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ORIGINAL ARTICLE

Economic, equitable, and affordable adaptations to protect coastal settlements against storm surge inundation

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Abstract The distribution of risk of coastal inundation, and the potential benefits of adapting to protect against inundation, vary greatly both within and between coastal communities. This diversity is a result of physical factors, such as the risk of storm surge, sea level rise projections, and the topography of the landscape, as well as socio-economic factors, such as the level of development, and the capacity within the community to adapt. Despite this strong local variation, various communities share common characteristics that constrain or enable different adaptation options in different situations. Understanding these drivers is likely to be important in engaging coastal communities in the discussion around adaptation and may provide new insights into which adaptation options are suitable for each of our at-risk coastal communities. We performed a property-level analysis of 6 suburb-sized case studies distributed along the coast of Queensland, Australia. We assessed the potential economic costs of inundation events now and in the future under sea level rise projections, and the potential avoided costs following adaptation to protect against inundation. We went beyond this to estimate the distribution of risk in each community and compared the potential costs of adaptation with the capacity of the community to pay for their implementation. We used these insights to propose a typology of coastal communities based on their exposure to total inundation risk, the distribution of that risk within the community, and their capacity to adapt.

Keywords Climate adaptation · Coastal inundation · Adaption · Equity · Economics

Introduction

Risk due to storm surge is exacerbated by the fact that people overwhelmingly choose to live near the ocean. In Australia, for example, over 80 % of the population lives in the coastal zone and 50 % within 7 km of the shore (Harvey and Caton 2003). This pattern is repeated in many places around the world (Harman et al. 2014). At-risk coastal areas continue to be urbanised (DCCEE 2011; Wang et al. 2010) despite predictions that rising sea levels will drive worsening storm surge events (Guofang et al. 2003; Hallegatte and Corfee-Morlot 2011).

There are a range of adaptation options that can ameliorate some of the effects of future coastal inundation events (Abel et al. 2011). Some, such as sea walls, 'protect' against inundation of infrastructure. Other adaptations 'accommodate' inundation by redesigning infrastructure to avoid adverse impacts when inundation occurs, for example by raising the minimum floor heights of buildings. Yet others, such as 'retreat', seek to move infrastructure out of

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areas likely to be inundated (Abel et al. 2011). Each adaptation has implementation costs, and each provides a distribution of benefits based on how they modify inundation risk (Fletcher et al. 2015; Penning-Rowsell and Pardoe 2012).

In addition, inundation risk itself is not uniformly distributed. At the provincial scale, the distribution of risk is driven by regional variations in the risk of storm surge (Harper et al. 2004) and expected sea level rise (CSIRO 2011b). Within individual communities, the distribution of risk is often highly uneven due to fine-scale topographic structure and variation in the density and location of development (Fletcher et al. 2015). The way this distribution of risk is perceived by coastal communities will drive engagement in the discussion about how best to manage it and, ultimately, which adaptation options each community prefers (Measham et al. 2011; Shackley and Deanwood 2002).

Of particular interest to the current study, each type of adaptation protects different numbers of properties, and each requires engagement and consensus at different scales in the community to successfully implement. The construction of a communal adaptation, such as a sea wall, can protect both the buildings and land values of many properties, as well as adjacent infrastructure such as roads (Fletcher et al. 2012). In Australia, such projects are usually coordinated and funded by local government, often with co-funding from State or Federal governments (Harman et al. 2014). In contrast, adaptations implemented at the property level, such as changes to minimum floor heights, impose extra construction costs for the private landholder while providing protection to their individual property (Fletcher et al. 2012). In some cases, the communal benefit provided by a sea wall adaptation may prove more efficient than many separate actions each protecting individual properties. At the same time, however, implementing a sea wall requires communal funding and therefore at least some consensus on the benefit to the overall community.

This is important, because even when adaptation is economically justified in the long term, communities may not choose to invest in adaptations in the short and medium term (Turner et al. 1995). This may be due to absolute financial constraints, but it can also reflect limited community buy-in because, for instance, the risks are perceived to impact only a small fraction of the community (Niven and Bardsley 2013). This is certainly the case with inundation risk in some coastal communities. A communal adaptation that could efficiently protect multiple properties may not be supported by the community if the costs are perceived to accrue to all while the benefits are enjoyed by only a few.

Balancing equitability and affordability in addition to overall economic efficiency when implementing adaptation has become central to many negotiations (Bowra et al. 2011). Although economics plays a part in both equitability and affordability, most studies of the drivers of community adaptation have been qualitative (Abel et al. 2011; Sterr 2008), with few providing a quantitative underpinning for their analysis (Granger 2003; McGranahan et al. 2007). At the other end of the spectrum, many quantitative studies have analysed the overall economic costs of inundation to infrastructure (Genovese et al. 2011; Hall et al. 2003; McLeod et al. 2010; Sterr 2008; Wang et al. 2010; Yohe et al. 1996) and property values (Bin et al. 2011; Yohe et al. 1996). Others have estimated the potential benefits of different adaptations (Wang et al. 2010). Few, however, have tried to quantify the distribution of economic costs and benefits within the community to inform considerations of equity and affordability.

