

ARTICLE TITLE:

Describing adaptation tipping points in coastal flood risk management

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27 **Abstract**

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

46 **Keywords**

47 Adaptation, climate change, inundation, tipping point, uncertainty, vulnerability

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52 **Highlights**

- 53 ▪ GIS software, open source data and programming languages can support coastal
- 54 flood risk management activities
- 55 ▪ Scenario discovery helps simplify complex environmental changes for use in
- 56 vulnerability assessment and adaptation planning
- 57 ▪ Scenario discovery can be used to describe conditions leading to adaptation
- 58 tipping points
- 59 ▪ The timing of adaptation responses can be better informed by knowledge of key
- 60 sensitivities in existing management controls
- 61 ▪ Insights from scenario discovery can facilitate targeted data collection and coastal
- 62 monitoring activities

63

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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 and 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 et al. 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 et al. 2016; Watkiss and Hunt 2013). When deep uncertainty exists, dynamic adaptive policy pathways (DAPP) (Haasnoot et al. 2013) and robust decision making (RDM) (Lempert et al. 2003) have emerged as two state-of-the-art decision support tools (Kwakkel et al. 2016a). 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 (Lempert et al. 2003; Kwakkel et al. 2016a). 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

101 uncertain future on the performance of new (or existing) adaptation policies, allowing key
102 sensitivities of the policy to be identified. When external changes cause the existing
103 system or future adaptation plans to no longer meet decision-maker objectives, an
104 adaptation tipping point is reached and new actions should be implemented (Kwadijk et al.
105 2010). Adaptation tipping points provide a practical way to communicate risks to the
106 community associated with a changing built and natural environment (Werners et al.
107 2013). This focuses coastal flood risk management towards understanding the sensitivity
108 of an urban area to change and assessing when management responses might be
109 needed to keep impacts at a tolerable level (Kwadijk et al. 2010).

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

118 There are few examples from local government that use RDM or DAPP to assess the
119 vulnerability of low-lying areas to coastal inundation and design adaptation pathways. This
120 could be due to many factors including unclear adaptation responsibilities in government
121 (Nalau et al. 2015), limited awareness of new decision support tools (Lawrence and
122 Haasnoot 2017), limited availability of relevant data to undertake such an analysis (Bhave
123 et al. 2016) and technological or financial constraints. Simplified applications of RDM (e.g.
124 Daron 2015) and adaptation pathways (e.g. Barnett et al. 2014) have been demonstrated
125 for resource-constrained decision-makers. However, the growing global repository of
126 spatial data and open source programming code (e.g. the exploratory modelling
127 workbench; Kwakkkel, 2017) means that local governments, business and individuals have

128 an opportunity to use more sophisticated techniques to analyse climate risks, quantify
129 thresholds and evaluate adaptation responses (Ramm et al. 2017a).

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

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

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

164 **2 Methods**

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

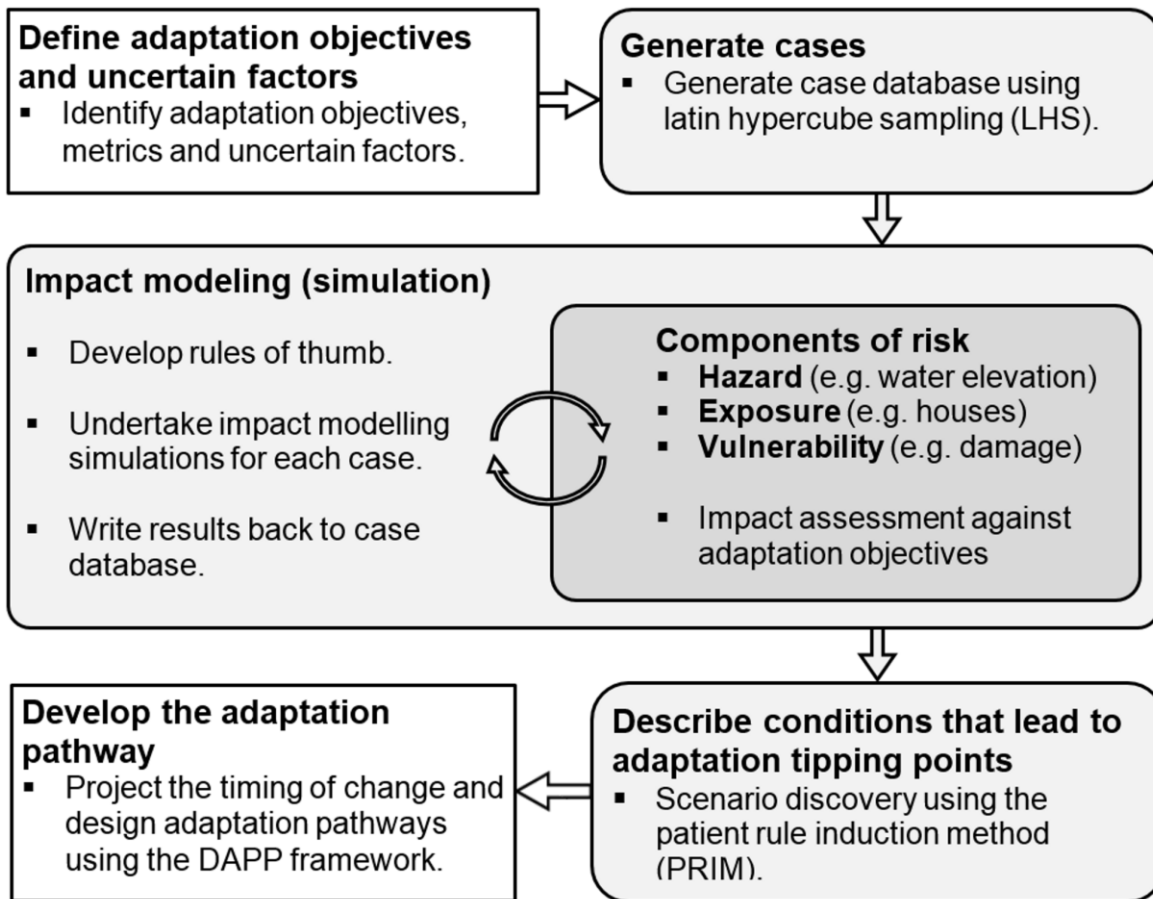


Fig. 1 Summary of methodological steps to describe conditions leading to adaptation tipping points for use in adaptation pathways planning. These steps are expanded on in Sections 2.1 to 2.7.

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 et al. 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.

186 **2.2 Define uncertain factors**

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

194 **2.3 Generate cases**

195 A case is a future realisation that represents a combination of randomly sampled
196 uncertain factors (analogous to a single ‘what if’ scenario). Each case captures a single
197 set of assumptions about the future state of uncertain factors. The generation of
198 numerous cases allows future realisations to be explored in a process of exploratory
199 modelling (Bankes 1993). Cases are generated by selecting values for uncertain factors
200 using latin hypercube sampling (LHS) (*lhs*¹ package¹), which then become inputs to the
201 computational experiments.

202 **2.4 Develop rules of thumb**

203 Rules of thumb are simple principles that relate the value of an uncertain external factor
204 (X) to a change in the model (R) (Section 2.5). For example, sea-level rise may affect the
205 depth and extent of coastal flooding, which is used to assess impacts to the adaptation
206 objectives for the case being explored. Rules of thumb can be derived from expert
207 judgement, prior knowledge, or from a set of detailed scientific models.

