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Describing adaptation tipping points in coastal flood risk management

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ABSTRACT

Assessing changing coastal flood risk becomes increasingly uncertain across multi-decadal timeframes. This uncertainty is a fundamental complexity faced in vulnerability assessments and adaptation planning. Robust decision making (RDM) and dynamic adaptive policy pathways (DAPP) are two state-of-the-art decision support methods that are useful in such situations. In this study we use RDM to identify a small set of conditions that cause unacceptable impacts from coastal flooding, signifying that an adaptation tipping point is reached. Flexible adaptation pathways can then be designed using the DAPP framework. The methodology is illustrated using a case study in Australia and underpinned by a geographic information system model. The results suggest that conditions identified in scenario discovery direct the attention of decision-makers towards a small number of uncertainties most influential on the vulnerability of a community to changing flood patterns. This can facilitate targeted data collection and coastal monitoring activities when resources are scarce. Importantly, it can also be employed to illustrate more broadly how uncontrolled societal development, land use and historic building regulations might exacerbate flood impacts in low-lying urban areas. Notwithstanding the challenges that remain around simulation modelling and detection of environmental change, the results from our study suggest that RDM can be embedded within a DAPP framework to better plan for changing coastal flood risks.

1. Introduction

Increasing rates of sea-level rise have the potential to alter coastal flooding regimes around the world (Hunter, 2010; McInnes et al., 2015; Nicholls & Cazenave, 2010), placing increasing pressure on decision-makers to minimise physical, environmental and social impacts. However, understanding what changes could lead to unacceptable impacts within the community and when such changes might occur is challenged by ambiguity (Dewulf, Craps, Bouwen, Taillieu, & Pahl-Wostl, 2005), different risk perceptions (Jones et al., 2014), multi-decadal climate variability (Hallegatte, 2009) and long-term uncertainty associated with varying regional responses to climate change.

Various decision support tools have been proposed to guide decision-makers through climate risk assessments and to evaluate adaptation responses under conditions of uncertainty (e.g. Dittrich, Wreford, & Moran, 2016; Watkiss & Hunt, 2013). When deep uncertainty exists, dynamic adaptive policy pathways (DAPP) (Haasnoot, Kwakkel, Walker, & ter Maat, 2013) and robust decision making (RDM) (Lempert, Popper, & Bankes, 2003) have emerged as two state-of-the-art decision support tools (Kwakkel, Walker, & Haasnoot, 2016). Deep uncertainty describes dynamic conditions where there is limited knowledge and agreement on the use of models, description of parameters in those models and what impacts are considered (Kwakkel et al., 2016; Lempert et al., 2003). Decision-makers are likely to encounter deep uncertainty when assessing the vulnerability of a community to changing coastal inundation patterns that may be experienced decades from now, or through coastal development and land use planning whereby near-term investments will influence urbanisation patterns over the coming decades.

RDM is a decision support method that evaluates the robustness of *new* policy options such as a flood alleviation scheme. DAPP is an adaptive management framework that begins by considering what future scenarios will cause *existing* management controls to fail, before evaluating the suitability and timing of new policy options. Both methods use hundreds to thousands of non-probabilistic 'what-if' scenarios to explore the impact of the uncertain future on the performance of new (or existing) adaptation policies, allowing key sensitivities of the policy to be identified. When external changes cause the existing system or future adaptation plans to no longer meet decision-maker objectives, an adaptation tipping point is reached and new actions should be

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implemented (Kwadijk et al., 2010). Adaptation tipping points provide a practical way to communicate risks to the community associated with a changing built and natural environment (Werners et al., 2013). This focuses coastal flood risk management towards understanding the sensitivity of an urban area to change and assessing when management responses might be needed to keep impacts at a tolerable level (Kwadijk et al., 2010).

RDM and DAPP aim to design robust policies, and they achieve this in different ways. RDM identifies adaptation policies that perform satisfactorily under many different future scenarios, whilst DAPP provides an adaptive management framework within which flexibility is created, allowing progressive review and update of policy options as more information becomes available (see Appendix A in the Online Resource for a comparison of RDM and DAPP). Importantly both approaches have the potential to provide complementary information to decision-makers under conditions of deep uncertainty (Kwakkel, Haasnoot, & Walker, 2016).

There are few examples from local government that use RDM or DAPP to assess the vulnerability of low-lying areas to coastal inundation and design adaptation pathways. This could be due to many factors including unclear adaptation responsibilities in government (Nalau, Preston, & Maloney, 2015), limited awareness of new decision support tools (Lawrence & Haasnoot, 2017), limited availability of relevant data to undertake such an analysis (Bhave, Conway, Dessai, & Stainforth, 2016) and technological or financial constraints. Simplified applications of RDM (e.g. Daron, 2015) and adaptation pathways (e.g. Barnett et al., 2014) have been demonstrated for resource-constrained decision-makers. However, the growing global repository of spatial data and open source programming code (e.g. the exploratory modelling workbench; Kwakkel, 2017) means that local governments, business and individuals have an opportunity to use more sophisticated techniques to analyse climate risks, quantify thresholds and evaluate adaptation responses (Ramm, White, Chan, & Watson, 2017).

