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Coastal inundation under climate change: a case study in South East Queensland

Climate Adaptation Flagship Working Paper #6

Helping Australia Adapt to a Changing Climate

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Important disclaimer

This material was prepared by Xiaoming Wang, Mark Stafford Smith, Ryan McAllister, Anne Leitch, Steve McFallan, Seona Meharg of CSIRO's Climate Adaptation Flagship, based on research in the South East Queensland Climate Adaptation Research Initiative. It analyses readily available information and expert knowledge to provide a realistic assessment.

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EXECUTIVE SUMMARY

Over the next few decades the risk of coastal inundation is expected to increase due to sea level rise and possible increases in storm intensity. At the same time, any growth in coastal populations will expose more people, property and infrastructure to inundation. Averting the escalating risks of inundation requires a strategic approach which involves governments, industries and communities working in partnership.

This study presents a preliminary assessment of the costs and benefits of proactive, planned adaptation on built infrastructure. These costs and benefits have been investigated by estimating the population and economic effects of an historical 1-in-100-year inundation event and then exploring how these may change under different scenarios of settlement adaptation in 2030 and 2070. We use information from South East Queensland (SEQ): a region recognised to face a high risk of inundation by both the insurance industry and governments.

In SEQ the upper range of sea level rise, under a mid-level emission scenario (A1B), is conservatively projected to be 0.2 m by 2030 and 0.5 m by 2070. Storm tides due to extreme weather events will be more intense and frequent: the current 1-in-100-year event will have a probability of occurring every 61 years by 2030. In addition to the mean sea level rise, the upper range of a current 1-in-100-year peak storm tide may reach 2.7 m by 2030 and 3.0 m by 2070, while a current 1-in-500-year tide event may reach 3.4 m in 2030 and 3.7 m in 2070. At present, it is estimated that about 227 000 in SEQ are at risk of inundation from a 1-in-100-year storm tide. If the population in SEQ does not change, sea level rise could see this number increase to rise to 245 100 people by 2030 and 273 000 people by 2070. However the population is expected to increase from today’s 2.69 million to 4.4 million by 2030, compounding the impact of climate change if the population remains at its current pattern of settlement.

Without adaptation, future populations may experience greater inundation damage. Currently in SEQ 35 200 residential buildings are exposed to a 2.5 m storm tide (approximately a 1-in-100-year event), risking structure and content damage of about $1.1 billion. By 2030, with an additional 0.2m sea level rise,(and with the same planning and building regulations as today) the number of residential buildings at risk from a 2.5 m storm tide will increase to about 61 500 and the costs will increase to about $2.0 billion. In 2070 this will affect approximately 121 000 residential buildings and cost about $3.9 billion.

Adaptation can manage climate risks. Adaptation could occur through tightening planning regulations so the risk on the existing stock of properties is held to today’s levels, despite sea level rise. For example, if planning regulations did not allow further developments in high risk areas (but with no action to protect existing housing stock), the impact of 2.5 m storm tides with an additional 0.2 m sea level rise in 2030 could be limited to approximately 40 300 residential buildings, and a cost of about $1.3 billion. This adaptation could limit the impact of 2070 storm tides to approximately 48 000 residential buildings and a cost of about $1.5 billion.

Adaptation measures to reduce or minimise the population at risk from inundation could also include: retrofitting existing developed areas, changing design standards for new buildings

within existing developed areas, wider planning initiatives for the long term, and improving governance across from local, regional and national scales.

This preliminary analysis shows the benefits from proactively adapting planning arrangements soon. Whatever the specific scenario, there seems to be as much to be gained by the adaptive step of simply preventing future risky development as from the added (and probably more costly) step of reducing the future risk on existing housing stock. However, this conclusion must be tempered by the need for more data and research.

1. COASTAL INUNDATION UNDER CLIMATE CHANGE

Coastal housing and infrastructure is at risk from sea level rise and storm tide during extreme inundation events (Church et al. 2008). The level of hazard is expected to increase over the coming decades, due both to sea level rise and to possible increases in storm intensity. In addition, population increases in many coastal areas mean that more infrastructure will be exposed to the hazard if there is no action taken to avoid this outcome (DCCEE 2009).