208 **2.5 Impact modelling (simulation)**

209 The ability to simulate many cases to assess coastal inundation impacts in a reasonable
210 timeframe requires a trade-off with the precision of the model (Bhave et al. 2016; Walker

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

211 et al. 2013). Proxy models are often useful in such instances (also referred to as
212 metamodels or surrogate models) (Haasnoot et al. 2012; Teng et al. 2017).

213 A simulation model was developed in Python 2.7 using geoprocessing tools from the
214 ArcPy module (ArcMap 10.4) and incorporating the 'spatial' and '3D analysis' ArcMap
215 extensions. Risk was conceptualised as the product of a hazard, an exposed element and
216 the associated vulnerability (de Moel et al. 2015; Klijn et al. 2015; IPCC 2012), which was
217 a useful way to organise various components of the simulation model. For example, a
218 floodwater elevation map reflects a hazard, property reflects an exposed element, and the
219 vulnerability of that element is described by monetary damage based upon flood depth.

220 **2.6 Describe conditions that lead to adaptation tipping points**

221 Scenario discovery searches through results in the case database and aims to identify a
222 small number of 'candidate scenarios' (Fig. 2) that best identify 'cases of interest'
223 (Lempert 2013). Cases of interest are those cases that result in acceptable impacts to
224 adaptation objectives. A candidate scenario describes a cluster of cases and resembles a
225 subspace of the uncertainty space that is explored in the computational experiments. It is
226 defined by a small set of factors and intervals (i.e. conditions) that capture a high
227 concentration of cases of interest. Should the small set of identified conditions occur
228 simultaneously in the future, an adaptation tipping point is likely to be reached and an
229 adaptation response would be needed to maintain impacts to the adaptation objectives at
230 or below the desired tolerance. Identifying a small number of candidate scenarios through
231 scenario discovery helps to keep the result interpretable for decision-makers.

232 The 'sdtoolkit' R package² was used to undertake scenario discovery, applying the Patient
233 Rule Induction Method (PRIM) algorithm (Friedman and Fisher 1999) to identify clusters of
234 the cases of interest. Whilst Classification And Regression Trees (CART) offer an
235 alternate data mining algorithm to PRIM (Breiman et al. 1993), neither algorithm currently

² See Bryant (2016) for package details.

has a strong advantage over the other (Lempert et al. 2008; Kwakkel and Jaxa-Rozen 2016).

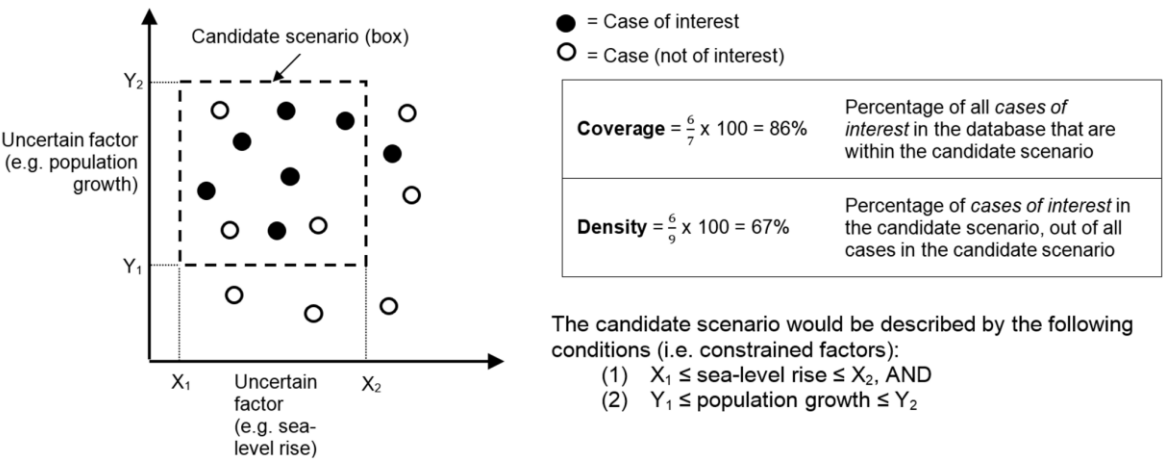


Fig. 2 Key concepts used in scenario discovery. Filled circles represent cases of interest. The candidate scenario is defined as a box (dashed line) that constrains key input factors. Coverage and density describe the quality of the candidate scenario.

The quality of the candidate scenario is measured by its ‘coverage’ and ‘density’ (Fig. 2). Coverage describes the cases of interest captured by the candidate scenario as a proportion of all cases of interest in the entire results database. Density describes the percentage of the cases of interest captured by the candidate scenario out of all cases captured by the candidate scenario (Bryant and Lempert 2010; Lempert et al. 2013). Other diagnostic measures, such as the quasi p-value and reproducibility statistics, are useful for understanding the significance of the constrained factors in the candidate scenarios (for more details see Bryant and Lempert 2010).

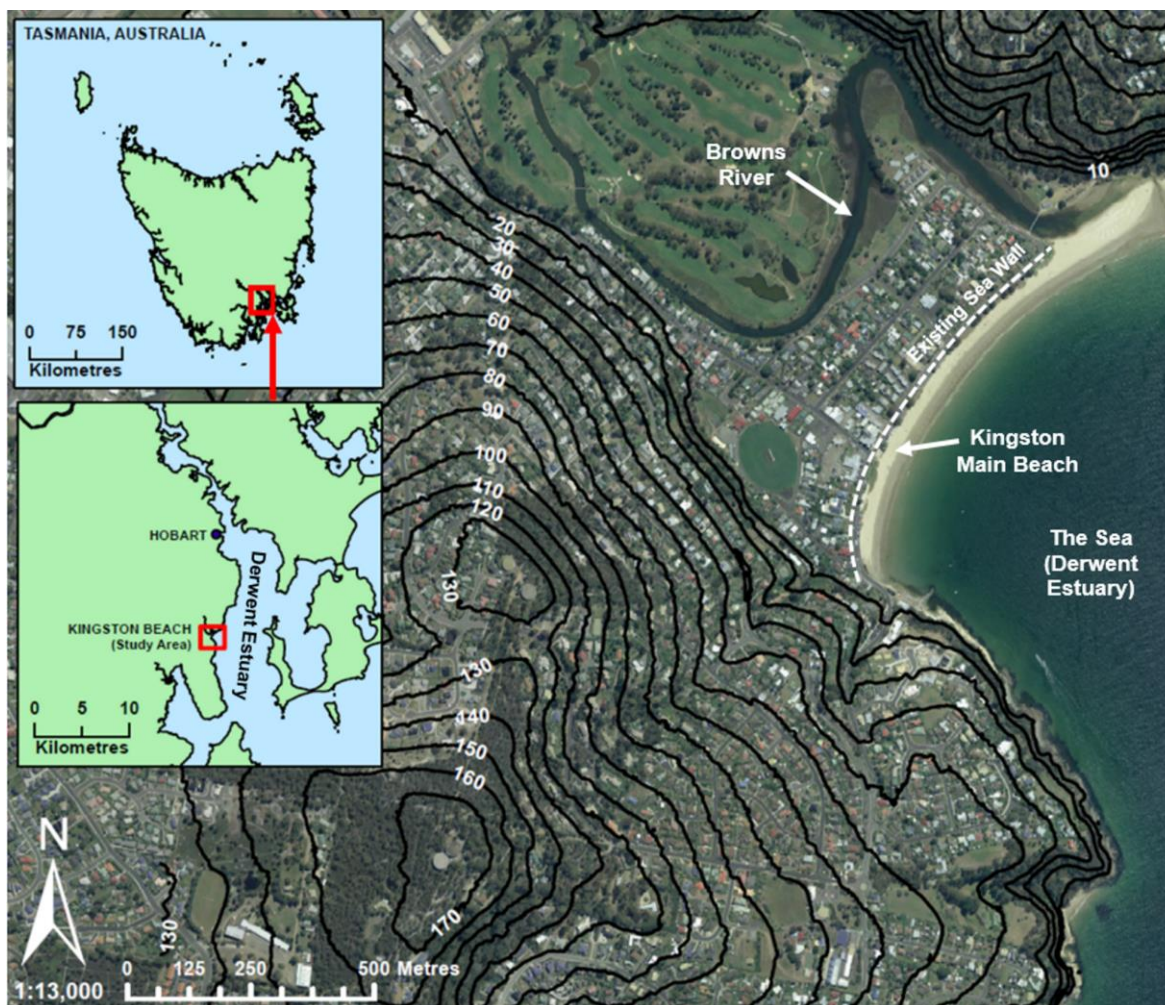
2.7 Develop the adaptation pathway

Once conditions under which adaptation objectives are no longer achieved have been identified through scenario discovery, scientific trends and projections can be considered to understand 1) the potential for such conditions to occur in the future based upon available evidence, and 2) over what timeframe such changes are projected to occur. This