In this paper, we attempt to calculate measures of economy, equity, and affordability for three types of adaptation across six case study communities spread along the Australian coast. We do this by calculating the economic benefits of a sea wall, changed minimum floor height, and retreat adaptation in terms of avoided damages to both infrastructure and property values under realistic distributions of inundation events and future sea level rise. We assess the overall costs and benefits to the community, the distribution of those costs and benefits, and the costs of adaptation relative to the capacity of the local community to fund adaptation actions. We then ask the question: Is each community likely to find a sea wall, an adaptation that protects communally but also imposes costs on the community, economic, equitable and affordable? We use the answer to this question to propose a potential 'typology' of coastal communities, to underpin discussions around the equity and affordability of communal adaptations in our coastal communities.

Methods

Case studies

We studied a range of settlement types selected in conjunction with local government stakeholders, along the coast of Queensland, Australia. The six settlements fell into a range of broad categories, based on their topography, risk of inundation, demography, and the socio-economic structure of the communities that live there (Table 1, 'Community characteristics'). The communities included a coastal central business district, a canal estate, and a range of coastal communities of various sizes, levels of

Table 1 Case study statistics and the risk and projected costs of inundation ($AUD)

	Community characteristics					Projected costs					
Case study	# modelled	Median property value ($k)	Median infrastructure value ($k)	Regional Population	Median annual household income ($k)	Year	# inundated	% inundated	Total loss ($m)	Mean loss ($k)	Median loss ($k)
1	560	181	89	3900	44	2010	212	38	7	12	0
						2030	237	42	12	21	0
						2050	250	45	25	44	10
2	312	241	125	1800	35	2010	1	0	0	0	0
						2030	1	0	0	0	0
						2050	1	0	0	0	0
3	122	169	88	500	38	2010	24	20	1	4	0
						2030	27	22	1	7	0
						2050	31	25	2	14	0
4	575	215	114	9900	52	2010	192	33	5	8	0
						2030	213	37	8	14	2
						2050	290	50	15	26	11
5	489	267	136	3000	67	2010	10	2	2	4	0
						2030	20	4	3	6	0
						2050	25	5	5	10	0
6	2620	290	141	4700	52	2010	117	4	4	2	0
						2030	118	5	7	3	0
						2050	121	5	13	5	0

development, and socio-economic capacity. Table 1 shows details on the demographic makeup of each community, including the number of residential properties, the median property (land) value, the median infrastructure (house) value, and median total household income (ABS 2011).

Case study 1 was a relatively flat coastal suburb, with minimum property heights ranging from just over 1 m up to 4 m above the Australian Height Datum (AHD) and exposed directly to bay-front waters. A significant fraction of properties there were at risk of an ARI 100 year event today, and more are likely to be exposed in future as sea levels rise (Fig. 1a). Case study 2 was an exposed hamlet, but had no properties below 3.5 m AHD, meaning that the risk of damage due to storm surge was very low (Fig. 1b). Case study 3 was a slightly protected coastal hamlet. It exhibited a flat area containing approximately 20 % of the residential properties up to 2 m above AHD, with the rest positioned on upward slopes in roughly equal proportions up to 10 m above AHD away from the waterfront. Case study 4 was an exceptionally flat coastal central business district with almost all properties lower than 3.5 m AHD. A large proportion of properties were at risk of an ARI 100 year event today, and practically all will be at risk by 2100 without adaptation measures as sea levels rise (Fig. 1d). On the other hand, the site was densely developed, which gave it a strong funding base for adaptation. It was administered by a proactive local government that managed inundation risk to mitigate economic losses. Case study 5 was a coastal hamlet directly exposed to the ocean, with significant topography up to 40 m AHD and most properties set on upward slopes near the water. As a result, only a small proportion of properties were at risk of an ARI 100 year event today. Although rising sea levels are likely to affect those properties already at risk in the future, many others were set high enough that they will remain unaffected (Fig. 1e). Case study 6 was a coastal canal estate protected from direct exposure to the ocean by a dune system, but exposed to tidal surge via short distances along canals to the ocean. Very few properties were at risk of an ARI 100 year event today, but the site was very flat and as ocean levels rise a small but increasing proportion of properties may face risk of inundation during major events (Fig. 1f).

Calculating the costs of inundation

The costs of inundation were calculated by estimating the depth of inundation on each property, and within each building, for an annual maximum inundation event. The size of the event was drawn from the observed extreme-