This preliminary study explores the issues involved in assessing the real costs and benefits of planned adaptation on residential housing and select infrastructure (commercial and educational buildings, roads and railway infrastructure) in the coastal zone to reduce exposure to future hazards from inundation events. To do this, we use data from South East Queensland (SEQ) to estimate the effects of an historical 1-in-100-year[1] inundation event, and how these effects may change in the future, due to both climate change and population growth under different scenarios of settlement adaptation. The SEQ region is recognised as facing a high risk of inundation by the Intergovernmental Panel on Climate Change (IPCC 2007).

1.1 Sea level in coming decades

Current expectations are that, under climate change, the upper range of sea level rise in Queensland is projected to be 0.2 m by 2030 and 0.5 m by 2070 under a mid-level emission scenario (A1B, which to date has been the only emissions scenario used for regional sea level rise analysis)[2]. Storm tides due to extreme weather events are likely to become more intense (IPCC 2007).

While sea level rise is one of the more certain impacts of climate change, it still involves uncertainty (Lowe and Gregory 2010). Uncertainties in sea level rise are derived from shortcomings in scientists' ability to model the real world, as well as our ability to know future social, technological and economic responses to managing greenhouse gas emissions (Hunter

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[1] A 1-in-100-year event represents the probability of the event occurring once in 100 years on average, or has a one per cent chance of occurring in any particular year.

[2] Local sea level rise of 0.2 m in 2030 and 0.5 m in 2070 is the 95th percentile estimate, based on the global averaged sea level rise and regional sea level departures from the global average under the mid-range A1B emission scenario. The local sea level rise is assumed as the sum of the global averaged and the regional sea level rise that are both random variables in normal distributions. The mean and standard deviation of the global averaged sea level rise are estimated from the 5th percentile minima (2030: 55 mm; 2070: 150 mm) and 95th percentile maxima (2030:143 mm; 2070: 413 mm) of the global averaged sea level rise that are both derived by adjusting the IPCC third assessment report projections to correspond to the IPCC fourth assessment report projections at 2095 (http://www.cmar.csiro.au/sealevel/sl_proj_21st.html). The mean and standard deviation of regional sea level departures from the global averaged sea level rise is derived from 17 SRES A1B simulations (http://www.cmar.csiro.au/sealevel/sl_proj_regional.html). These estimates may be conservative because they do not account for all factors which contribute to sea level rise, such as accelerated melting of Greenland ice sheets (http://esciencenews.com/articles/2009/03/10/rising.sea.levels.set.have.major.impacts.around.world)

2009.). Further uncertainty stems from the question of how much ice will be lost from the Greenland and Antarctic ice sheets through ice flow (Lowe and Gregory 2010). This means that we cannot predict precisely when changes in sea level rise will occur – they might be a few years earlier or later than the estimated date – however they are virtually certain to occur (IPCC 2007).

1.1.1 Inundation events

The rise in sea level will be experienced as an increased frequency of flooding events and coastal erosion of sandy shores (Hunter 2009). Storm tides are coastal seawater movements that raise water levels relative to the land as a result of low pressure weather systems, cyclones or storm winds. At present the 1-in-50-year storm tide levels observed in Moreton Bay, together with wave setup, can reach 2.3 m. For 1-in-100, -500-year and -1000-year events the observed[3] levels reach 2.5 m, 3.2 m and 3.5 m. Depending on the sea level rise, the average return period or recurrence interval (ARI) of current events can be considerably reduced, as shown in Table 1 and Figure 1. For example, given a 0.2 m sea level rise in 2030, a 1-in-100-year event today would become a 1-in-61-year event in 2030, which implies there will be more frequent extreme events.

Allowing for sea level rise, storm tide levels could reach up to about 2.7 m and 3.0 m for 1-in-100-year event in 2030 and 2070[4]. A 1-in-500-year event would reach about 3.4 m in 2030 and 3.7 m in 2070.