256 information can then be used to develop adaptation pathways using the DAPP framework
257 (for more details see Haasnoot et al. 2013).

258 **3 Case study: Kingston Beach, Tasmania**

259 The method presented in Section 2 is illustrated for the case of the coastal suburb of
260 Kingston Beach, Tasmania (Australia). The study area is located approximately 13 km
261 south of the capital city of Hobart (Fig. 3). A unique aspect of the study area is that
262 approximately 86% of the housing stock located in low-lying areas were built before 1980
263 (Dunford et al. 2014). Thus, they were built prior to the introduction of higher building
264 standards. The suburb is predominantly residential, with approximately 20-40 small
265 businesses in low-lying areas and many natural landscapes including beaches, grassland,
266 saltmarshes and forests. Whilst new dwellings will be subject to more stringent building
267 regulations and land use planning controls, the characteristics (e.g. floor level, building
268 materials) of many existing houses in the study area could remain unchanged for decades.
269 Therefore these houses may have increasing exposure and vulnerability to changing flood
270 hazards in the future. Extreme sea-levels from storm tides are considered to be a lower
271 threat to people and property in the study area compared to the inundation threat of
272 riverine flooding from Browns River. However, sea-level rise will threaten low-lying coastal
273 landscapes of significant social and cultural value, such as the Kingston Main Beach
274 (Ramm et al. 2017b).



275

276 **Fig. 3** Study location in the suburb of Kingston Beach, Tasmania. The topographical
 277 terrain is shown with 10 m contours relative to Australian Height Datum (AHD), to highlight
 278 low-lying areas. The existing sea-wall is identified (white dashed line) from which beach
 279 width is estimated.

280

281 **3.1 Define adaptation objectives**

282 Three adaptation objectives were chosen to manage impacts to people, property and
 283 lifestyle, and these were grouped into key results areas (KRA) as might be done in a
 284 strategic coastal management plan (Table 1). This number of objectives is consistent with
 285 other RDM applications (e.g. three objectives were studied by Lempert et al. 2013; two
 286 were used in Bonzanigo and Kalra 2014). The average beach width objective was
 287 selected on the basis that: 1) the beach is a highly valued coastal landscape by residents,

288 and 2) there are many social values associated with the beach, including recreational use,
 289 being free of access restrictions, and providing residents with a sense of identity (Ramm
 290 et al. 2017b). The tolerable impacts signify whether an adaptation tipping point is reached.

291

292 **Table 1.** Adaptation objectives selected for illustrating the methodology, grouped into key
 293 result areas (KRA). Acceptable (tolerable) impacts to people (AAPE) and property (AAD)
 294 reflect an increase of 10% from the current-day baseline risk. Arriving at the tolerable
 295 impact threshold signifies that an adaptation tipping point is reached. Baseline risk is
 296 determined by modelling impacts with current-day best estimates for the uncertain factors
 297 (see Table 2).

ID	KRA	Adaptation objective	Metric	Tolerable impact
1	People: Minimise exposure	Maintain people exposed to within 10% of current baseline	AAPE	AAPE < 23.5 people / year
2	Property: Minimise damage	Maintain dwelling damage to within 10% of current baseline	AAD	AAD < \$650,000 / year
3	Lifestyle: Preserve social values	Maintain a minimum average beach width of 5 m from sea wall to MHWS level ^{a.}	Average width of Kingston Main Beach	Average beach width > 5m

298 ^{a.} Mean high spring water level (MHWS) is 0.623 m above the Australian Height
 299 Datum (Kingborough Council 2017, p.47) and reflects the average of spring tide
 300 high water observations over a 19 year period (Woodroffe 2003).

301

302 **3.2 Define uncertain factors**

303 A total of seven exogenous uncertainties (X) were identified in our case study illustration
 304 (Table 2). Three of the uncertainties related to the hazard component of risk and four
 305 characterised the vulnerability. The Bruun factor in Table 2 represents a simplified
 306 relationship between coastal recession and increasing sea-levels.

307 **Table 2.** Uncertain factors used for the study site, showing their range and the adaptation objective(s) to which they apply.

Risk dimension	Uncertain factor	Adaptation objective			Range ^{a.}			Basis for selected range
		(1) AAPE	(2) AAD	(3) Beach width	Min	Baseline (current-day best estimate)	Max	
Hazard	Sea-level rise (increase from 2010 levels)	✓	✓	✓	0m	0m	+1 m	User defined, guided by McInnes et al. (2016)
	Changing 9-hour rainfall intensity (relative to present) ^{b.}	✓	✓		-10%	0%	+30%	White et al. (2010; 2013)
	Bruun Factor			✓	10	N/A	100	Carley et al. (2008); Mariani et al. (2012)
Vulnerability	Maximum structural damage (per 4 m ²) ^{c.}		✓		\$4,000/4 m ²	\$5757/4 m ²	\$10,000/4 m ²	Dunford et al. (2014) ^{c.}
	Maximum contents damage (per 4 m ²)		✓		\$500/4 m ²	\$1058/4 m ²	\$2,500/4 m ²	Dunford et al. (2014) ^{c.}
	Damage index at 10 cm inundation		✓		-0.1	N/A	+0.1	Approximate deviation from the vulnerability curve (Geosciences Australia 2012)
	Average people per house	✓			2	2.2	3	Value is 2.15 for low-lying statistical area, 2.3 for Kingston Beach and 2.6 for Australia (ABS 2013)

308 ^{a.} The range is not limited to scientific consensus (e.g. IPCC) and can be inclusive of resident perceptions.

309 ^{b.} 9-hour rainfall intensity is the critical duration for the study area (Kingborough Council 2017, p.22)

310 ^{c.} The raster cell size is 4 m² in the impact model. The damage in *real* dollars for 2016 was obtained from the NEXIS building exposure

311 database (Dunford et al. 2014) by dividing the ‘resident structural value’ by the ‘residential building footprint’ for low-lying houses. House

312 reconstruction cost estimates could alternatively be obtained from insurance providers using representative dwelling details (e.g. 3-bedroom;

313 pre-1980’s; slab on ground; weatherboard) or industry publications such as Rawlinsons (2017).

314 **3.3 Generate cases**

315 A total of 1,000 cases were generated using Latin Hypercube Sampling (LHS). The results
316 were stored in a simple flat file database (ASCII csv).

317 **3.4 Develop rules of thumb**

318 Three 'rules of thumb' were determined for this study to incorporate the effect of uncertain
319 factors on the simulation model: 1) the change in floodwater elevation for each meter of
320 sea-level rise, 2) the change in the floodwater elevation for each percentage increase in
321 the 9-hour critical rainfall intensity, and 3) the horizontal beach recession for each meter of
322 sea-level rise.