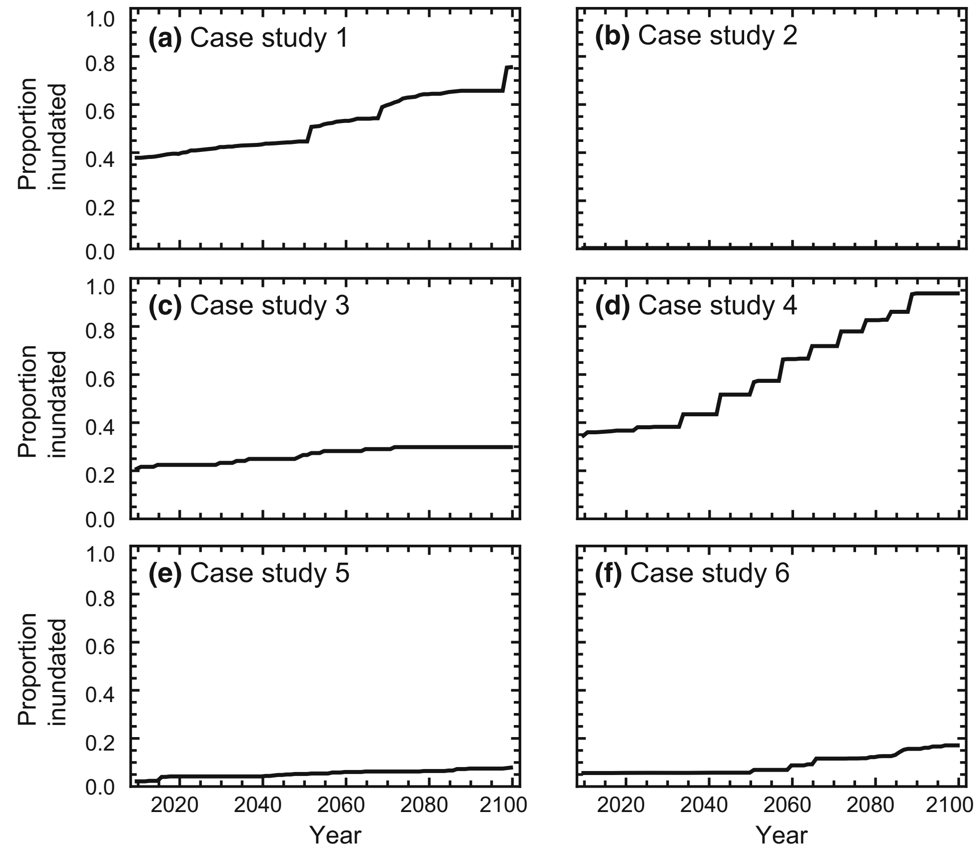

Fig. 1 The proportion of properties in each case study expected to be at risk of inundation from an ARI 100 year event under sea level rise out to 2100

value distribution at each site, with an offset to account for expected sea level rise in future years (Table 1, 'Projected costs'). Inundation depths were converted to a dollar value of damage to infrastructure using published damage curves (Middelmann-Fernandes 2010). In addition, the devaluation of residential property due to increasing inundation risk was estimated based on hedonic analysis of the value of inundation security in the Australian residential property marketplace (Rambaldi et al. 2013).

A Geographic Information System was used to analyse high-resolution data describing case study terrain, the position and location of buildings (ESRI Inc. 2010). It was also used to calculate spatial factors contributing to the value of residential buildings, including distances to coastlines, waterways, parks, schools, shops, and public transport and other infrastructure (Rambaldi and Fletcher 2014). This was combined with non-spatial housing attributes from commercial house sales datasets including number of bedrooms, bathrooms, car spaces, and building age (Rambaldi and Fletcher 2014).

A high-resolution DEM was created from 2 m resolution LiDAR data (DERM 2010). Minimum and maximum property heights above AHD were calculated by intersecting council cadastral data with this high-resolution DEM. Building footprints were extracted using learning algorithms analysing return data from both the ground and first return signals of the LiDAR dataset and multichannel aerial imagery on the colour profile of building roofs. This process automatically generated building footprint polygons, which were manually checked and cleaned against aerial imagery. Building minimum floor heights and maximum height of the built structure were extracted by intersection with the high-resolution DEM. Some councils provided manually collected floor height data, which were used where possible, otherwise floor height was estimated as ground level plus freeboard of 300 mm (DCCEE 2011).

Probabilistic distributions of storm surge events were described by the generalised extreme-value distribution, fit to observed council inundation data from each case study (Gumbel 1958). Each year of each model run, the maximum height of an extreme storm surge event was drawn from the distribution. An offset was added equal to the projected sea level rise expected at that point in the future. We used the global averaged SRES A1B sea level rise scenario (Hunter 2010) with corrections for regional departures (CSIRO 2011a). We use the A1B scenario because it is the only one for which regional corrections were available at the time of analysis. This yielded sea level rise of approximately 0.2 m by 2030 and 0.5 m by 2070 (Wang et al. 2010). These estimates may be conservative, because they do not account for all factors which contribute to sea level rise, such as accelerated melting of the Greenland ice sheets. With a changing climate, other inundation-related events, such as coastal erosion and inland flooding, are likely to occur both in isolation and in conjunction with changing storm surge regimes. However, we do not consider these more complicated events here. Some reports have identified the possibility of coincident storm surge coupled and changed storm intensity and wind speed as major risks for low-lying developed urban areas (DCCEE 2011). However, estimates of these affects are much less certain than sea level rise. Along Australia's east coast, best estimates suggest that the joint probability of storm surge and rainfall-driven flooding is unlikely to change (Abbs and McInnes 2011).