Table 1: Varied average recurrence interval (years) due to sea level rise

Current Events	***Sea Level Rise (m)***				
	0.2	**0.4**	**0.6**	**0.8**	**1.0**
1-in-50	31	19	12	7	4
1-in-100	61	38	23	14	9
1-in-500	306	188	115	70	43
1-in-1000	613	375	230	141	86

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[3] Data from Granger and Hayne (2001)

[4] In 2030: 2.5 m (storm tide + average wave setup height) +0.2 (sea level rise) =2.7 m. In 2070: 2.5 m (storm tide + average wave setup height) + 0.5 (sea level rise) = 3.0 m. The 1-in-500-year event is calculated similarly. Data source: Footnotes 1 and 2

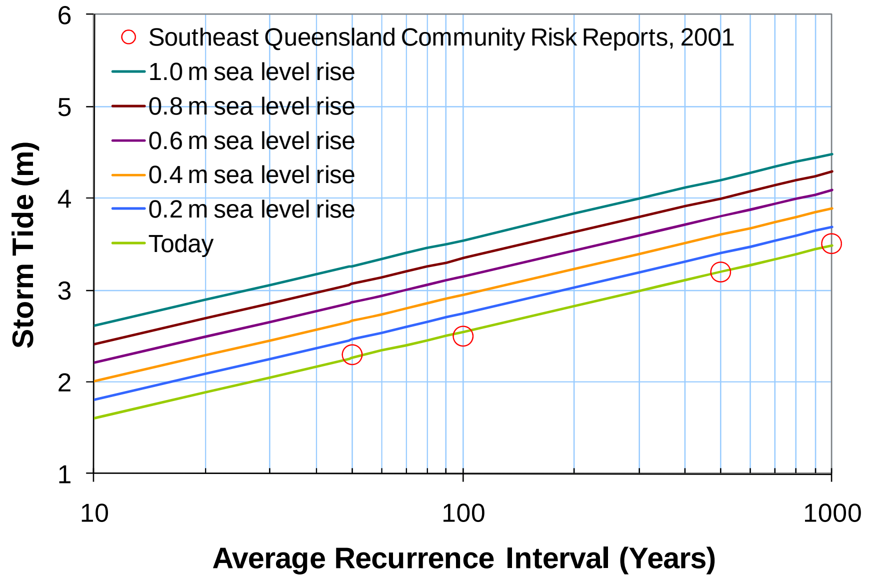

Figure 1: Variation of the average recurrence interval of current event in relation to sea level rise

1.2 Implications of sea level rise

SEQ covers about 22 000 km^2, following the 240 km coastline from Noosa in the north to the Queensland–New South Wales border in the south, and 160 km west to Toowoomba. Tidal zones in this region include the coast, and areas open to the coast, such as densely populated Brisbane.

The area comprises 11 councils, five of which are bordered by sea and so have the need to respond to the challenge of adapting to sea level rise.

About 10% of this area is designated as urban footprint, including four major urban centres. Most of this footprint is within 10 km of the tidal zone. The region is home to more than 2.69 million people today[5], with more than 1.76 million (63%) in Brisbane.

1.2.1 Buildings and infrastructure at risk

Prior to 1960, there were around 200 000 properties in SEQ. Since then this number has risen rapidly, to the point where there were more than 1.65 million building addresses in SEQ in 2008[6]. More than half of these residential buildings are within 5 km of the tidal zone and about 75% are within 10 km of the tidal zone.

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[5] Data derived from Australian Bureau of Statistics 2006 Census

[6] Data derived from PSMA information (www.psma.com.au)

Many commercial buildings in SEQ are also located close to the coast. Of the total estimate of approximately 97 000 commercial buildings, more than 68 000 or 70% are within 5 km of the tidal zone, and almost 87 000 or 90% are within 10 km of the tidal zone. Similarly, 80% of educational buildings are within 5 km of the tidal zone and 90% are within 10 km of the tidal zone.

SEQ road and transport infrastructure also tends to be coastal. Of the total 37 000 km of roads in the region, 28% lie within 5 km of the tidal zone and 44% within 10 km. Of the total 932 km of railways, 20% are within 5 km and 42% within 10 km from the tidal zone[7].

By 2030 the population in SEQ is expected to be approximately 4.4 million, and an extra 735 000 dwellings will have been constructed[8].

1.3 Assessment of impacts

A preliminary assessment of impacts, their risks and costs, is presented here to provide guidance for decision making (see the Appendix for calculations). However, it is important to note that this assessment depends on the publicly available Digital Elevation Map (DEM)[9] with one metre vertical resolution, 2006 ABS Census data and the PSMA address database, all of which may contain some inconsistencies and limitations. As a consequence, changes in inundation events can only be assessed in one metre increments. The effects of an inundation event with intermediate values (e.g. 2030 and 2070 events) are obtained by interpolation. For this purpose, we analyse the sensitivity of population economic impacts in terms of 2 m, 3 m and 4 m plausible inundation events (see Table A1 in the Appendix).

