ARTICLE TITLE:

Strategic adaptation pathway planning to manage sea-level rise and changing coastal flood risk

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Abstract

Communities around the world are already committed to future sea-level rise. Long-term adaptation planning to manage associated coastal flood impacts is, however, challenged by uncertainty and contested stakeholder priorities. This study provides a proof of concept for a combined robust decision making (RDM) and dynamic adaptive policy pathways (DAPP) approach in coastal flood risk management. The concept uses model-based support and largely open source tools to help local government plan coastal adaptation pathways. Key steps in the method are illustrated using a hypothetical case study in Australia. The study shows how scenario discovery can provide multi-dimensional descriptions of adaptation tipping points which may inform the development of technical signpost indicators. Transient scenarios uncovered limitations in seemingly robust adaptation policies, where historical path dependencies may constrain the rate of adaptation and the extent to which future coastal flood impacts can be successfully managed. Lived values have the potential to offer insights about non-material social trade-offs that residents may need to accept for the benefit of reduced flood risk, and could form a basis for defining socially-oriented signpost indicators. However, the nuances and subjectivity of lived values means that ongoing engagement with residents is essential as part of a combined RDM and DAPP approach to preserve the communities' way of life. The learnings from this hypothetical case study suggest that testing in a real world participatory setting could be valuable to further develop a combined RDM and DAPP approach to plan adaptation pathways and manage future coastal flood risk.

Keywords

Adaptation tipping point; climate change; coastal flooding; decision support; risk management; uncertainty.

1 Introduction

Sea levels are expected to continue rising for centuries regardless of whether greenhouse gas emissions are stabilised (Church et al., 2013). Globally, this will exacerbate coastal flood patterns, causing more frequent extreme sea-level events (Hunter, 2010), nuisance flooding (Ray and Foster, 2016) and permanent inundation of low-lying areas. However, projecting the effect of such environmental change and planning long-term adaptation options is fundamentally a 'wicked problem' that challenges clear definition (Rittel and Webber, 1973). In the context of climate change adaptation this is due to factors such as deep uncertainty (Lempert et al., 2003), natural climate variability (Hallegate et al., 2009), contested stakeholder values (Bosomworth et al., 2017), short-term interests and social power inequalities (Few et al., 2009).

Local government are at the forefront of community decision-making. They have an important role in communicating climate change risk and supporting local adaptation planning. However, local government typically have unclear responsibilities, limited financial capacity and technical expertise, governance constraints and face liability concerns about adaptation policies (Productivity Commission, 2012). Notwithstanding these existing barriers, adaptation pathways are noted by users in Australian local government as being a useful planning tool (Lin et al., 2017) and experiences abroad suggests adaptation pathways have utility in supporting strategic decision-making (Bloemen et al., 2017).

Adaptation pathways represent sequences of promising options that provide alternate ways for decision-makers to achieve objectives through time. An adaptation tipping point is reached when a policy no longer achieves the decision-makers objectives, signifying that a new option needs to be implemented (Kwadijk et al., 2010). The year at which the adaptation tipping point is projected to occur is called the 'use-by year' (Haasnoot et al., 2015). Flexibility is a key attribute of adaptation pathways as multiple options are kept open to decision-makers in the future. Notably adaptation pathways have utility in coastal flood risk management where change in stressors that influence flood impacts, such as sea-level rise, are characterised by slow moving trends (Bloemen et al., 2017).

Faced with an uncertain future, exploratory modelling can help decision-makers reason with system behaviour and the interaction amongst models and variables. Exploratory modelling performs a series of computational experiments to analyse the implications of future assumptions on policies (Bankes, 1993). It does this by using models and simulations to systematically explore a large set of future scenarios (Kwakkel, 2017), providing insights to decision-makers about potential shortcomings in the policy (Walker et al., 2013). The use of exploratory modelling across many scenarios enables a wide set of futures to be considered (Gong et al., 2017), helping to overcome limitations in human cognition (Lempert, 2013) and biases that individuals tend to exhibit when forming judgements about an uncertain future (Tversky and Kahneman, 1974). Two prominent decision support methods that utilise exploratory modelling concepts to support decision-making under conditions of uncertainty are robust decision making (RDM) (Lempert et al., 2003) and dynamic adaptive policy pathways (DAPP) (Haasnoot et al., 2013). Although each method has its own strengths, both are complementary in nature (Kwakkel et al., 2016). A combined RDM and DAPP approach was demonstrated by Ramm et al (2018) using scenario discovery to describe adaptation tipping points, which can be used to begin planning adaptation pathways. Scenario discovery provides visibility around what key uncertainties cause policies to no longer manage flood impacts successfully (i.e. an adaptation tipping point reached), adding value to traditional pathway methods. The use of exploratory modelling and analysis techniques in coastal flood risk management is becoming increasingly accessible to resource constrained authorities through open source spatial data, programming languages, tools (e.g. Kwakkel, 2017) and GIS software.

Exploratory modelling is appropriate for assessing the implications of adaptation policy in measurable terms, however, evaluating the implications of adaptation policy on non-material social values is not as straightforward as values are shaped by ethics, risk, priorities, culture, knowledge and power structures (Adger et al., 2009). They also change over time and space (Meze-Hausken, 2008). Values-based approaches to climate change adaptation contribute knowledge about *what* people value in their everyday lives, *where* values are assigned to natural or manmade areas and *whom* increasing coastal flooding is likely to cause the greatest disruption (Ramm et al., 2017). A greater consideration for values-based research acknowledges that “something greater than money is at stake” (O’Brien and Wolf, 2010: 233) and that individuals may face difficult trade-offs decisions between what values are worth preserving and what climate change impacts are acceptable (Tscharket et al., 2017). Examples of values-based approaches include social and cultural values mapping (Novackzek et al., 2011) and the lived values approach (Graham et al., 2014), where a lived value is a “valuation made by individuals about what is important to their lives and the places they live” (Graham et al., 2013: 49).