323 Peak floodwater elevation maps were developed by Kingborough Council using SWMM
324 2D hydrodynamic modelling software for 11 different scenarios (see Appendix B in the
325 Online Resource for details). This allowed the current-day baseline risk to people and
326 property in Table 1 to be established. The 11 scenarios also allowed the relationship
327 between sea-level rise and peak floodwater elevation to be investigated, revealing that a 1
328 m rise in sea-level only increases the peak floodwater elevation by 1 cm. The relationship
329 between rainfall intensity and floodwater elevation was based upon prior flood study work
330 by Kingborough Council, which suggested that the peak floodwater elevation of Browns
331 River changed by about 0.1 m per 10% increase in the 9-hour rainfall intensity
332 (Kingborough Council 2017, p.40). The baseline scenarios from the hydrodynamic
333 modelling were converted into peak floodwater elevation raster grids. These grids could
334 then be adjusted using the rule of thumb relationships in the simulation model, depending
335 on the change to sea-level and 9-hour rainfall intensity.

336 The relationship between horizontal beach recession and sea-level rise was underpinned
337 by the Bruun rule (Bruun 1962). Notwithstanding the dynamic nature of sandy beaches
338 and the difficulty in modelling coastal processes, Kingston Main Beach is understood to be
339 threatened by inundation from long-term sea-level rise (Sharples 2016), regardless of its
340 historic ability to recover from erosion events (CoastAdapt 2016). Although there are
341 many simplifications of the Bruun rule (e.g. Cooper and Pilkey 2004), there are currently

342 few scientifically recognised alternatives for policy design (Mariani et al. 2012). Prior
343 studies of nearby beaches in the Derwent Estuary suggest that the Bruun factor could be
344 in the range of 15-37 (Carley et al. 2008), whilst Mariani et al. (2012) suggest that a Bruun
345 factor of 50 be used for Tasmania (and a factor of 100 for a conservative estimate). The
346 presence of a sea wall in the study area makes application of the Bruun rule further
347 problematic. We therefore only apply it to generate indicative beach loss seaward of the
348 existing sea-wall at Kingston Main Beach.

349 **3.5 Impact modelling (simulation)**

350 A schematic diagram of the model used to simulate impacts against the three adaptation
351 objectives is shown in Fig. 4. Spatial datasets were sourced online from the Tasmanian
352 State mapping authority (DPIPWE 2015). Low-lying houses were digitised into polygon
353 shapefiles using georectified aerial imagery, and a 2 m x 2 m raster grid was specified for
354 all geoprocessing analysis. This provided adequate model resolution whilst improving the
355 processing speed, which was important when raster grids were converted into NumPy
356 arrays to evaluate coastal flood impacts. Looping through each row in the case database
357 and applying the rules of thumb allowed different proxy flood depth rasters to be
358 generated (peak floodwater levels). These rasters could then be overlaid above the land
359 use raster to identify exposed dwellings and to determine the vulnerability of those
360 dwelling in terms of damage costs (see Appendix C in the Online Resource for details on
361 the data and geoprocessing tools used in the simulation model).

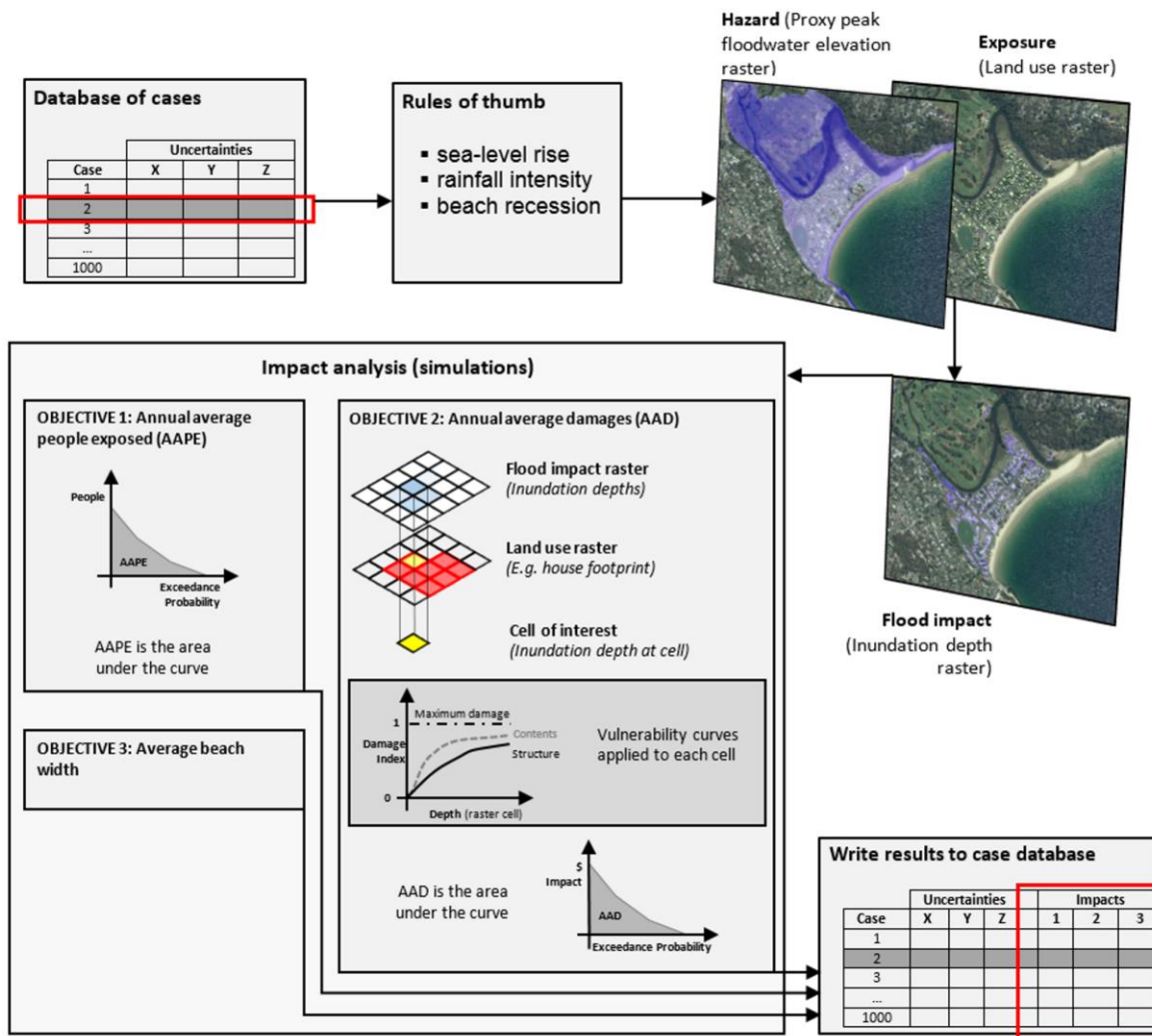


Fig. 4 Schematic diagram of the main activities undertaken to assess impacts to AAPE, AAD and average beach width. The case database was generated using the R programming language, before being imported into Python. Impacts on the adaptation objectives for each case were assessed in Python using geoprocessing tools (ArcPy module).

3.5.1 Calculating AAPE

The number of people exposed to hazards was estimated for 1%, 2%, 5% and 20% AEP events by multiplying the average number of people per dwelling by the number of houses inundated. AAPE was then determined by applying the trapezoidal rule to calculate the area under a plot of AEP against the number of people exposed. A similar measure to AAPE was used by Lempert et al. (2013).

