic uncertainties, stemming from lack of knowledge (Kiureghian and Ditlevsen, 2009; Winkler, 1996). Such typologies may serve various purposes. The reducibility of epistemic uncertainties through data collection or research may, for instance, give rise to option value, possibly making it economically optimal to postpone a risky venture until the uncertainties are smaller (Arrow and Fisher, 1974). When, however, the prospect for learning is absent or when learning is prohibitively costly or time-consuming, the origins of uncertainty will be of little practical relevance to decision making.

The risk of coastline recession arises from the combination of vulnerable objects and uncertainty related to the future position of the coastline. Similar to the future position of the coastline, future potential losses will often be uncertain. This is because socio-economic variables that influence the consequences of coastline recession, such as population and economic growth rates, are not deterministic but uncertain quantities. Their probability density functions may be derived from statistical analyses, model predictions and/or expert elicitation techniques, similar to the methods used for deriving probability density functions for physical parameters, such as water levels and wave heights.

Time dependencies and correlations in the time domain differ strongly across the numerous variables that determine the risk associated with coastline recession. Extreme wind speeds, for instance, are often seasonal and of relatively short duration. Sea level rise, on the other hand, is a slow and continuous process. Because of time dependencies and imperfect correlations in the time domain, the probability of occurrence of an adverse outcome in a 100 year period is likely to be significantly greater than observing it in a 1 year period. Risk, as defined by Equation (1), thus depends on the time frame under consideration.

When dealing with planning decisions that involve long time horizons, time preferences have to be taken into consideration as these determine today's equivalents of losses at different future dates. This means that a 1/100 loss probability for a 100 year period will be evaluated differently when the underlying annual probability of damage increases, decreases or stays the same from year to year. We therefore focus on the estimation of risks on an annual basis, for multi-year periods. This approach allows decision makers to evaluate the balance between risk and return, based on their own risk and time preferences.

To obtain probabilistic estimates of the amount of annual