This study makes two contributions to the planning of coastal adaptation pathways. Firstly, it builds on the combined RDM and DAPP methodology developed in Ramm et al. (2018) by including transient scenarios (i.e. time-series of future realisations considering relevant uncertainties) to evaluate policy use-by years after adaptation tipping points have been described through scenario discovery. Secondly, prior knowledge of lived values are introduced into the adaptation pathways planning process to qualitatively evaluate alternate adaptation pathways. Future opportunities to utilise lived values information in a combined RDM and DAPP approach are also considered. These contributions are illustrated using a hypothetical case study in the coastal town of Lakes Entrance, Australia (referred to herein as the case study). Whilst the study is hypothetical, it seeks to provide a proof of concept of the keys steps in a combined RDM and DAPP approach, illustrating how local government might begin developing long-term strategic adaptation pathways to manage impacts from coastal flooding.

Section 2 of this paper provides an overview of the case study area and the methodology is outlined in Section 3. Results are summarised in Section 4 along with a baseline adaptation pathway map. The results are discussed in Section 5 and conclusions are drawn in Section 6.

2 Case study site: Lakes Entrance

Lakes Entrance is a regional town located on the Gippsland Lakes in south-east Victoria, 320 km east of Melbourne (Fig. 1.). It has a permanent population of 4,810 (ABS, 2016). Access to the ocean from the Gippsland Lakes is provided through an artificial channel. A significant part of the town is less than 3 m above mean sea-level, including the esplanade which is located on the Princes Highway and is a key precinct for tourism and business. Major flooding in Lakes Entrance occurred in 1952 (1% AEP[1] flood), 1998 (20% AEP flood) and 2007 (20% AEP flood) – the latter isolating over 150 properties and inundating houses, businesses, roads and public amenities (SES, 2014). Important lived values identified by residents in Lakes Entrance include the natural environment, climate, proximity to the water, scenery, relaxed lifestyle and feeling of safety (Graham et al., 2014).

Extreme flood water levels at Lakes Entrance are influenced by catchment steam flows into the Gippsland Lakes, low frequency ocean water level fluctuations and wind setup from prevailing south-westerly winds (Grayson et al., 2004). Prior studies suggest that whilst changing catchment rainfall patterns from climate change could affect lake levels, increasing mean sea-level is likely to have an important contribution to extreme flood water levels experienced in Lakes Entrance (McInnes et al., 2006; Water Technology, 2014). Notwithstanding the complex interaction between environmental forcings that contribute to extreme flood water levels in the Gippsland Lakes, this study focuses on flood hazards exacerbated by mean sea-level rise. This is because prior information was available for Lakes Entrance modelling the relationship between sea-level rise and extreme lake flood levels (Water Technology, 2014).

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[1] Annual exceedance probability (AEP). The flood water elevation of a 1% AEP flood event at Lakes Entrance is 1.8 m AHD.