1.3.1 Population and Infrastructure at risk from inundation[10]

The land area of SEQ is 22 000 km^2. Current land use includes residential (14.5%), agriculture (62.5%) and park (19.9%), with 1.1% for industrial and 0.4% for commercial (see Figure 2) (ABS 2006).

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[7] Data derived from PSMA information (www.psma.com.au)

[8] SEQ Regional Plan 2009-2031

[9] The Shuttle Radar Topography Mission (SRTM) derived Digital Elevation Model (DEM): the vertical resolution of this DEM is limited to 1 m, so more detail cannot be differentiated until a higher resolution DEM is available.

[10] The numbers of people and houses were estimated based on the population (sourced from ABS Census 2006) and households (sourced from addresses of PSMA 2007) in low-lying areas (derived from SRTM DEM). Note that there can be multiple addresses in one building, especially in a city, leading to alternative estimates in numbers.

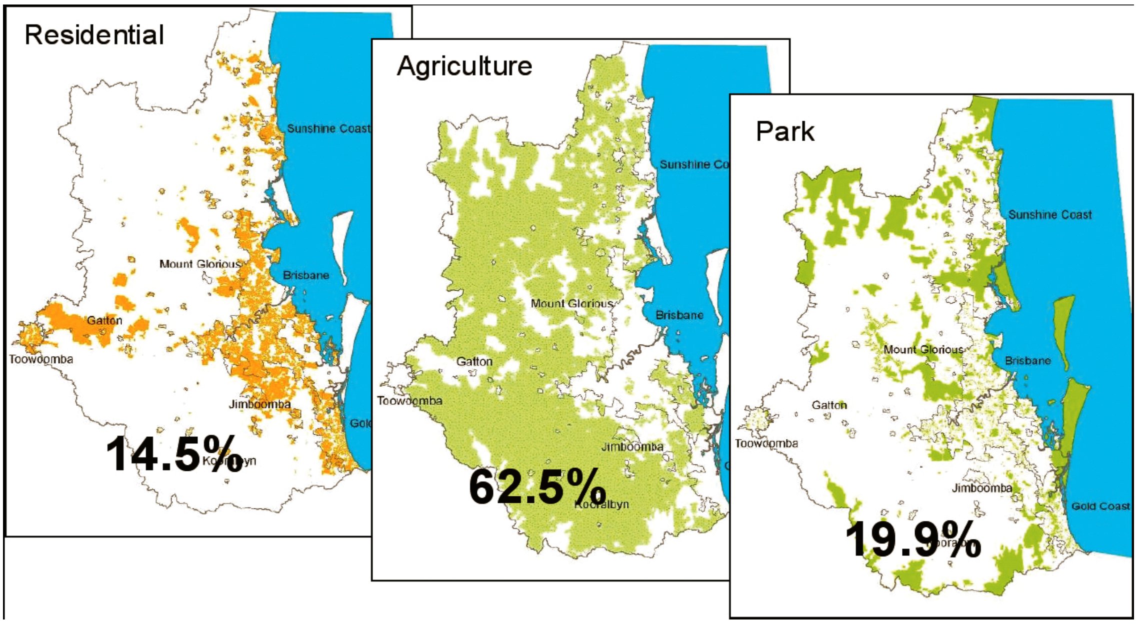

Figure 2: Current allocation of land use in South East Queensland

Analysis of the DEM shows that in SEQ, assuming that population growth and distribution remain as they are today:

- A **2 m inundation event** is likely to inundate 28 km^2 of residential land. This would affect about 180 000 people (6.7% of the current population). It would also inundate 22 500 residential building addresses (1.6% of SEQ total) and 1600 commercial building addresses (1.6%). It would affect 370 km of the region's roads (1.0%). Details are in the Appendix (see Table A1)

- A **3 m inundation event** is likely to inundate 57 km^2 of residential land. This will affect about 273 000 people. It would also inundate 47 900 residential buildings (3.4%) and 2900 commercial building addresses (3.0%). It would affect 760 km of the region's roads (see Appendix: Table A1)

- A **4 m inundation event** is likely to inundate 97 km^2 of residential land. This will affect about 372 000 people. It would also inundate 86 000 residential buildings (6.2%) and 5600 commercial building addresses (5.8%). It would affect 1300 km of the region's roads (3.5%) (see Appendix: Table A1).