375 **3.5.2 Calculating AAD**

376 Calculation of the AAD to dwellings was based upon established practice used to assess
377 monetary flood impacts (de Moel et al. 2015; Egorova et al. 2008). The proxy peak
378 floodwater surface was used to determine an inundation depth at each 2 m x 2 m raster
379 cell, from which vulnerability curves were applied to exposed dwellings to determine a
380 damage index. The damage index reflects the percentage of damage relative to the full
381 replacement cost. A separate vulnerability curve was used to assess damages to the
382 house structure (i.e. fixed elements) and contents (i.e. movable assets), and vulnerability
383 curves were guided by empirical data from Geosciences Australia (2012) (see Appendix D
384 in the Online Resource for details). The monetary impact to all dwellings in each case was
385 calculated by summing the damage across all raster cells for the 1%, 2%, 5% and 20%
386 AEP events, allowing the AAD to be determined using the trapezoidal rule (Ramm et al.
387 2015).

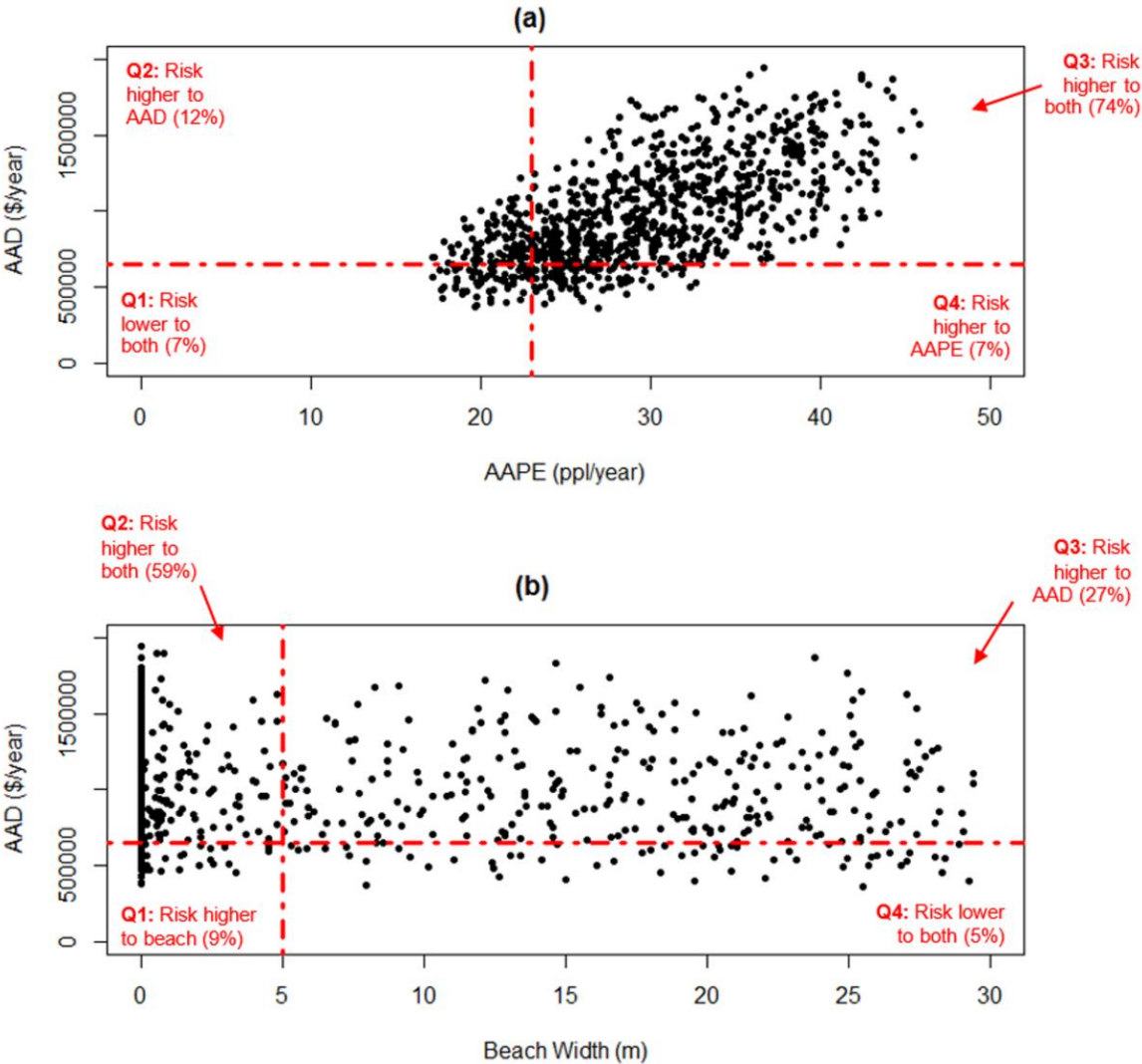
388 **3.5.3 Calculating average beach width**

389 The average beach width was determined by creating a transect line at five
390 distinguishable locations along Kingston Main Beach, corresponding to beach access
391 points. A buffer distance based on the Bruun factor was created around the sea-level rise
392 polygon (at MHSW) based upon the amount of sea-level rise in the case being considered.
393 The transect length was then calculated as the horizontal distance from the fixed sea wall
394 to the adjusted sea-level polygon. The average width across the five locations was then
395 calculated.

396 **3.5.4 Simulation results**

397 The impact model took 85 hours to analyse 1,000 cases on a standard 16GB RAM
398 machine with a 3.4 GHz Intel processor. Plotting the cases against the adaptation
399 objectives (Fig. 5) suggests that although the majority of case realisations resulted in
400 unacceptable impacts to the adaptation objectives (i.e. Q3 in Fig. 5a and Q2 in Fig. 5b),
401 there are cases that lead to reduced impacts on adaptation objectives (i.e. Q1 in Fig. 5a

402 and Q4 in Fig. 5b). Scatter plots were used as an initial diagnostic tool to visualise the
 403 sensitivity of the individual input factors on the adaptation objectives (Pianosi et al. 2016).



404
 405 **Fig. 5** Plot of impacts to (a) AAPE and AAD objectives and (b) average beach width and
 406 AAD objectives, for the 1,000 cases. The upper bound of tolerable impacts to the
 407 objectives (see Table 1) are defined by red dashed lines. The percentage of cases in each
 408 quadrant of the plot is also shown (denoted Q1-Q4).

409
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 411

3.6 Describe conditions that lead to adaptation tipping points

Scenario discovery validated observations made from the scatter plots that rainfall intensity and maximum structural damage costs were the most important uncertainties in defining the candidate scenario for the AAD adaptation objective. The significance of these variables was confirmed by the reproducibility statistics and p-values at the 0.05 level. Coverage and density trade-offs were further investigated for a range of candidate scenarios (see Appendix E in the Online Resource for further details). The strongest candidate scenarios for the three adaptation objectives are summarised in Table 3. These candidate scenarios describe the conditions beyond which coastal inundation impacts related to the adaptation objectives are unacceptable (i.e. signify adaptation tipping points are reached).

Table 3: Scenario discovery results showing candidate scenarios beyond which impacts related to the adaptation objectives become unacceptable.