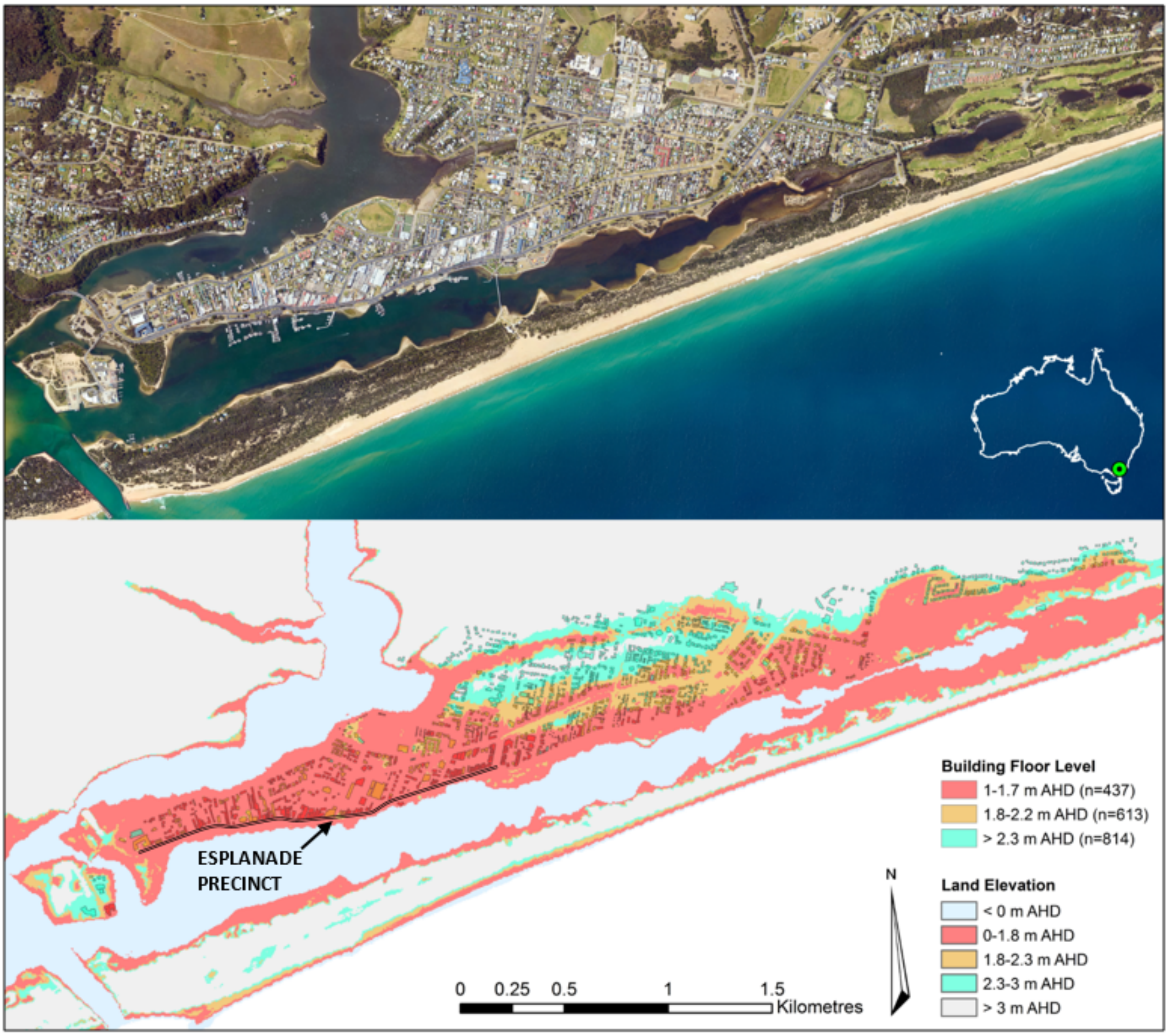

Fig. 1. Aerial image of Lakes Entrance (top panel) and the GIS model (bottom panel) showing digitised properties (n = 1864) and vertical land elevation relative to the Australian Height Datum (AHD). Please refer to the web version of this article for a colour version of this figure.

3 Methods

Ramm et al. (2018) combined elements of RDM and DAPP to show how multi-dimensional descriptions of adaptation tipping points can be illuminated using scenario discovery, before projecting the timing of adaptation tipping points using a small set of climate change scenarios. This study further develops the combined RDM and DAPP approach in two main ways. First, it incorporates transient scenarios – a key feature of DAPP – to project policy use-by years for a range of adaptation policy options. This enables temporal changes in coastal flood risk to be accounted for using different rates of change in the built and natural environment. Second, the study considers the extent to which lived values information might be used in the evaluation of adaptation pathways. The methodological steps followed in this case study are shown in Fig. 2. and outlined in sections 3.1 to 3.3.

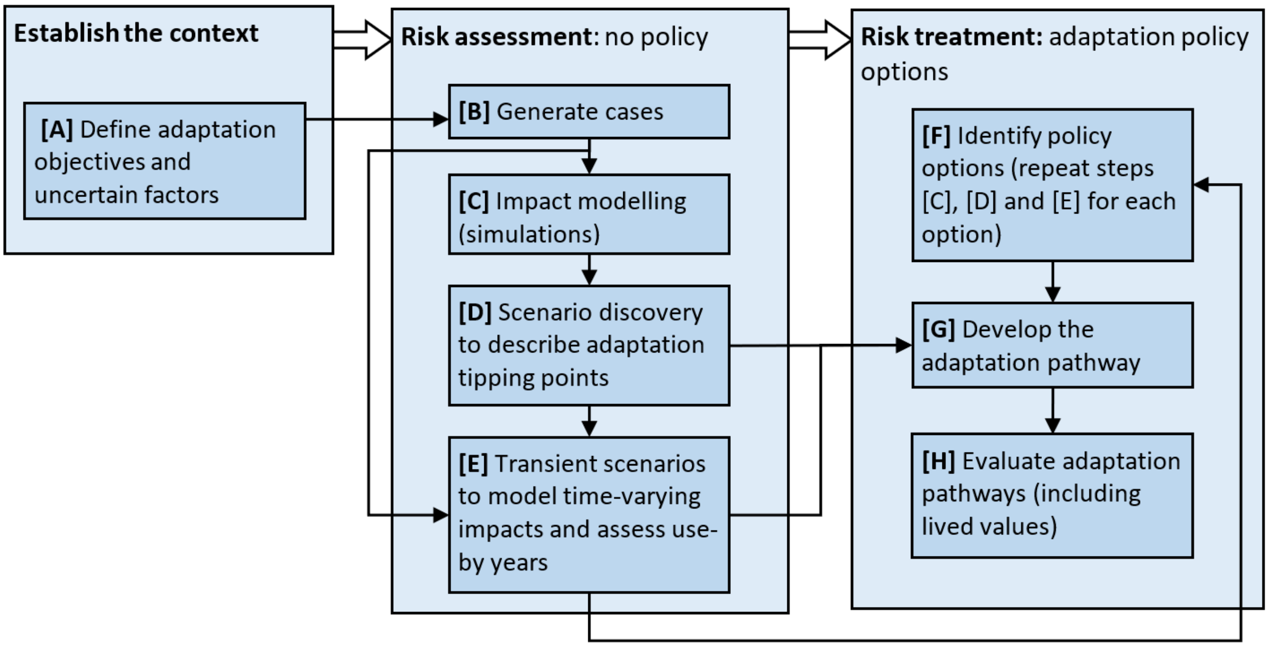

Fig. 2. Overview of the methodology used in the Lakes Entrance case study which has been organised within the ISO31000 risk management framework. These steps are expanded in sections 3.1 to 3.3.

The international ISO31000 standard for iterative risk management guides users through the identification, assessment, management and monitoring of risk. Fig. 2 has been aligned to the key stages of ISO31000 because such principles are evident in both emergency management and contemporary climate change adaptation frameworks. Additionally, risk management is recognised as an appropriate framework to support climate change adaptation (Jones and Preston, 2011). Risk is described in this case study as the consequence to objectives, caused by a combination of hazard, exposure and vulnerability factors (IPCC, 2014).

3.1 Establish the context

3.1.1 Define adaptation objectives

The adaptation objectives selected for this study are shown in Table 1. The metrics chosen are consistent with other flood risk studies (e.g. Lempert et al., 2013; Scussolini et al, 2017) and reflect traditional Australian emergency management objectives that relate to the protection of life and property. The average annual damages (AAD) metric represents the average damage each year to property that would occur from flooding over a long period of time. Similarly, the average annual people exposed (AAPE) is the average number of people exposed to flooding per year over a long period of time, where a person is considered exposed if flood water levels reach their property. The baseline AAPE from flooding in Lakes Entrance was estimated in this study to be 47 people/year, whilst the baseline AAD to property from flooding was $1.8 million/year. The tolerable impact was arbitrarily set at twice the baseline levels since stakeholder engagement was unable to be undertaken in this study. This was a key limitation since engagement with the community would be necessary in a real world applications to build consensus on the adaptation objectives and level of tolerable flood impacts (e.g. Barnett et al., 2014; Zandvoort et al., 2017).