Based on the population and buildings affected by a 2 m and 3 m event, future SEQ scenarios can be approximated by interpolation.

A current 1-in-100-year or 2.5 m inundation event will expose about 42 km^2 of built-up residential land. Such an event is likely to inundate residences of 227 000 people. It will also inundate 35 200 residential addresses (2.5% of the SEQ total), 2300 commercial building addresses (2.3%), and 560 km of roads (1.5%) (see Appendix: Table A2).

By 2030, 1-in-100-year events will reach 2.7 m which will inundate about 48 km^2 of built-up residential land. Even without population growth, such an event would affect about 245 000 people, 40 300 residential building addresses and 2540 commercial building addresses (8.2%, 14.4%, and 11.9% increases over today's 1-in-100-year events of 2.5 m).

Populations are expected to increase by 2030. Hence 1-in-100-year events that reach 2.7 m will have greater impacts in 2030 if development continues in its current pattern. Some 48 km^2 of built-up residential land will still be exposed to inundation, but now about 399 400 people and 61 500 residential building addresses will be impacted (76.3% and 74.9% increases over today's 1-in-100-year 2.5 m events). When the same population and building growth rate is assumed after 2030, affected population could increase to 772 000 as 1-in-100 year events begin to reach 3 m. This is a 241% increase from the 1-in-100-year 2.5 m events of today.

1.3.2 Economic costs of inundation

There are both direct and indirect impacts of inundation. Assuming that population levels and locations remain as they are today, and assuming 2009 prices, the direct and indirect costs in SEQ on residential properties and roads of a 2.5 m inundation event would be about $1.1 billion (see Table 2). For a 2.7 m event the costs will be about $1.3 billion.

Damage to residential buildings at risk of inundation is assessed as about $914 million for a 2.5 m event and $1046 million for a 2.7 m event. Indirect costs include the costs of cleanup and providing alternative accommodation, and are about $210 million in a 2.5 m event, and $237 million in a 2.7 m event[11] (see Table 2).

Table 2: Direct and indirect costs of a 1-in-100-year inundation events for now and 2030.

Costs of inundation	**2.5m event today: 1-in-100-year event now**	**2.7m event today: 1-in-100-year event in 2030**
Damage to current residential building (at $25 970 damage per building)	About 2.5% of residences resulting in **$914 millio**n damage to buildings and contents	About 2.9% of residences resulting in **$1 046 million** damage to buildings and contents
Indirect costs		
Household alternative accommodation (estimated at $232/person/event)	$53 million – about 8.4% of total residents, about	About 9.1% of total residents – about $57 million
Household clean-up (estimated at $4472/house)	~$157 million	~$180 million
Total indirect costs for 1-in-100-year tide in alternative accommodation and household cleanup	**~$210 million**	**~$237 million**
Total direct and indirect costs of initial road repair, accelerated deterioration and increased maintenance	~$18 million	~$20 million
Total costs	**~$1.1 billion**	**~$1.3 billion**

Damage to roads (based on the potential costs of repair and increased maintenance due to flooding) was estimated in 2001 to be at $59 000/km for arterial and major roads, and

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[11] Data derived from PSMA addresses, ABS land use, and SRTM DEM. Costs from Bureau of Transport Economics (2001) are corrected to 2009 values assuming average 3% inflation.

$18 500/km for other roads. Hence the damage to roads from a 2.5 m inundation event damage is about $18 million, and for a 2.7 m event is about $20 million. (Additional calculations are provided in the Appendix. Note, no current cost estimations are done for railways or commercial buildings due to data limitations.)

Based on the interpolation presented in the Appendix, the total cost to residential buildings at risk of inundation is assessed as about $1280 million for a 2.7 m event in 2030 and $1520 million for a 3 m event in 2070. These figures include indirect costs, such as cleanup and providing alternative accommodation, which are about $237 million in a 2.7 m event in 2030 and $278 million in a 3 m event in 2070.

Considering the current population and building growth, the damage to residential buildings at risk of inundation is assessed to be about $1970 million for a 2.7 m event in 2030. Indirect costs include the costs of cleanup and providing alternative accommodation and are about $368 million.

Assuming that the same population and building growth rate after 2030 is maintained, the damage to residential buildings at risk of inundation is assessed as about $3870 million for a 3 m event in 2070. The same indirect costs are about $722 million.