Adaptation objective	Candidate scenario		
	Conditions (factor and values)	Cases of interest	Coverage / Density
1: AAPE	9-hour rainfall intensity < 4.8%, AND Average people per house < 2.4	194 / 1000	73% / 88%
2: AAD	9-hour rainfall intensity < 6.3% AND Maximum structural damage < \$1,536/m ²	167 / 1000	75% / 76%
3: Beach width	Sea-level rise < 0.3m AND Bruun factor < 83	320 / 1000	70% / 97%

Key factors in the selected candidate scenarios are shown in Table 4, along with projected trends and associated timeframes. The timing is not intended to be exact. Rather it focuses on identifying an indicative time period at which conditions describing adaptation tipping points could be reached, thereby indicating a use-by year (Haasnoot et al. 2013).

431 For the environmental factors, projections for lower (RCP4.5) and higher (RCP8.5)
432 emissions scenarios are useful to understand timeframes for a range of potential changes
433 (Bates et al. 2016). Time-series were available for projected mean sea-level rise in coastal
434 council areas (McInnes et al. 2016), providing an indication of when the conditions
435 associated with this uncertain factor might be exceeded. Additionally, guidance was
436 sought from the Australian Rainfall and Runoff guide for projecting changes to rainfall
437 intensity. This relates future rainfall intensity changes to temperature change using a
438 scaling estimate of 5 % per °C of warming, based on the Clausius-Clapeyron vapour
439 pressure relationship (Bates et al. 2016). However, uncertainty remains with this approach,
440 with research suggesting that extreme rainfall intensities could increase by more than 15 %
441 per °C in Tasmania by the end of the century (Mantegna et al. 2017). Projected
442 temperature change was obtained from the Climate Change in Australia web portal
443 (CSIRO and Bureau of Meteorology 2015), which guided the indicative timeframes for
444 changes to rainfall intensity based on the relationship used by Bates et al. (2016).

445 The projections suggest that changing rainfall intensity is likely to cause unacceptable
446 impacts to AAPE between the years 2040-2060, if the average people per house exceeds
447 2.4. The impacts to AAD are projected to remain acceptable for a longer timeframe, until
448 years 2050-2070, if the maximum replacement cost of dwellings exceeds \$1,536/m² in
449 *real* dollars. The impacts to average beach width may become unacceptable between the
450 years 2060-2070, which is conditional on the Bruun factor exceeding 83 (a conservative
451 value for the study area). Ongoing monitoring of each key factor at local, regional and
452 national scales is necessary to confirm the adequacy of the presently projected trends and
453 to update the projected time periods at which adaptation tipping points may be reached.

454 **Table 4.** Projected timeframe for changing factors. The selected factors are those identified in the candidate scenarios.

Condition		Projected change		Adaptation objective		
Factor	Value	Indicative timeframe	Scientific basis	(1) AAPE	(2) AAD	(3) Beach width
Sea-level rise increase (<i>relative to 2010 levels</i>)	0.3m	2060 (RCP4.5) – 2070 (RCP8.5)	McInnes et al. (2016)			✓
Changing 9-hour rainfall intensity (<i>relative to present</i>)	4.8% 6.3%	2040 (RCP4.5) – 2060 (RCP8.5) 2050 (RCP4.5) – 2070 (RCP8.5)	Bates et al. (2016); CSIRO and Bureau of Meteorology (2015)	✓	✓	
Bruun factor	83	-	Nil ^{a.}			✓
Max. structural damage per m ² (<i>real dollars in 2016</i>)	\$1,536/m ²	-	Dunford et al. (2014) ^{b.}		✓	
Average people per house	2.4	Minimal change ^{c.}	ABS (2010)	✓		

455 ^{a.} No data is available on the Bruun factor for Kingston Beach. Estimates from nearby areas are lower than the value shown.

456 ^{b.} No projections available. Periodic updates to the structural value are necessary (e.g. NEXIS building exposure database; Dunford et al.

457 2014), which are then adjusted from *nominal* to *real* dollars using the ‘average weekly earnings’ figures (Department of Environment and

458 Climate Change 2007) that are tracked by the Australian Bureau of Statistics (e.g. ABS 2017).

459 ^{c.} The average household size is estimated to fall to between 2.2-2.3 by 2031 in Tasmania (ABS 2010).

460

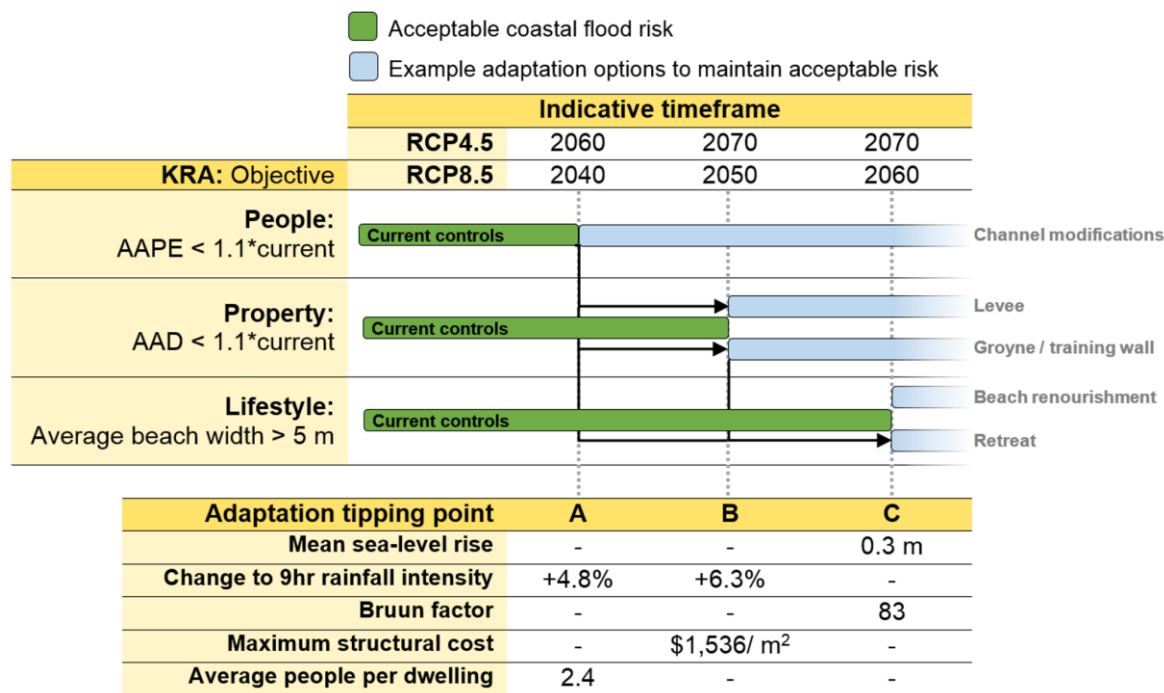
461

462 **3.7 Develop the adaptation pathway**

463 The key conditions that lead to adaptation tipping points and time projections identified in
464 Section 3.6 can be brought together within a DAPP framework to begin developing an
465 adaptation pathway. The steps in the DAPP framework require identifying possible
466 adaptation responses, evaluating the responses, assembling the pathways, identifying
467 preferred pathways, contingency planning, and creating a dynamic adaptive plan
468 (Haasnoot et al. 2013). The key factors identified through scenario discovery can also
469 support the definition of technical signposts in the DAPP process. The first part of the
470 adaptation pathways mapping process for the study area is shown in Fig. 6, which
471 indicates when an adaptation response would be needed to manage the different
472 adaptation objectives in the case where no adaptation measures are taken. Planning and
473 implementation timeframes for each adaptation response needs to consider the lead time
474 as the option progresses through project/policy governance systems. Each subsequent
475 adaptation option identified in the pathway can be assessed for robustness by repeating
476 the steps in Section 2.2 through to Section 2.6, or evaluated using other decision support
477 tools (e.g. Dittrich et al. 2016). Furthermore, some options may impact on multiple
478 adaptation objectives (e.g. a levee could provide benefits to both the AAD and AAPE
479 objectives). Therefore the evaluation of the costs and benefits of each adaptation option
480 would need to consider the implications to multiple objectives.