The inundation depth was converted to an inundation region using a static 'bath tub' approach, filling the terrain hydrologically connected to the ocean at the specified level. Bath tub models are widely utilised due to their ease of implementation, but they do not account for dynamic processes such as erosion or coastal recession, nor drainage processes or the interaction of flows with obstacles. The inundation depth within each property and building was calculated. The economic costs of inundation damage to residential infrastructures were estimated using observed property growth rates and stage damage curves to reflect a percentage or dollar damage as a function of the depth of inundation on each property (Middelmann-Fernandes 2010). In addition to infrastructure damage to residential housing stock, we assessed the loss of value to the land on which residential houses were built. This potential loss represents a vital component of the impacts of sea level rise on individual households. This arises partly because land values appreciate over time (Rambaldi et al. 2011). In addition, the land on which the family home rests represents the largest single asset of most Australians (Wilkins et al. 2009). Rambaldi et al. (2013) calculated the historical devaluation of residential land in Australia due to inundation risk as 1.28 + 5.45 % per metre of inundation during a 100-year Average Recurrence Interval (ARI 100 year) event. This value quantifies the devaluation of residential property due to inundation risk, relative to the value of an identical property protected from a 100-year ARI event. Thus, it provides an estimate of the potential property-value benefit of adapting to protect against inundation, a major part of how individuals will be affected by adaptation. This is likely to strongly influence the motivations of communities to support and/or undertake action. On the other hand, public assets will also be at risk of inundation during storm surge events, and these will contribute to broader impacts felt both individually and across the community as a whole. A full benefit–cost analysis would need to take into account all of these factors. Because public assets are 'community owned', and damage to them must be repaired from the public purse, incorporating these effects may more evenly spread the risks and benefits of inundation and adaptation throughout the community.

The model was run a thousand times for each case study, drawing peak annual storm surge events under sea level rise scenarios between 2010 and 2100. The depth of inundation on each property and building was calculated, along with the associated damages. These were accumulated as net present values (2010 dollars) using a real discount rate of 4.08 %, the average of the long-term indexed capital bond rate from 1994 to 2003 (Reserve Bank of Australia 2010). The sensitivity of the model outcomes was also tested using discount rates of 2.08 and 6.08 %, as described in the Discussion. In most years of each model run, storm surges were too low to cause significant damage, as observed in the real world. However, over each 90-year run damages from the few uncommon extreme events accumulated. Statistical estimates of the likely costs of inundation, incorporating the fundamentally variable nature of weather into the future, were calculated across the thousand of model runs from each case study. This approach provided a significantly more advanced picture of the likely accumulated costs of inundation compared to the more traditional estimate of the costs due a single specified event (usually an ARI 100 year event) at a specified point in the future (usually 2030, 2050 or 2100).

Calculating the benefits of adaptation

We estimated the potential avoided costs due to three types of adaptation. The first was a communal sea wall which was assumed to 'protect' against all damage for inundation levels below its height, and proportional protection for inundation levels above it. The second was changed building codes specifying the minimum floor height of buildings, implemented on a property-by-property basis. This 'accommodated' inundation by preventing building damage if inundation did not reach the floorboards and reducing it for inundation that exceeded the floorboard level, but did nothing to protect land values. The third was 'retreat', in which the houses most at risk of inundation were purchased by council and rezoned non-residential, avoiding any future costs due to inundation. In each case, the extent of each adaptation was specified in terms of protecting properties likely to experience any inundation during a 100-year ARI event in 2050, implemented today.

Approximate costs of adaptations were estimated from council data or the literature. The cost of implementing sea walls varies greatly depending on location, access, foundation materials, length and height. A recent report in the study region identified four different sea wall projects, with budgeted costs ranging from \$1250 to \$4200/m, similar to estimates from the literature (Walsh et al. 2004; Yohe et al. 1996). We assumed build costs of $2500/m for a worst-case scenario of a sea wall constructed across the entire vulnerable coastline of each case study region, capable of withstanding an ARI 100 year event in 2050. Council reports from elsewhere in Australia budget costs for raising houses at approximately $40,000 per residence (Webb McKeown and Associates Pty. Ltd. 2001), although the costs of raising masonry buildings on in-ground foundations are recognised to be higher. Buildings were raised to avoid inundation during an ARI 100 year event in 2050. As part of retreat operations, residential lots that would experience any inundation during a 100-year ARI event in 2050 were purchased today at their market value within the model. This proved the most economical way of implementing retreat because property values have historically grown faster than the combination of the rate of return of alternative investments and the discount due to inundation risk.

The per-household cost of each type of adaptation was estimated assuming that all property owners contributed equally to funding the adaptation, a reasonable assumption for communal adaptations funded from the common pool of local government rates. In practice, communal adaptations often receive partial co-funding from higher levels of government (Harman et al. 2014). More advanced funding mechanisms based on estimated risk could be used to modify the distribution of costs and equitability. Both of these refinements are beyond the preliminary analysis performed here, but we consider their importance further in the Discussion. In Australia, a potential model for funding such a mechanism currently exists in a special charge (~$1000/year) levied on canal estate residents for long-term maintenance costs of canals, in addition to normal council rates. Looking at households in case study 6 (a canal estate, Table 1), this charge represents ~1.92 % of the annual median income of an estate household. We estimate, then, the ability of a community to fund adaptations as 1.92 % of the median annual income in the community. We index this to the discount rate, with a planning and funding horizon of 40 years out to 2050. If the ability of the community to fund a sea wall exceeded its cost, we said that the adaptation was 'affordable'.