Assuming that half the population and building growth rate after 2030 is maintained, the damage to residential buildings at risk of inundation is assessed as about $2700 million for a 3 m event in 2070, of which indirect costs comprise about $500 million.

1.3.3 Other sources of information

Given that there have been no recent storm tide events from which costs can be calculated, it is useful to compare these estimates with information from other sources. For example, the scale of the above estimates is reasonably comparable to flooding damage cost data from Insurance Council of Australia (see Table 3). While these are due to terrestrial sources of flooding rather than inundation due to storm tides, they indicate that the present estimates are realistic.

Table 3: Estimates of flood damage in present values for 2009 (Insurance Council of Australia 2009)

Date of the flood event	**Location of the flood event**	**Present value in 2009 ($ million)**
25 January 1974	Brisbane	2095
7 February 1981	Dalby	200
26 December 1990	Rockhampton to Cairns	147
30 May 1996	South East Queensland	87
10 January 1998	Townsville	154
7 February 1999	South East Queensland	4
7 February 2000	Longreach	19
17 November 2000	Mackay	10
9 March 2001	Brisbane	63
30 June 2005	South East Queensland	62
17 January 2008	Emerald region	104
14 February 2008	Mackay	342

2. ADAPTATION RESPONSES

Adaptation to inundation occurs across a spectrum of responses, and ranges from reactive responses after a flood has happened (for example abandoning destroyed properties) through to pro-active preparations to reduce the impacts of an inundation event. Pro-active, planned adaptation options can substantially reduce damage, both for existing housing and for future developments, considering population and climate changes.

What is needed is a systematic assessment of the appropriate combination of options, as well as action on these options outside the pressures of an actual flood event. This assessment of the options could occur across the following categories of actions.

2.1 Retrofitting existing developments

- Develop maintenance programs for individual properties and public infrastructure, such as roads, drains, and bridges, to defend against minor inundation; these have considerable costs, but could deliver benefits in reduced claims for damages.

- Consider putting barrages in place on the main access waterways into near-sea-level inland estates. These options are extremely expensive and will eventually be overcome by higher degrees of sea level rise. However, they could protect many low lying inland properties in the medium term.

- Improve engineering structures on frontal dunes to protect against erosion for beach-front properties in some regions. However, these too may eventually be overwhelmed and will usually only be stop gap measures.

- Repossess developed areas at risk, by not permitting re-building after damage, high insurance premiums, changing building code requirements, etc.

2.2 Design standards for new buildings within existing developments

- Upgrade design standards for new houses (and public infrastructure) within existing at-risk areas, to increase resistance to many events; e.g. minimum floor heights above sea level, flood tolerant lower floors, demountable homes easily moved. The adjustment of such standards in itself is reasonably cheap and has substantial benefits, although changes may make some buildings more expensive.

- Promote or permit house insurance rates that are scaled relative to whether houses are best-practice flood resistant in flood prone areas. Again the direct public costs of such action are low, but have indirect impacts on industries.

2.3 Wider planning initiatives

- Upgrade planning codes to prevent or discourage new developments, or at least set best practice risk assessment standards for them, such that they do not occur in areas which are likely to be flood prone in the next 100 years (at least). These could be via nationally agreed planning guidelines. This is a key long-term action with low direct costs and great benefits, although these are slow to accumulate; of course, it creates opportunity costs of not being able to develop flood prone areas that may be seen to have high real estate values in the short term.

- Upgrade design standards for coastal public infrastructure, and have a process to continually monitor the adequacy of these standards, particularly in relation to specification of extreme events. Again, changing standards is cheap with large benefits, although public expenditure on the infrastructure thus affected may then increase.

- Support capacity building and resourcing in coastal local governments to ensure they have the capability to manage the planning and construction properly. This is a relatively cheap option, with many ancillary benefits.

- Develop effective early-warning systems and evacuation pathways for extreme events that exceed the design specifications of different development areas (i.e. spatially explicit and backed up by appropriate social networks to assist those most at risk). This is a relatively cheap option, with ancillary benefits since such extreme events may occur today anyway.

2.4 Governance across scales

- State government support for local governments’ capacity to plan and implement effective land use and coastal inundation hazard management policies through technical assistance, funding, political and legislative backing.

2.5 General

- Carry out a generalised review of the use of national standards vs. local regulation vs. ‘regulated’ private sector (insurance premiums, etc) vs. public insurance approaches to obtaining changes in behaviour without perverse effects in coastal developments.