481

482



484

485 **Fig. 6** Development of the adaptation pathway using adaptation tipping points and the
486 projected timeframe of change. Adaptation objectives and future options to be explored
487 are organised into key result areas (KRAs) to guide long-term planning. Options shown
488 are mutually exclusive and black arrows indicate options that can improve outcomes for
489 correlated objectives. Timeframes are indicative and require ongoing monitoring and
490 reassessment as part of iterative risk management.

491

492 4 Discussion

493 4.1 Greater insights for coastal flood risk management

494 The ability to simulate coastal flood impacts across many future scenarios better equips
495 decision-makers to address questions such as ‘*what change leads to unacceptable*
496 *impacts?*’ and ‘*when are adaptation responses needed?*’. The case study illustrates that
497 open source spatial data and programming, combined with commercial GIS software, can
498 be used to address these questions by uncovering key risk management considerations in
499 communities that face uncertain long-term change. There is an opportunity for local

500 government and other coastal authorities to replicate the illustrated method whilst
501 customising it for their local needs.

502 The use of scenario discovery to identify conditions whereby existing plans no longer
503 meet the adaptation objectives can simplify complex changes to the built and natural
504 environment in a meaningful format for stakeholders to understand. As demonstrated in
505 the case study, RDM offers the potential to explore the interaction between a broad set of
506 uncertain hazard, exposure, and vulnerability factors and how they influence coastal
507 inundation impacts. This recognises that societal development, building codes, and other
508 land use policies can exacerbate flood impacts in low-lying communities, especially when
509 coupled with changing flood patterns. This approach is an improvement on seminal
510 adaptation pathway methods that focus on changes to a single hazard parameter (Kwadijk
511 et al. 2010; Reeder and Ranger 2011). However, using multiple uncertain factors to
512 describe conditions leading to adaptation tipping points adds further complexity to the risk
513 monitoring process. Each variable may change in different directions and with varying
514 rates. Therefore a vulnerability assessment to coastal inundation, including periodic
515 monitoring, needs to be done routinely as part of the managing authorities' iterative risk
516 management process.

517 The key factors uncovered with scenario discovery can support the selection of signposts
518 that are identified in the later stages of the DAPP process. They can also allow causal
519 factors to be further explored to better understand leading indicators that signify changing
520 risk (Bonzanigo and Kalra 2014). For example, population growth and housing density is
521 driven by land use and development decisions, which influences the average number of
522 people per dwelling exposed and therefore achievement of the AAPE objective.

523 Techniques like root cause analysis, systems thinking, or hazard chains (Downing 2012)
524 can be undertaken at this stage of the assessment to identify (and treat) causal risk
525 factors that are interconnected but less apparent. These insights can build a case for
526 targeted data collection and monitoring activities in urbanised coastal areas, which is
527 important when financial resources are limited. In further developing adaptation pathways,

528 technical signposts such as those noted above would need to be considered alongside
529 political signposts to be inclusive of different stakeholder needs (Hermans et al. 2017).

530 The methodology illustrated in the case study takes a different approach to traditional risk
531 management methods, such as the ISO31000 process that is recognised worldwide. Our
532 methodology requires tolerable risks to be defined at the outset and baseline impacts to
533 be assessed, before the sensitivities of the site to coastal inundation are uncovered.

534 Conversely, the ISO31000 process begins with a risk assessment, then prioritises risks
535 based on likelihood and consequence matrices before evaluating whether risks are
536 acceptable, tolerable, or intolerable. Identification of a baseline risk acknowledges that
537 there is already a certain coastal inundation threat that the community has accepted,
538 knowingly or not. This allows analysts to focus their efforts on searching for what changes
539 to the current built and natural environment will cause unacceptable inundation impacts.

540 This makes the process of communicating risks more straightforward and salient to
541 concerned parties, since they can consider how environmental change might affect them
542 relative to what they are experiencing today. An important strength of the ISO31000
543 process over our method is that it considers a much broader set of impacts. For example
544 the National Emergency Risk Assessment Guidelines used in Australian emergency
545 management considers consequences to people, environment, economy, public
546 administration, social setting and infrastructure (National Emergency Management
547 Committee 2010). Our approach was limited to a quantitative assessment of impacts to
548 people, property, and lifestyle objectives. Therefore there is scope for the presented
549 method to increase the number of adaptation objectives and include a qualitative
550 assessment of intangible consequences.

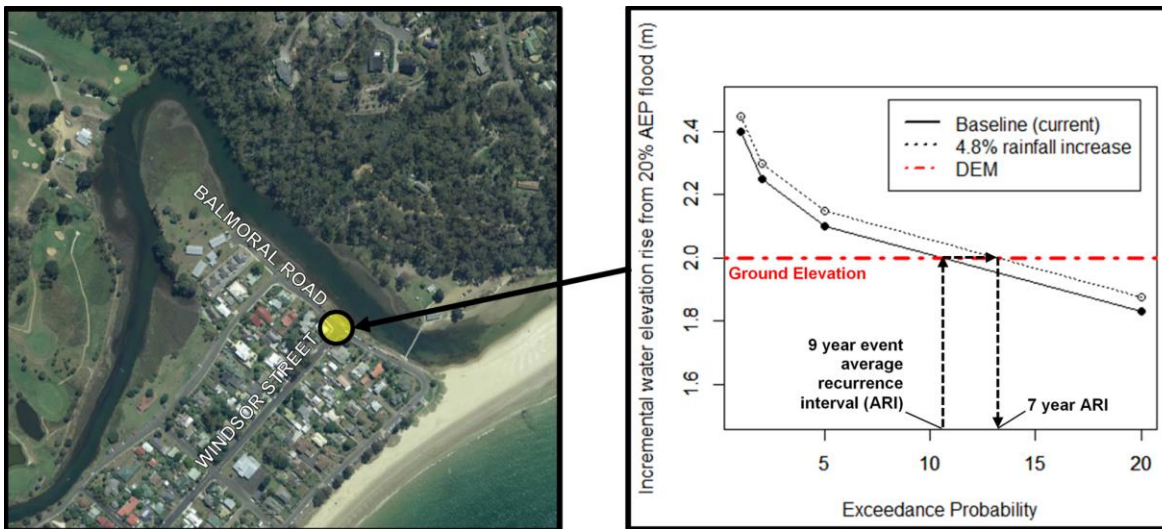
551 **4.2 Making change salient in the community**

552 A characteristic of the key factors identified by scenario discovery in the case study was
553 that they change slowly over time. However, detecting such environmental changes can
554 be problematic due to natural variability, sparse data records, and non-stationarity (Milly et
555 al. 2008). Detecting a modest 4-7% increase to 9-hour rainfall intensity – as identified in

556 our case study – is difficult in practice, and a coastal authority asserting that such change
557 has occurred is likely to be challenged by residents with different views.

558 Translating changes to key variables into observable impacts can provide an evidence-
559 based approach to substantiate claims within the community that they may be
560 approaching a threshold or adaptation tipping point. For example, a 4.8% increase in
561 rainfall intensity in the study area suggests that inundation of the Windsor Street /
562 Balmoral Road intersection may occur once every 7 years, instead of 9 years (Fig. 7).
563 Consequently, flooding of this intersection twice in a 7-year timeframe could signal that
564 the rainfall intensity is approaching its adaptation tipping point limit. Although this does not
565 account for changing catchment characteristics (e.g. upstream development) and
566 changing extreme rainfall frequencies that can affect the recurrence interval of peak
567 floodwaters, it does serve to convert an otherwise meaningless number into demonstrable
568 evidence that change may be occurring.