Table 1. Selected adaptation objectives, metrics and tolerable impacts

ID	Criteria	Adaptation objective	Metric (measure of risk)	Tolerable impact
1	Safety	Maintain number of people exposed to extreme flooding to below double the current baseline	AAPE	< 94 people / year
2	Property damage	Maintain property damage costs (commercial and residential) to below double the current baseline	AAD	< $3.7 million / year

3.1.2 Define uncertain factors

Six uncertainties (Table 2) were identified for stress-testing the adaptation policies and describing adaptation tipping points with scenario discovery (section 3.2.3). The uncertainties used to generate transient scenarios and assess policy use-by years (section 3.2.4) incorporated rates of change for different uncertain hazard, exposure and vulnerability factors to reflect changing flood risk over time.

Table 2. Summary of the uncertainties used in the case study. The uncertainties have been grouped into 1) those used to stress-test adaptation policies and describe adaptation tipping points with scenario discovery, and 2) those used to generate time-varying transient scenarios to assess use-by years.

Risk dimension	Objective		Uncertain factor	Range			
	AAPE	AAD		Minimum	Baseline	Maximum	Basis for range [a]
Impact modelling (for use in scenario discovery)							
Hazard	✓	✓	Sea level rise	0 m	+0 m	+2.0 m	User defined, guided by IPCC (2013)
	✓	✓	Sea level response factor	0.8	0.9	1.0	Water Technology (2014)
Vulnerability		✓	Max. structural damage (real $) [b]	-10 %	0 %	+ 10%	User defined
		✓	Max. contents damage (real $)	-10 %	0 %	+10 %	User defined
		✓	Damage index uncertainty [c]	-10 %	0 %	+10 %	Wehner et al. (2017)
	✓		Average people per dwelling	-50%	0 %	+50%	User defined
Impact modelling (transient scenarios)							
Hazard	✓	✓	Rate of sea level rise	+0.09 mm yr^{-1}		+5.3 mm yr^{-1}	Min: Church and White (2011) Max: RCP2.6 upper curve (IPCC, 2013)
	✓	✓	Sea level acceleration	-0.006 mm yr^{2}		+0.07 mm yr^{-2}	Min: RCP2.6 lower curve (IPCC, 2013) Max: RCP8.5 upper curve (IPCC, 2013)
	✓	✓	Rate of abrupt sea level rise	0 mm yr^{-1}		+20 mm yr^{-1}	Min: user defined Max: guided by DeConto and Pollard (2016)
	✓	✓	Timing of abrupt sea level rise	40 years		90 years	Min: guided by DeConto and Pollard (2016) Max: user defined
Exposure	✓	✓	Option 1: Rate of retreat (zone 4)	5 houses yr^{-1}		10 houses yr^{-1}	User defined
	✓	✓	Option 2: Rate of redevelopment	5 buildings yr^{-1}		10 buildings yr^{-1}	User defined
	✓	✓	Option 3: Rate of retreat	5 houses yr^{-1}		19 houses yr^{-1}	User defined
	✓	✓	Option 4: Rate of all retreat	5 buildings yr^{-1}		19 buildings yr^{-1}	User defined
Vulnerability		✓	Annual rate of change for structural damage	-0.01 % yr^{-1}		+0.01 % yr^{-1}	User defined
		✓	Annual rate of change for contents damage	-0.01% yr^{-1}		+0.01 % yr^{-1}	User defined
	✓		Annual rate of change for average people per dwelling	-0.05 % yr^{-1}		+ 0.05 % yr^{-1}	User defined

[a] Refer Table A.2 of online supplementary material for more details.

[b] Property replacement costs estimated using Rawlinsons (2017). Real dollars relative to 2010 used to account for annual growth / decline in the absence of inflation.

[c] Difference between the analytical stage-damage curves applied and the actual surveyed data for the case study area.

3.2 Risk assessment: no policy

3.2.1 Generate cases

A case is a ‘what-if’ scenario used to assess impacts to adaptation objectives for different future realisations. Each case resembles a combination of uncertain hazard, exposure and vulnerability risk factors. A total of 5,000 cases were generated with Latin Hypercube Sampling (LHS) incorporating the uncertainties defined in Table 2. The cases generated were stored in a simple flat file database (csv file).

3.2.2 Impact modelling (simulations)

Impacts to the AAPE and AAD metrics (Table 1) were assessed for each case in the database. A simple ‘rule of thumb’ was established between mean sea-level rise and extreme lake flood water level based upon prior hydrodynamic modelling (Water Technology, 2014). This was important in the impact assessments to model flood hazards for 0.1%, 0.2%, 0.5%, 1%, 2%, 5%, 20%, 40%, 60% and 90% AEP events using a bathtub approach. Commercial ArcGIS software was used to evaluate the impacts to people from different flood events, using LiDAR data and digitised property footprints. A database of low-lying properties, their approximated floor levels and building characteristics was developed using aerial imagery, LiDAR data and Google Street View. Structural damage to properties in this database was then assessed using flood depth, with damage expressed as a percentage of the total replacement cost (i.e. damage index) (Geosciences Australia, 2017). Contents damage was only considered for residential properties. Further details on the data and model set-up is provided in Appendix A of the online supplementary material.

Impact modelling was undertaken to stress-test the policy options and describe adaptation tipping points using scenario discovery. It took 12 hours to assess impacts across 5,000 cases (9 seconds per case) (3.4 GHz Intel processor, 16GB RAM).

3.2.3 Scenario discovery to describe adaptation tipping points

Scenario discovery is a data mining algorithm used to search the results of the impact assessment for all cases and identify decision-relevant clusters (Bryant and Lempert, 2010). These clusters are a subspace of the total input uncertainty space and are achieved by constraining one or more of the input uncertainties. The clusters contain a high proportion of 'interesting cases', which get flagged when impacts to the AAPE and AAD metrics are assessed as tolerable. The constrained uncertainties defining the clusters provide a simple description to predict interesting cases (Bryant and Lempert, 2010), which are used as the basis for defining adaptation tipping points (Ramm et al., 2018). Scenario discovery was implemented using the PRIM (patient rule induction method) package in Python (Hadka, 2016)[2].