- Continue to refine and build on national attempts (e.g. DCCEE 2009) to identify regions and localities which are most vulnerable to coastal inundation and ensure national investment targets these areas first.

3. ESTIMATED COSTS AND BENEFITS

Assessing the costs and benefits of all the planned adaptation options outlined in the previous section is beyond the scope of this preliminary exercise. However, even with the current datasets ,we can explore the costs and benefits from two perspectives. We can broadly approximate the likely benefits of adaptation at the regional scale, and we can approximate the net present values of the cost of no action as a means of thinking about how much can rationally be spent on adaptation.

3.1 Benefits of adaptation

The residential impact figures for 2.5 m and 2.7 m events today described earlier may be approximately extrapolated to three scenarios for 2030 with a total population of 4.4 million and 2.4 million buildings, all using today's dollars (no NPV, etc). We assume that, in the absence of planning changes, a pro rata proportion of buildings and people will be at risk given the expected population increase by 2030[12].

On this assumption, the three scenarios are:

(i) *The same planning and building regulations as today:*
The pro rata proportion of population and residential buildings at risk would now be 399 422 people and 61 549 buildings affected and ~$2 billion total costs (76%, 75% and 75% increases over today respectively). If we consider the same population and building growth rate after 2030, 772 296 people and 121 367 residential buildings are at a high risk of inundation for 1-in-100-year event in 2070 at a total cost of $3.9 billion (241%, 245% and 245% increase over today)

(ii) *Planning regulations tightened up today to allow no further risky developments, but no action taken to protect existing housing stock:*
This is the scenario calculated above 245 000 people and 40 300 buildings affected and $1.3 billion total costs (a 8%, 14% and 14% increase over today respectively) by 2030, and 273 000 people and 48 000 buildings affected and $1.5 billion total costs (a 21%, 36% and 35% increase over today respectively) by 2070.

(iii) *Planning regulations tightened up as in (ii), but further adaptation implemented to maintain the risk on the existing stock to today's levels despite sea level rise:*
This is holding to the same numbers of people and properties at risk at ~$1.1 billion total costs (i.e. 0% increase over today, by definition).

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[12] The detailed calculations for these three scenarios are provided in the Appendix: some number have been rounded here fore presentation purposes.

Thus, compared to no action on planning or adaptation, preventing new at-risk developments would protect about 153 thousand people and $683 million costs in a 2.7 m storm event by 2030 (scenario (i) compared to (ii)). Additionally retrofitting or reclaiming existing development to maintain the risk at today's levels would protect about 173 thousand people and $842 million in residential property costs compared to no action if a 2.7 m event occurred in SEQ by 2030 – scenario (i) compared to (iii).

If we consider the same population and building growth rate after 2030, compared to no action on planning or adaptation, preventing new at-risk developments would protect about 500 thousand people and $2.4 billion costs in a 3 m storm event by 2070 – scenario (i) compared to (ii). Additionally retrofitting or reclaiming existing development to maintain the risk at today's levels would protect about 546 thousand people and $2.8 billion in residential property costs compared to no action if a 3 m event occurred in SEQ by 2070 – scenario (i) compared to (iii).

If we consider half the population and building growth rate after 2030, compared to no action on planning or adaptation, preventing new at-risk developments would still protect about 250 000 people and $1.2 billion costs in a 3 m storm event by 2070 – scenario (i) compared to (ii). Additionally retrofitting or reclaiming existing development to maintain the risk at today's levels would protect 296 thousand people and $1.6 billion in residential property costs compared to no action if a 3 m event occurred in SEQ by 2070 – scenario (i) compared to (iii).

More than half the benefit in reducing the costs is obtained through the option of simply preventing new at-risk developments. This is likely to be much cheaper than actively protecting or retrofitting existing buildings.

None of these calculations includes public costs, such as disaster assistance, public infrastructure damage (to roads, railways, sewers, etc), lost productivity, extra emergency services, etc.

3.1.1 The present value of adaptation

The present value of damage caused by 1-in-100-year inundation events can be calculated by modelling the frequency of events over long time frames, but discounting the cost of future events (to account for the opportunity cost of money). The present value of damage caused by 1-in-100-year inundation events is, on average, roughly 34% what such a single, isolated event would cost if it occurred today (mean net present value (NPV) with 3% discount rate). With climate change, the magnitude of the current 1-in-100-year events will be exceeded more often and become more frequent. When these events start to occur as 1-in-61-year events, the net present value of the costs will rise to 56% of the single event's damage bill. When they occur as 1-in-23-year and 1-in-9-year events, the present value of costs is expected to be 149% and 381% of the single event's damage bill.