The total costs of inundation damage and devaluation were calculated for each case study and each inundation sequence under four scenarios: 1) no adaptation, 2) a sea wall adaptation, 3) changed minimum floor heights, and 4) retreat. The costs for each scenario were accumulated at the household level. The benefits due avoided costs for each adaptation were calculated by subtracting the damage and devaluation costs incurred from the unadapted case.

The mean household benefit/cost ratio was calculated for each scenario, averaged across the entire case study community. This mean benefit/cost ratio is the same as the total benefit/cost ratio of the case study, the metric most commonly used in these sorts of analyses (Wang et al. 2010). If the case study was expected to see a net benefit due to avoided damage costs by 2100 following implementation of the communal sea wall adaptation, we said that the adaptation was 'economic' (Table 2, 'Economic').

In addition, the 25, 50 (median), and 75 % benefit quartiles were calculated to capture the distribution of benefits within the community. The median emphasises rare large values less than the mean, so if only a few properties benefited from an adaptation the median benefit was low even when the mean benefit was high. The point at which the median benefit exceeded the mean costs of adaptation represented the point at which most properties in the case study realised a net benefit, assuming that all property owners contributed equally to funding the adaptation. When most of the households in the community achieved a net benefit, we said that the adaptation was 'equitable' (Table 2, 'Equitable').

Results

The costs of inundation

Table 1 ('Projected costs') shows a summary of the predicted costs of inundation due to an ARI 100 year event today. It also shows costs over typical planning horizons in 2030 and 2050, under sea level rise scenarios consistent with A1B scenarios with local corrections. It shows absolute costs, proportional or per-property costs, and median costs.

All three costs varied dramatically from case study to case study. This was due to case study size, the proportion of residential properties that were at risk, and the interaction between the topography of the land and sea level rise. Absolute damages were highest for heavily developed areas (case studies 1, 4, and 6, Table 1, 'Projected costs'). Mean damages were highest where a significant portion of the community was at risk (case studies 1, 4, and 5, Table 1, 'Projected costs'). Median damages depended critically on the risk profile for the specific location. However, they were always much lower than mean damages, indicating that many households faced little risk of inundation. Case study 2 was naturally protected from storm surge events, and the predicted risk across the community was extremely small, even out to 2050 (Fig. 1). Because case study 2 faced no appreciable risk, no significant economic benefit in terms of avoided damages accrued from adaptation. We omit it from Table 2 to avoid unnecessary reporting of null results, but return to it again when we examine different categories of adaptations in the Discussion.

Table 2 The affordability, economy, and equitability of adaptation ($AUD)

			Affordable			Economic			Equitable		
Case study	Adaptation	Adaptation cost ($k/property)	Adaptation budget ($k/property)	Adaptation budget:cost	Sea wall affordable?	Mean benefit ($k)	Mean benefit:cost	Sea wall economic?	Median Benefit ($k)	Median Benefit:cost	Sea wall equitable?
1	Sea wall	37	34	0.92	No	1155	31.15	Yes	281	7.59	Yes
	Floor height	14		2.47		736	53.15		4	0.27	
	Retreat	170		0.20		1104	6.47		241	1.42	
3	Sea wall	34	30	0.87	No	382	11.22	Yes	0	0	No
	Floor height	7		4.08		259	35.61		0	0	
	Retreat	59		0.50		378	6.43		0	0	
4	Sea wall	6	40	6.65	Yes	155	25.73	Yes	95	15.8	Yes
	Floor height	2		25.98		3	1.85		1	0.44	
	Retreat	83		0.48		148	1.78		95	1.13	
5	Sea wall	9	52	5.46	Yes	39	4.09	Yes	0	0	No
	Floor height	1		40.12		1	0.65		0	0	
	Retreat	56		0.92		39	0.71		0	0	
6	Sea wall	26	40	1.52	Yes	27	1.03	Yes	0	0	No
	Floor height	6		6.61		4	0.58		0	0	
	Retreat	209		0.19		28	0.13		0	0	

The costs of adaptation

Table 2 shows the estimated costs of each type of adaptation within each case study site. The cost reported is the average cost per household, or in the case of the coastal CBD, per household and commercial property. Table 2 ('Affordability') shows the median adaptation budget per property assuming a contribution of 1.92 % median annual income per year, indexed to the discount rate out to 2050, a forty-year funding horizon. It shows the ratio of the cost of each adaptation to the adaptation budget and notes whether the estimated adaptation budget is sufficient to fund a sea wall adaptation. In all cases, sea walls and increasing floor heights were significantly more affordable to implement than retreat.

The per-household cost of implementing a communal adaptation such as a sea wall was determined by the length of sea wall to be constructed, the number of properties contributing, and the median household income in the community. Small communities, such as case study 3, incurred high per property costs and low affordability due to the low number of households contributing, exacerbated in this case by low median household income. Larger communities, especially those with a compact exposure to the ocean, such as case studies 4 and 5, realised much lower and more affordable per-property costs. However, large communities with complex and extended exposure to storm surge events, such as case study 6, faced significant per-property adaptation costs despite large numbers of relatively high income households being available to contribute to adaptation.

The benefits of adaptation

Table 2 ('Economic') shows the mean expected benefits per property in each case study, when all benefits were accumulated to 2100. Comparing these benefits to the mean adaptation cost per property, we calculated the estimated benefit/cost ratio of the adaptation across the community.