3.2.4 Transient scenarios to model time-varying impacts and assess use-by years

Scenario discovery enabled a small set of uncertainties to be illuminated at which policies no longer keep flood impacts below tolerable levels. The rates of change for those key uncertainties were used to generate transient scenarios that modelled changing impacts over time and enabled the policy use-by year to be assessed. The transient scenarios also included a rate of implementation for the policy options (e.g. rate of retreat). This was done to capture how the exposure of people and property changes, which influences the resultant flood impacts over time (refer Box 2 of the online supplementary material). An arbitrary assessment horizon of 90 years was adopted for all policies (2010-2100) and a time-step of 5-years was used to improve the computational simulation time. The distribution of use-by years across all transient scenarios was summarised in a box plot and the median year used to give an indicative timeframe for mapping adaptation pathways (Haasnoot et al., 2012; Haasnoot et al., 2015; Kwakkel et al., 2016). The impact modelling using transient scenarios took much longer than those simulations done in section 3.2.2, taking 34 hours to analyse 1,000 cases (2 minutes per case).

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[2] Scenario discovery can also be implemented in R with the sdtoolkit (Bryant, 2015), or in Python using the open source exploratory modelling workbench (Kwakkel, 2017), noting that the Python implementation can handle heterogenous uncertain factors (Kwakkel and Jaxa-Rozen, 2016).

Sea-level rise was a key uncertainty considered in this case study. A second-order polynomial was used to project changing sea-level rise over time in the transient scenarios, accounting for the rate of sea-level rise, acceleration and rate of abrupt sea-level rise (based upon Lempert et al. (2012) and Oddo et al. (2017)). Since the historical mean sea-level rise at Lakes Entrance was observed to be consistent with the global trend, the coefficient values used in the polynomial were guided by global projections from the Intergovernmental Panel on Climate Change fifth assessment report (IPCC, 2013) as shown in Table 2. An upper bound for the rate of abrupt sea-level rise was based upon DeConto and Pollard (2016) to define a scenario with instability of the Antarctic ice sheet. Although such studies are under scientific debate, this was incorporated for the purposes of exploratory modelling (refer Fig. A.2. in the supplementary material).

3.3 Risk treatment: adaptation policy options

The activities in sections 3.2.2 to 3.2.4 were repeated on each policy option (Table 3) to assess adaptation tipping points and use-by years. The options considered were non-exhaustive. Further details of the options are provided in Appendix C of the online supplementary material.

Table 3. Overview of selected adaptation policy options for this study showing their potential to mitigate extreme lake flooding and permanent inundation from the sea.

	ID	**Option**	**Description**	**Mitigate lake flooding**	**Mitigate permanent inundation**
Do nothing	N1	No policy	Do nothing option (business as usual)	✗	✗
Protect	P1	Barrier protection	Protect properties from floods up to 2.5 m. Changed land use to commercial only in unprotected low-lying areas, retreating residential properties. Barrier protection could be achieved by levees and/or raising roads. Further information is needed about the implication of rising groundwater tables on property/road foundations, and the effectiveness of sheet pile and pumping measures to control seepage under barriers.	**?**	**?**
Accommodate	A1	Changed building requirements	Revise building development requirements. In low-lying areas, infill land to 2.3 m, raise minimum residential floor level to 2.6 m and change property foundation requirements (e.g. piled foundations) which permits future raising of floor levels or relocation of properties. Option likely to be slow given existing property stock in the floodplain.	✓	✓
	A2	Land use change	Changed land use in low-lying areas to commercial only, retreating residential properties. Retreat might be achieved through voluntary land swap, voluntary acquisition and physical relocation of existing houses.	✓	✓
Retreat	R1	Planned retreat	Progressive voluntary acquisition of property/land in low-lying areas. Re-purposing land use (e.g. natural wetland, parks and recreational areas). Re-align the Princes Highway. Retreat mechanisms may include voluntary land swap, voluntary acquisition and physical relocation of existing houses.	✓	✓

3.3.1 Develop the adaptation pathway

Adaptation pathways were developed and mapped using the adaptation tipping points and use-by years for assessed policies. Subsequent DAPP activities not undertaken as part of this case study illustration – but necessary as part of a complete RDM and DAPP approach – include selecting a preferred pathway, determining contingency actions (including signposts and triggers), specifying a dynamic plan, implementing the plan and monitoring (Haasnoot et al., 2013).

3.3.2 Evaluate adaptation pathways (including lived values)

Lived values information for Lakes entrance was obtained from prior research using semi-structured scoping interviews and survey (Graham et al., 2014). A simple qualitative assessment of the potential implications of different adaptation pathways on the top five lived values in Lakes Entrance was undertaken based upon judgement and knowledge of the study area. Other criteria used to qualitatively evaluate the adaptation pathways were cost, political risk and rate of implementation. Further opportunities to use lived values in a combined RDM and DAPP approach are discussed in section 5.3.

4 Results

4.1 Risk assessment: no policy

Scenario discovery results for the no policy option are shown in Table 4, along with the median use-by year determined from transient scenarios. Further details from the analysis is provided in Appendix E of the online supplementary material.

Table 4 Results from scenario discovery (describing adaptation tipping points) and transient scenarios (median use-by year) for the no policy option.