Many of the adaptation pathway examples to date in coastal flood risk management describe conditions that lead to an adaptation tipping point with a single parameter like sea-level rise (Reeder & Ranger, 2011) or storm surge height (Kwadijk et al., 2010). This conceptualisation of risk suggests that flood impacts could be treated by controlling the single hazard with a sea wall or levee (Klijn, Kreibich, de Moel, & Penning-Rowsell, 2015). However, important factors that relate to land use or property design are often omitted, which can overlook broader risks in urbanised areas that may exacerbate coastal inundation impacts.

We contribute to adaptation pathways planning research by exploring whether RDM and DAPP methods can be integrated to support coastal adaptation planning under conditions of uncertainty. We propose that RDM is well suited to describe a set of conditions where existing or future plans would no longer satisfy adaptation objectives in low-lying urban areas, signifying that an adaptation tipping point is reached. Knowledge of conditions that lead to adaptation tipping points can be used to further develop adaptation pathways using the DAPP framework, whereby each pathway represents a different set of adaptation options sequenced over time. A more comprehensive understanding of an area's sensitivity to coastal inundation allows questions such as *'what change in the built and natural environmental is important?'* and *'when might such change occur?'* to be explored. A similar philosophy was used by Kalra et al. (2015) to manage water resources in Lima. However, we are not aware of any literature that proposes the integration of RDM and DAPP for use in coastal flood risk management and adaptation planning. The methodology presented herein uses open source spatial datasets and programming languages for the benefit of resource constrained decision-makers. However, it relies on commonly used commercial software (ArcGIS) and flood modelling capability. We illustrate the potential for the approach on a case study site in Kingston Beach, Australia, to identify what future change might lead to unacceptable coastal flood impacts to people, property and lifestyle objectives.

With over $200 billion of infrastructure in Australia exposed to a 1.1 m sea-level rise (Commonwealth of Australia, 2011), strategic investment in coastal adaptation responses is important to avoid an increasing burden on the nation's resources. A greater upfront investment in risk identification and adaptation planning using state-of-the-art decision support methods could generate sizable budget savings to all levels of government and the community. Section 2 of this paper presents an overview of the methodology. The approach is demonstrated with a case study in Section 3. The implications and prospects of the method are discussed in Section 4, with conclusions drawn in Section 5.

2. Methods

We present a methodology that draws on the strengths of RDM to describe conditions leading to adaptation tipping points that can be used in a DAPP framework to map adaptation pathways. The basis of the presented methodology overlaps with the XLRM framework used in RDM to organise exogenous uncertainties (X), policy levers (L), relationships and models (R) and metrics (M) (for more details see Lempert et al., 2013). The key steps in the methodology are summarised in Fig. 1. Details about each step are provided in Sections 2.1 to 2.7.

2.1. Define adaptation objectives

Adaptation objectives describe what coastal decision-makers are trying to achieve by managing coastal inundation impacts. The objectives can be guided by organisational requirements or through stakeholder engagement. An example of an adaptation objective that accounts for physical impacts might be *minimising the length of critical access roads inundated during a flood*, whilst an environmental adaptation objective might be *minimising the loss of beach and dune area* (e.g. Ward, Butler, & Hill, 1998). Both of these objectives could also relate to intangible social values held by local residents, such as ensuring recreational opportunities, aesthetic value and an ongoing feeling of safety.

2.2. Define uncertain factors

Uncertain factors are those that cannot be influenced by decision-makers, are relevant to the adaptation objectives, and whose future state is unknown. They can be exogenous (X) to the system and outside the decision-makers control, or influence relationships inside the system (R) itself. An example of an uncertainty in the context of coastal adaptation is relative sea-level rise. The range of values that uncertain factors might take in the future is specified a priori and can be based upon stakeholder participation or guided by scientific evidence.

2.3. Generate cases

A case is a future realisation that represents a combination of randomly sampled uncertain factors (analogous to a single 'what if' scenario). Each case captures a single set of assumptions about the future state of uncertain factors. The generation of numerous cases allows future realisations to be explored in a process of exploratory modelling (Bankes, 1993). Cases are generated by selecting values for uncertain factors using latin hypercube sampling (LHS) ('lhs' package[1]), which then become inputs to the computational experiments.

[1] LHS is a sampling technique and the package is implemented in the free open-source R environment. See Carnell (2016) for details.