Case studies 1, 3, and 4 exhibited benefit/cost ratios greater than unity for all types of adaptation, even retreat. This was because a significant proportion (>25 %) of properties in these communities were expected to be at risk of an ARI 100 year event by 2100. Raising floor heights was the cheapest adaptation to implement in each case study and sometimes led to high benefit/cost ratios (case settlements 1, 3, and 4). However, when the bulk of expected damages due to future inundation events lay in land devaluation, benefit/cost fell below unity (case studies 5 and 6). Interestingly, for all examples other than case study

2 (not shown), building a communal sea wall was expected to yield net benefits by 2100. This was true even if only a small proportion of the community was at risk of an ARI 100 year event by 2100 (case studies 5 and 6). That is, looking at these case studies as a whole, as is the norm in most benefit–cost analyses, we might conclude that there is an economic justification for implementing a communal adaptation like a sea wall.

However, the benefits of implementing an adaptation were not spread uniformly across the community. Table 2 ('Equitable') shows the median benefit received in the community along with the benefit/cost ratios for each of those households. Asking whether most people in each community would achieve net benefits by contributing to a communal sea wall (Table 2, 'Equitable'), we see that in many cases the answer was no, even though a case-study level analysis suggested that the adaptation was economically justified (Table 2, 'Economic').

The fact that the median benefit/cost ratio of adaptation was always lower than the corresponding mean benefit/cost ratio indicated that in all case studies a few properties received a disproportionate benefit from the construction of a sea wall. In case studies 3, 5, and 6, this effect is very pronounced: the median benefit/cost ratio was ~0.00 and more than 50 % of properties receive no benefit whatsoever from their contribution to the communal sea wall. Although not shown in Table 2, in case studies 5 and 6 not even 25 % of properties received benefit/cost ratio greater than unity from the adaption. This implies that a very small number of properties in these locations were receiving a very large benefit from adaptation, while the bulk received little to no benefit. Case study 3 represents an interesting intermediate case. Although 25 % of the community did realise a benefit/cost ratio greater than unity from a sea wall adaptation, beyond this 'at-risk' proportion, very few others benefited.

Figure 2 shows that the accumulation of the distribution of benefits also varied through time. It plots the relationship between the per-household cost of each adaptation (solid line), the mean benefit across the whole case-study (dashed line), and the median per-household benefit (dotted line) with the 25 and 75 % quartiles shaded around the