Metric	Conditions describing adaptation tipping point	Coverage / density	Cases of interest / total cases	Median use-by year Note 1
AAPE	Mean sea-level > 0.17 m *and* Average people per dwelling > 32%	72% / 88%	449 / 5000	2050 *(2045-2060)*
AAD	Mean sea-level > 0.33m *and* Damage index uncertainty > -0.015	74% / 94%	436 / 5000	2050 *(2045-2060)*

Note 1: The 25th and 75th percentiles are shown with *italics* in parentheses

A change in frequency of a 1.1 m flood event was used as an analogue to describe flood risk and improve the salience of adaptation tipping points to residents. Residents are familiar with impacts from a 1.1 m flood as such events have been experienced in the recent past. Flood events of this magnitude cause disruption to the functioning of the town by closing the Princes Highway, esplanade precinct and triggering additional flood mitigation actions. Flood frequency analysis suggests that the current annual chance of a 1.1 m flood event is 15%, which corresponds to an average recurrence interval (ARI) of one in seven years (Grayson et al., 2004: 25).

Mean sea-level rise was a dominant factor driving flood impacts and a rise in mean sea-level of approximately 0.2–0.3 m may cause flood impacts to people and property to become intolerable without adaptation action (Table 4). This amount of sea-level rise could reduce the ARI of a 1.1 m flood event from seven years down to two years, raising the annual chance of occurrence from 15% to 40%. Flood impacts were projected to become unacceptable in about 2050, as determined from the transient scenario analysis which considered uncertain factors like the rate of sea-level rise, acceleration, rate of abrupt sea-level rise and annual rate of change in average people per dwelling.

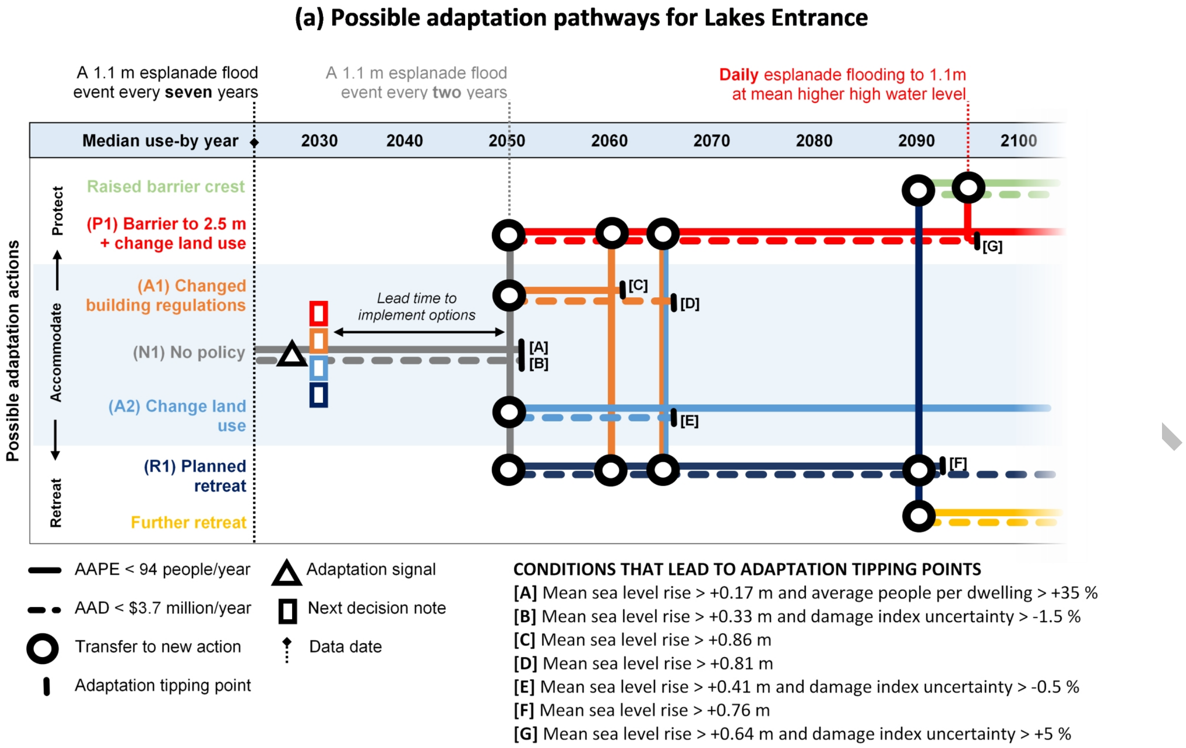
4.2 Risk treatment: adaptation policy options

The adaptation tipping points and use-by years for all policy options were analysed individually (Table 5). The map in Fig. 3a. reflects the early stages of developing and evaluating adaptation pathways for Lakes Entrance using a combined RDM and DAPP approach. The relative implications of the adaptation pathways on the top five lived values in Lakes Entrance are also shown in Fig. 3b., along with a qualitative evaluation of cost, political risk and rate of implementation for the adaptation pathways.

Table 5. Results from scenario discovery (describing adaptation tipping points) and transient scenarios (median use-by year) for future policy options.

Option (ID)	Metric	Conditions describing adaptation tipping point	Coverage / density	Cases of interest / total cases	Median use-by year [Note 1]
1 (P1)	**AAPE**	Mean sea level > 0.96 m	92% / 96%	2503 / 5000	2100+ *(2100+)*
	AAD	Mean sea level > 0.64m *and* Damage index uncertainty > 0.05	79% / 91%	1445 / 5000	2095 *(2080-2100+)*
2 (A1)	**AAPE**	Mean sea level > 0.86 m	89% / 98%	2388 / 5000	2060 *(2050-2075)*
	AAD	Mean sea level > 0.81 m	88% / 91%	2100 / 5000	2065 *(2055-2080)*
3 (A2)	**AAPE**	Mean sea level > 0.76 m	91% / 97%	2052 / 5000	2100+ *(2090-2100+)*
	AAD	Mean sea level > 0.40m *and* Damage index uncertainty > -0.005	72% / 93%	609 / 5000	2065 *(2055-2075)*
4 (R1)	**AAPE**	Mean sea level > 0.76 m	91% / 97%	2052 / 5000	2090 (2060-2100+)
	AAD	Mean sea level > 0.86m	87% / 94%	2320 / 5000	2100+ (2055-2100+)