569 A similar philosophy was used by Barnett et al. (2014) in their case study at Lakes
570 Entrance, whereby an adaptation response was planned in the event that the esplanade
571 flooded for 5 or more days in a year. Importantly, observed changes to rainfall intensity
572 and/or flood frequency at a local scale requires robust assessment against expected
573 variability. In this regard, local agencies require input from national agencies (e.g. CSIRO,
574 Bureau of Meteorology and Geosciences Australia) who are concerned with the scientific
575 assessment of changes across various spatial and temporal scales. This ensures decision
576 are based on robust scientific understanding of changes that are occurring, reducing the
577 chance of reactive decisions being made by coastal authorities in the face of chance
578 events or natural variability.



579

580 **Fig. 7** Selected location at the intersection of Windsor Street and Balmoral Road (circled –
 581 left panel) that could be used to observe changing coastal flood risk. The average change
 582 to peak flood water elevations (above AHD) for a 20% AEP flood event with increased
 583 rainfall intensity of 4.8% is shown in the right panel.

584

585 The case study presented here made an important assumption that measurable
 586 adaptation objectives and tolerable impacts could be defined and agreed upon in the
 587 community. The study was also limited to a small subset of the possible values that may
 588 exist in the community. In practice, public collective decision-making processes are likely
 589 to face contested adaptation goals and conflicting knowledge among stakeholders
 590 (Bosomworth et al. 2017), whilst social power inequalities and varying short-term interests
 591 can hamper long-term planning efforts (Few et al. 2007). Although there are increasing
 592 calls for social impacts to be better accounted for in climate change impact assessments
 593 and to evaluate adaptation responses (Adger et al. 2009; Downing 2012), such
 594 considerations are not straightforward due to complex and subjective interactions among
 595 values, ethics, priorities, culture, knowledge, and power structures, all of which change
 596 with time (Adger et al. 2009). Engagement with community stakeholders may be a useful
 597 starting point to identify contested values in the scoping phase of adaptation planning and
 598 to define key issues (e.g. Barnett et al. 2014). This can then form a basis for identifying
 599 the adaptation objectives, metrics and tolerable impacts upon which subsequent analysis

600 is based. The use of decision relevant information produced by activities such as scenario
601 discovery can better inform participants at various stages of the planning process and can
602 also strengthen the credibility of the resultant strategy. Although deliberation with analysis
603 is increasingly being recognised in complex environmental policy problems (National
604 Research Council 2009), further research is needed to explore how this can be most
605 effectively utilised in a combined RDM and DAPP approach.

606 **4.3 The prospects and limitations: Towards better informed planning**

607 The case study highlights that there is a need to improve the accuracy of simulation
608 modelling, in particular the generation of rules of thumb and proxy floodwater rasters.
609 Simplifications in the model meant parameters such as flood duration, contamination,
610 debris, rate of rise, and flood velocity were omitted, which can cause overall damage
611 estimates to be underestimated (Merz et al. 2010; Middelmann-Fernandes 2010).
612 Similarly, the use of the Bruun rule is likely to be overly simplistic given (among other
613 things) it does not consider coastal storms that can exacerbate beach erosion nor other
614 coastal processes that may affect the shoreline response. Notwithstanding these
615 limitations, changing beach widths can be easily monitored by coastal authorities,
616 community groups, or residents to confirm trends in the face of uncertainty (e.g. ACECRC
617 n.d.; UNESCO 2005), and the beach management authority could develop contingency
618 plans to address unexpected near-term beach loss.

619 The timing at which adaptation tipping points were projected in this study was relatively
620 simple by focussing on a small set of projected changes to key variables. The use of
621 transient scenarios to identify a range of use-by years (e.g. Haasnoot et al., 2015) is a
622 potential improvement to the methodology presented in Section 3.6, as it would allow
623 different rates of change (positive and negative) for the key conditions describing
624 adaptation tipping points to be combined across many cases. This could better inform the
625 timing of adaptation tipping points to support the development of long-term master plans
626 and future resource requirements.

627 Implementation of the presented methodology requires data availability, technical
628 capability, and financial resources to perform the analysis, collect data, and monitor
629 change over time. Given that technical knowledge and financial constraints are likely to
630 remain a barrier for local government in the near-term, such resources could be
631 centralised in a nationally coordinated authority. This authority could work with local
632 government to apply a nationally consistent approach to describe conditions leading to
633 adaptation tipping points and develop adaptation pathways. The presented method could
634 also be applied at a municipal, state or national scale to identify coastal settlements that
635 are most vulnerable to changing coastal flood hazards, using the timing at which their
636 adaptation tipping points would be exceeded as an indicator. For resource-constrained
637 authorities, the ability to prioritise adaptation investment towards those communities that
638 yield the greatest risk mitigation benefits would improve the allocation of scarce financial
639 resources.

640 It is too early to fully understand the effectiveness of the illustrated methodology in this
641 study given that it reflects *ex ante* planning, yet such conditions are faced in all risk
642 identification activities. What the methodology offers is a new way of integrating two state-
643 of-the-art decision support tools so that decision-makers can explore and identify future
644 vulnerabilities to coastal inundation and design adaptation pathways.

645 **5 Conclusions**

646 This research has examined whether RDM can be embedded within a DAPP framework
647 to improve planning for changing coastal flooding risks. Our method was underpinned by
648 GIS software, open source data, and programming languages, making it pragmatic and
649 possible to replicate in other coastal communities.

650 The use of RDM to uncover sensitivities in the existing system to changing coastal flood
651 patterns focuses the attention of decision-makers towards those uncertainties that are
652 most relevant for achieving their adaptation objectives. This is useful not only for
653 understanding *what* change leads to intolerable risk and *when* such change might occur,

654 but considers more broadly how societal development, land use, and existing building
655 regulations might exacerbate impacts from changing coastal flood patterns.

656 A better understanding of the key conditions that lead to adaptation tipping points in flood
657 risk management can support targeted data collection, monitoring activities, and
658 adaptation responses. It can also help identify signposts in the adaptation pathway.

659 However, detecting changes in multiple factors can be difficult given natural variability,
660 and challenges are enhanced by sparse long-term data records and little financial
661 resources allocated to coastal monitoring activities. Furthermore, reaching agreement on
662 the adaptation objectives, a clear definition of what the community deems as tolerable
663 impacts and exploring how deliberation with analysis is most effectively used in a
664 combined RDM and DAPP approach remains a question for further research.

665 The use of scenario discovery to describe conditions leading to adaptation tipping points
666 offers an alternative conceptualisation of the DAPP approach, which uses transient
667 scenarios to focus on the timeframe at which an adaptation tipping point is reached. In a
668 combined RDM and DAPP approach, transient scenarios could be used after scenario
669 discovery to project the timing of adaptation tipping points based upon changes to a
670 reduced set of key factors. This sequence of steps would improve the description of
671 adaptation tipping points and the basis for projecting the use-by year of existing and future
672 adaptation policies.

673 Our study illustrates that RDM can be a powerful method to uncover a small set of
674 conditions that together can characterise adaptation tipping points in the face of uncertain
675 environmental change and the simulation results are well suited for use within a DAPP
676 framework. Notwithstanding the challenges that remain around simulation modelling and
677 detection of environmental change, the ability to make sense of complex environmental
678 dynamics for use in vulnerability assessments and adaptation planning can provide much
679 needed support to coastal authorities who are facing increasing pressure to minimise
680 costly impacts and ensure the sustainability of their communities.

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