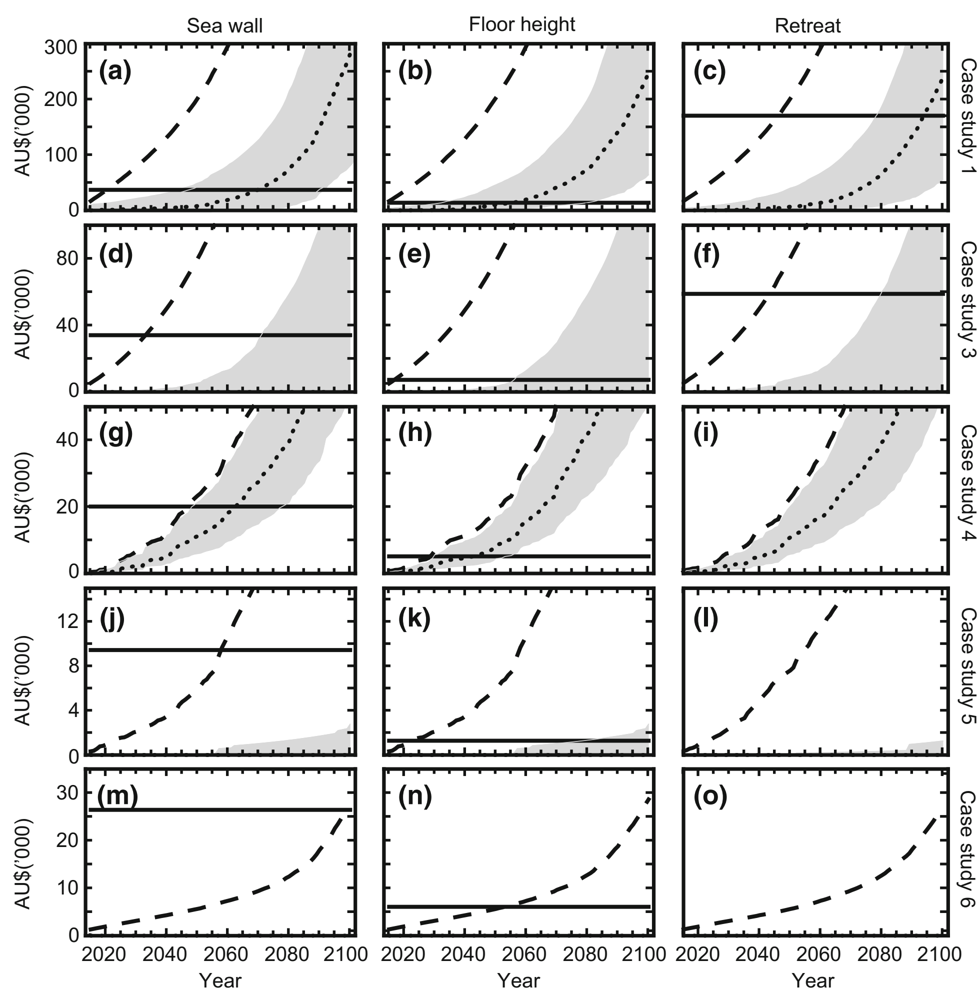

Fig. 2 The per-household cost of adaptation (*solid line*), mean benefit of adaptation (*dashed line*), and median (Q50) benefit of adaptation (*dotted line*). The *grey region* encompassing the median benefit represents the boundaries of the Q25 and Q75 quartiles. In figures (**i**), (**l**), and (**o**), the cost of adaptation is greater than the scale of the plot. For all adaptations in case studies 3, 5, and 6, the median benefit is so low as to be difficult to distinguish from the *x* axis, and the median benefit/cost ratio does not exceed unity by 2100

median. The first year in which each case study, on average, achieved a net benefit from adaptation is determined by the point at which the dashed line crosses the solid line. In contrast, the year in which most of the properties in each case study first achieve a net benefit from their contribution to adaptation is determined by the point at which the dotted line crosses the solid line. With the exception of case study 4, the point at which most properties achieve a net benefit occurs much later, often greater than 50 years later, than the point at which a traditional benefit–cost analysis would calculate the mean net benefit. Moreover, even the 25 % of properties that realised the greatest benefit (indicated by the top edge of the grey region) took far longer to achieve a net benefit than the case study average as a whole. This highlights, again, that a very small proportion of households in the community received the bulk of the benefits of adaptation.

Discussion

Around the world, studies have calculated how much to spend on adaptations at specific case study locations now to avoid future damages using a benefit–cost analysis (Genovese et al. 2011; Hall et al. 2003, 2005; Kazama et al. 2010; McLeod et al. 2010; Snoussi et al. 2009; Sterr 2008; Wang et al. 2010; Yohe et al. 1996). Some others have considered the social factors that can foster or impede adaptation in coastal communities (Abel et al. 2011). However, very few have tried to assess how these costs and benefits might be distributed throughout at-risk communities, and even fewer have generalised their results across a range of case studies, as we do here.

Starting to develop such insights is important, however, because of the increasingly widespread nature of the problem faced by coastal communities around the world (McGranahan et al. 2007). Studying specific adaptations in specific locations is vital. However, the scale of the problem also demands a broader perspective to help prioritise areas for action and draw out useful comparisons across similar physical or social systems in different locations.

What general insights can be drawn from these observations? Firstly, the benefit of adapting to protect against inundation is closely related to the risk of inundation for a specific coastal community. If the community is naturally protected from storm surge (e.g. case study 2, Table 1 ‘Projected costs’, Fig. 1b), it is unlikely that significant benefits may be realised from further adaptation. On the other hand, many coastal communities will be at risk of coastal inundation. A simple benefit–cost analysis may indicate that some adaptation options are likely to avoid more damages than they cost to implement under future sea level rise scenarios (case studies 1, 3, 4, 5, and 6, Table 2 ‘Economic’).

However, the distribution of risk within these communities is also important (Table 2 ‘Equitable’, median benefit/cost, Fig. 2). In some cases, only a small proportion of properties are likely to experience risk from coastal inundation, even under sea level rise scenarios. In these communities, most properties may not experience a net benefit from contributing to a communal adaptation, such as a sea wall, for a long time to come. This may be true even if a traditional benefit–cost analysis might suggest that the community, on average, would receive a net benefit from adaptation.

Even when adaptation is both economic and equitable, not all communities will have the financial capacity to fund communal adaptations in the short or medium term. The per-property costs of implementing a communal adaptation are reduced as the density of development increases and the expected benefits increase as more properties are protected. This suggests that while some at-risk communities will have the capacity to implement communal adaptations to protect themselves from storm surge under sea level rise scenarios, some others, especially small, low-density communities, may not.

Broadly speaking, a local government or community deciding how to equitably manage inundation risk could allow individual property holders to implement and fund their own protections or invest in a communal adaptation that could protect many properties. Investing community funds to protect against inundation will raise questions around who will benefit and who should pay (Measham et al. 2011; Shackley and Deanwood 2002). Although the details will differ, similar underlying questions around equity and affordability are likely to recur in many coastal communities around the world. A full engineering analysis is not necessary to realise that communities where risk affects only a few properties and communities with a small funding base are likely to find communal adaptations inequitable or unaffordable.

Based on the analysis across our six case studies, therefore, we propose a typology of coastal settlements defined by their exposure to risk and the distribution of risk in the community, the potential benefits of adaptation, and the potential capacity for adaptation in the community (Table 3). The typology is logically structured around whether investment in a communal adaptation is likely to be perceived as economic, equitable, and affordable in different types of coastal community. The framework in Table 3 is populated from the ‘affordability’, ‘economy’, and ‘equity’ results of the sea wall adaptation from Table 2. Although these results reflect specific adaptations in specific locations, the distribution of risks and adaptation

Table 3 A typology of coastal settlement types

Economic	Equitable	Affordable	Case study	Action
No	–	–	2	Do nothing
Yes	No	No	3	Retreat/household adaptation
		Yes	5, 6	Household adaptation
Yes	Yes	No	1	Funding from larger scale government for community engineering, e.g. sea wall
		Yes	4	Local council to fund community engineering, e.g. sea wall

costs are community characteristics, so similar relationships are likely to apply to other communal adaptation options.