Note 1: The 25th and 75th percentiles are shown with *italics* in parentheses



CONDITIONS THAT LEAD TO ADAPTATION TIPPING POINTS
[A] Mean sea level rise > +0.17 m and average people per dwelling > +35 %
[B] Mean sea level rise > +0.33 m and damage index uncertainty > -1.5 %
[C] Mean sea level rise > +0.86 m
[D] Mean sea level rise > +0.81 m
[E] Mean sea level rise > +0.41 m and damage index uncertainty > -0.5 %
[F] Mean sea level rise > +0.76 m
[G] Mean sea level rise > +0.64 m and damage index uncertainty > +5 %

(b) Scorecard showing the relative implications of potential adaptation pathways

Adaptation Pathways		Relative $ cost to community	Relative gain or loss to top five lived values Notes 1,2					Short-term political risk Note 3	Rate of implementation Note 4
			Scenery	Natural environment	Safety	Proximity to water	Lifestyle		
1		$	~	-	+	~	~	L	🕒 🕒 🕒
2		$ $	-	-	+	~	~	L	🕒 🕒
3		$	-	-	+	~	~	L / M	🕒
4		$ $	- -	- -	+	~	~	L / M	🕒
5		$	~	~	+	- -	-	M	🕒 🕒
6		$ $	-	-	+	-	-	M	🕒 🕒
7		$ $	+	+	+ +	- -	-	M / H	🕒
8		$ $ $	-	-	+ +	- -	-	M	🕒 🕒
9		$ $ $	+	+	+ +	- -	-	M / H	🕒

Note 1: Lived values based upon Graham et al (2014). Refer to Appendix B of the online supplementary material.
Note 2: '- -' large relative loss; '-' relative loss; '~' no change; '+' relative gain; '+ +' large relative gain
Note 3: Based upon 'outrage potential' discussed in Gibbs (2016)
Note 4: Assumes no large scale redevelopment of existing property stock following a shock event

Fig. 3. Possible adaptation pathways for Lakes Entrance (a). Conditions the lead to adaptation tipping points for policy options (assessed individually) are shown along with the median use-by year for individual policies across the top axis. A simple qualitative scorecard showing possible trade-offs to lived values from adaptation pathways are shown in the bottom panel (b). Please refer to the web version of this article for a colour version of this figure.

A key feature of Fig. 3a. is that conditions leading to adaptation tipping points can be presented alongside policy options in the pathways map (denoted by letters A to G) to communicate the conditions at which individual policies no longer manages coastal flood impacts successfully. The adaptation pathways map would need to be further developed to consider short-term low regret and/or win-win options that could enhance – or keep open – the policy options mapped. Such actions might include reviewing spatial planning rules (e.g. set-back lines or land use zones) or researching new financial instruments to enable policies like retreat. Short-term flood mitigation options like wet proofing, dry proofing or installing flood barriers (Maqsood et al., 2017) could also be considered, with due consideration needed about potential intergenerational implications of delaying transformational options like retreat. Additionally, further effort is needed to identify technical, social and political signpost indicators which might precede the decision nodes. This is particularly important for options A1, A2 and R1 as implementation can take many years and decisions will need to be triggered well in advance of the anticipated use-by year to manage flood impacts successfully.

5 Discussion

5.1 A customisable model-based approach combining RDM and DAPP

The case study used a combined RDM and DAPP approach to illustrate keys steps that local government might undertake in the early stages of long-term strategic adaptation pathway planning to manage future coastal flood impacts. The model-based approach provided insights about the sensitivity of the community to change without adaptation, the anticipated timing at which adaptation policies are needed and the robustness of those policies.

A strength of using scenario discovery from RDM is that it can provide multi-dimensional descriptions of adaptation tipping points. This is potentially a useful basis upon which technically-oriented signpost indicators and trigger levels might be specified as part of the monitoring system (Hermans, et al., 2017). For example, AAPE impacts were modelled to double without any adaptation policy in a future scenario characterised by sea-level rise greater than 0.17 m and household occupancy levels 35% higher than present (Table 4). Such signpost indicators might be useful to monitor as their change is slow and detectable. However, further development of early-warning triggers is needed to anticipate upcoming adaptation decisions ahead of adaptation tipping points, especially when the lead time on implementation is significant.

Sea-level rise was a dominant uncertainty in the case study which was unsurprising given sea-level rise was the key hazard factor modelled influencing change to extreme lake flood levels. Translating sea-level rise into a changed flood frequency can be a useful analogue for communicating to residents about how impacts to local people, their lives and experiences might be affected by future change (e.g. Barnett et al., 2014). The flood frequency of a 1.1 m event was considered in the case study and this could be a useful signpost indictor that is salient to the everyday lives of residents. A difficulty that remains with using flood frequency is that it can take decades for local and national scientific agencies to detect and confirm the signal, which can cause difficulties reaching consensus about whether a trigger has been reached. Consequently, multiple signposts are likely to be needed to cater for different stakeholder needs. Monitoring a variety of indicators could provide a robust basis to detect changed coastal flood risk and trigger adaptation decisions.

The inclusion of transient scenarios in a combined RDM and DAPP approach highlighted how future flood impacts experienced in the community depend upon the rate of climate change and the speed at which policies can be implemented. For example, scenario discovery suggested that the A1 option (changed building regulations) was robust to 0.8 m of sea-level rise (Table 5). However, the median use-by year was much earlier than expected because the rate at which existing properties can infill land, raise floor levels and change building types is likely to be constrained by characteristics of the existing built environment (this rate was assumed to be in the range of 5-10 properties per year based upon that rate of recent redevelopments in the study area). Therefore, this option could be improved if: (1) it is implemented earlier, (2) the rate of implementation is faster, or (3) the community accepts higher annual risk of damages. Similar findings also applied to options A2 (changed land use) and R1 (planned retreat) where long lead times are needed in existing settlements to realise flood mitigation benefits from policies. Therefore, transient scenarios can draw the attention of decision-makers to limitations of policy options in managing flood impacts over time, which enables iterative improvements to be made to the policies and pathways.