Case study 2 is an example of a coastal community that is unlikely to face significant risk from storm surge, even under sea level rise scenarios out to 2100, due simply to the topography of the case study site. Unless there are other reasons for protecting the coast, such as erosion of tourist beaches (Raybould and Lazarow 2009), no adaptation may be necessary. Where there is an economic argument for adaptation at the case study level, the distribution of risk throughout the community should be assessed. If only a small proportion of properties are at-risk, such as case studies 3, 5, and 6, a communal adaptation is unlikely to be equitable, and focused property-level adaptations may make sense. If a large proportion of the community faces risk of inundation, as in case studies 1 and 4, a communal adaptation may be more efficient. In cases where there is a clear justification for communal adaptation, an assessment of affordability may constrain which adaptation options are realistic within the community (e.g. case study 4), and which ones may require support from larger scales of governance (e.g. case study 1).

Sensitivity of the model and potential refinements

Our analysis relied on modelling specific adaptation options, at specific locations, with a specific funding model. Other adaptations would exhibit different costs and levels of protection for different properties, yielding different trade-offs between communal and individual adaptations. Different funding mechanisms could distribute those costs amongst the community more or less equitably. Nevertheless, similar underlying issues of risk and cost distribution will apply to any communal adaptation. The simple framework we propose here is designed to underpin discussions around the equity and affordability of communal adaptations in our coastal communities. In future, the framework could be strengthened by further comparison with additional examples of adaptation in coastal communities.

Benefit–cost analyses are sensitive to the choice of discount rate. We tested the sensitivity of our outcomes at real discount rates of 2.08 and 6.08 %. Higher discount rates decrease the benefit/cost ratios for future-focussed infrastructure projects, but they do so uniformly across the community so their distributional impact is expected to be minor. A real discount rate of 2.08 % did not modify the 'affordable', 'economic' or 'equitable' results for any case study. A real discount rate of 6.08 % did not modify the 'affordable' or 'equitable' results, but it did change the sea wall adaptation from 'economic' to uneconomic for case studies 5 and 6. This has little impact on our proposed typology, which recommends individual adaptation of the small proportion of properties at risk in case studies 5 and 6. More importantly, it does not alter the insight that in some communities a communal adaptation may be inequitable because the benefits accrue to only a few properties.

Communal adaptations create benefits and costs broader than those we consider in our analysis. In Australia, sea walls have most often been constructed to protect against risks other than coastal inundation, such as erosion (Harman et al. 2014). They also play a role protecting communal infrastructure such as roads and shorefront parks in addition to private property. At the same time, however, sea walls are increasingly recognised to have several non-economic costs. These include environmental impacts due to modified shoreline dynamics (Mitsova and Esnard 2012), amenity impacts due to view impingement (Raybould and Lazarow 2009), and perverse development outcomes in at-risk areas due to the sense of security they create. Many coastal communities are considering alternative adaptations such as soft shorelines and beach renourishment (Harman et al. 2014). In future, our framework could be refined to consider these communal costs and benefits.

Our analysis used a fairly coarse measure of affordability, as a constant proportion of mean household income normalised to similar levies for coastal infrastructure already existing in Australia. This simple measure averaged affordability across individual households and neglected the fact that low-income households would be less able to afford an adaptation levy than those with a higher income. This could affect overall affordability in communities with a high proportion of low-income households. In future, some of these issues may be addressed by more complicated funding models, reflecting a more nuanced understanding of affordability.

Conclusions

Communal adaptations can provide a good mix of protection and return on investment. On the other hand, they require coordination and funding from the entire community. Perceptions of equity and affordability are known to affect community engagement and the likelihood of achieving workable consensus (Measham et al. 2011; Shackley and Deanwood 2002). These perceptions will be affected by the distribution of the risks of coastal inundation and the potential benefits of adaptation, both of which vary greatly within and between coastal communities. Despite these differences, however, many coastal communities will face similar overall distributions of risks, costs, and considerations of affordability. The typology we propose here is designed to underpin discussions around the equity and affordability of communal adaptations in our coastal communities. As detailed data on the distribution of coastal risks and property characteristics become more readily available, the typology could be generalised further. Specific infrastructure projects undergoing benefit–cost analysis could incorporate some analysis of the distribution of costs and benefits, as demonstrated here.

Although our framework is focussed on decision making at the local government level, one clear outcome is that some coastal communities that would be most efficiently protected by a communal adaptation may not be able to afford it. This highlights the role of multi-scale governance in the debate about adapting our coastal communities to sea level rise (Harman et al. 2014; Tribbia and Moser 2008). In regions of low density, widely dispersed development like Australia, it makes sense to focus and coordinate adaptations at the local government level that most closely matches the fine-scale distribution of risk (Measham et al. 2011). In some cases, however, coordination and funding from State or National governments will enable adaptation options not available to the community on its own (Groven et al. 2012; Harman et al. 2014). Because these broader levels of governance typically bear the brunt of recovery costs and compensation following a natural disaster, sharing the costs and benefits of adaptations like this can benefit everybody.

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