The use of open source data, programming tools and commercial GIS software in the combined RDM and DAPP approach enabled the impact assessments to be customised to cater for location-specific data constraints and coastal flood characteristics. The programming requirements for the case study became complex when accounting for different objectives, data sets, models and policy options (refer Fig. D.1. and Fig. D.2. in the supplementary material). This can become a barrier for resource-constrained authorities undertaking a combined RDM and DAPP approach. Whilst technical capability could be procured in the short-term, further research is needed to improve the efficiency and usability of the overall programming steps. Conversely, the growing repository of open source data, programming packages and access to national datasets to support impact assessments (e.g. the census data and the NEXIS database in Australia) are enabling factors for a combined RDM and DAPP approach. Further research into the feasibility of software like QGIS could make all steps in the combined RDM and DAPP approach open source.

5.2 The use of lived values in adaptation pathways planning

Increasing coastal flood events will undoubtedly have different impacts on the way residents experience lived values in Lakes Entrance. Whilst this study was constrained insofar as it was unable to engage with participants to use lived values in the identification of adaptation objectives, metrics and risk tolerances, knowledge of lived values was used to qualitatively evaluate alternate adaptation pathways. The assessment (Fig. 3b.) provides a simple entry point for considering how adaptation pathways might affect key lived values in Lakes Entrance, along with what non-material trade-offs could be acceptable for the benefit of reduced coastal flood risk. This could further enable conversations about how to improve adaptation pathways so that they preserve – or enhance – important lived values for residents. For example, whilst those adaptation pathways that include levees may trade-off impacts to the natural environment for improved safety, they could enhance recreational opportunities by including new walkways and cycle paths. Retreat pathways could include repurposing low-lying land with parks, wetlands, marinas or recreational facilities and enhance scenery, natural environment and recreational opportunity values over the coming decades. It would do so at the trade-off of monetary cost and may cause discontent from property owners in the floodplain whose tradable property value may be affected (Gibbs, 2016).

The adequacy of claims about how the everyday lives of residents might be affected by adaptation pathways needs further validation through community engagement as lived values are nuanced and highly subjective. Whilst an initial assessment can provide a simple entry point for decision-makers to contemplate the effect of adaptation pathways on lived values early in the planning processes, it has limited use without being able to engage with participants to reach consensus about adaptation decisions. There is further potential for lived values information to be used in developing socially-oriented signpost indicators as part of the monitoring system, but more research would be needed to operationalise key lived values (e.g. natural environment, scenery and safety) for use as signpost indicators.

5.3 Closing remarks

Communities around the world are already committed to future sea-level rise (Mengel et al., 2018). The complexity of wicked problems such as coastal adaptation means that a clear solution will not present itself and decisions will need to be made iteratively over time to reflect the complexity and dynamics amongst actors (Moser et al., 2012). Adaptation pathway planning can help anticipate the timing of multiple options to achieve long-term coastal flood risk management objectives. The adaptation strategy requires periodic updates to incorporate the latest data, knowledge, uncertainties and lived values to support an ongoing monitoring of the objectives, uncertainties, options, pathways, signposts and triggers. Creation of appropriate regulatory instruments, governance arrangements and a willingness to adapt from residents (Productively Commission, 2012) will also be necessary to enable the implementation of timely adaptation policies by local government.

Informed decision-making at all levels of government is important as choices made today about coastal development and land use will shape the pattern of urbanization over the coming century, influencing what gets exposed to future coastal flooding. This is particularly important for coastal towns whose long-term sustainability relies upon their natural environment and proximity to the coast to attract residents, tourists and support industry (Cooper and Lemckert, 2012). A combined

RDM and DAPP approach can account for interactions between hazard, exposure and vulnerability factors which can then inform flood impact assessments and an evaluation of policy robustness. Future opportunities to engage with participants and consider lived values in a combined RDM and DAPP approach include: 1) defining adaptation objectives, metrics and risk tolerance, 2) identifying policies and evaluating adaptation pathways, and 3) identifying signposts and triggers. Achieving consensus on these factors through community engagement is critical because the adaptation tipping points, use-by years and hence resultant adaptation pathways are fundamentally dependent on the specified adaptation objectives and the communities level of tolerance for coastal flood impacts.

6 Conclusions

This study provides a proof of concept of the keys steps in a combined RDM and DAPP approach in coastal flood risk management, illustrating how local government might begin planning strategic adaptation pathways using model-based support and largely open source tools. A combined RDM and DAPP approach can account for spatial and temporal interactions between hazard, exposure and vulnerability flood risk factors, which improves the way the robustness of policies are assessed in wicked problems like long-term coastal adaptation. Open source data and programming tools, along with commercial GIS software, provide a customisable process for local government to cater for location-specific constraints. However, programming can be complex for resource-constrained authorities which can limit uptake of the method.

The inclusion of scenario discovery in a combined RDM and DAPP allows multi-dimensional descriptions of adaptation tipping points to be generated for policy options. This can form a basis for developing technically-oriented signposts indicators and triggers. Transient scenarios can uncover limitations in seemingly robust adaptation policies, where historical path dependencies constrain the rate of adaptation and the extent to which coastal flood impacts can be kept below accepted levels. This helps decision-makers direct further efforts towards improving the efficacy of those policies, such as considering earlier or faster rates of implementation, or accepting an increased level of annual flood risk.

Lived values have the potential to offer insights about non-material trade-offs that residents may need to accept for the benefit of reduced flood risk. They also have potential use in designing more socially-oriented signpost indicators as part of a broad adaptation pathway monitoring system. However, the subjectivities behind how residents experience lived values mean that ongoing engagement is essential throughout the adaptation planning process to provide a forum for learning and debating losses and gains to residents' way of life. Engaging residents is important in small coastal communities to reach consensus on adaptation objectives, metrics and tolerable flood impacts, which are critical inputs in the adaptation pathways planning process. The learnings from this hypothetical case study suggest that testing in a real world participatory setting could be valuable to further develop a combined RDM and DAPP approach to plan adaptation pathways and manage future coastal flood risk.

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