From the individual resident's viewpoint, assuming damages of around $32 000 per property in a 1-in-100-year inundation event, climate change induced infrastructural vulnerability is not insurmountable (at an NPV of $11 000 for a 1-in-100-year event, increasing to $17 900 when such events occur every 61 years). Though, in addition to tangible costs of flooding, land values may be severely devalued by repeated flooding.

For the region, the present value of current 1-in-100-year events stands at $386 million. This might be seen as the maximum additional investment a rational government would consider to protect against private damage from a storm tide (further complicated by what levels of private insurance are held). Using the same scenarios (i) and (ii) from above we can consider how climate change may impact on the investments of governments.

(i) Assuming a future where 1-in-100-year inundation events now occur as 1-in-61-year events, unchanged planning and building regulations will see the number of residential properties at risk from such events increase to 61 500 buildings. The result will be that the net present value of damage will increase 189% (i.e. by $718 million) to $1.10 billion.

(ii) Assuming a future where 1-in-100-year inundation events now occur as 1-in-61-year events, but with tightened planning regulations allowing no further risky developments, the net present value of damage will increase 64% (i.e. by $247 million) to $634 million.

While these figures are indicative of the additional investments a rational government would spend to protect against private damage from a storm tide, this analysis only includes private residential infrastructure. These net present values of the costs are likely to be significantly lower than estimates of a broader set of costs. For example, to protect the land values, a rational economist might be prepared to spend much more.

Again, even though climate change is likely to induce major inundation costs, the option of tightening planning regulations alone can reduce the net present value of future inundation costs by over $470 million. However, considerably more discussion is needed to define useful scenarios for valuation.

4. CONCLUSION

Our preliminary analysis suggests that there are considerable benefits to be obtained from proactively adapting planning arrangements soon. Critically, whatever the specific scenario, there seems to be as much gain to be made by the adaptive step of simply preventing future risky development as from the added (and probably more costly) step of reducing the risk on existing housing stock.

However, this conclusion must be tempered by a need for (i) more reliable estimates of property at risk for different inundation event levels (a better resolved DEM); (ii) better data on the differentiated impacts of flooding on property damage according to location (which involves significant survey and mapping effort); and (iii) more realistic economic analysis (based on a more comprehensive analysis of alternative adaptation options and their implications for property and land values). Whilst important for improving confidence and precision in the analysis, (i) and (ii) are unlikely to change the general conclusion that a serious appraisal of adaptation options is needed; (iii) may significantly alter the attractiveness of action, however, and is the subject of further study.

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APPENDIX: IMPACT CALCULATIONS FOR INUNDATION EVENT IN SOUTH EAST QUEENSLAND

On the following pages we estimate:

- the sensitivity of storm tide impact to the plausible tidal height range from 2 m to 4 m (Table A1)
- the impact of a 1-in-100-year inundation today, by 2030 and 2070 with no more new development at risk (Table A2)
- the impact of a 1-in-500-year inundation today, by 2030 and 2070 with no more new development at risk (Table A3)
- how a 1-in-100-year event will change by 2030 and 2070 with population increase, without adaptation (Table A4 and Table A5).

These calculations of adaptation options illustrate the cost effectiveness of acting now.

Calculation 1: Storm tide impact to plausible tidal height

Table A1: Sensitivity of storm tide impact to plausible tidal height from 2 m to 4 m

	2 m event	3 m event	4 m event
Established area exposed (km^2)	28	57	97
Total population	2 700 000	2 700 000	2 700 000
Population exposed	6.7% or 180 000	10.1% or 273 000	13.8% or 372 000
Total buildings (1)	1 650 000	1 650 000	1 650 000
Total residential houses(1)	1 392 000	1 392 000	1 392 000
Residential houses exposed	1.6% or 22 500	3.4% or 47 900	6.2% or 86 000
Total commercial buildings(1)	97 000	97 000	97 000
Commercial buildings exposed	1.6% or 1596	3% or 2947	5.8% or 5594
Roads exposed	1.0% or 367 km	2.1% or 759 km	3.5% or 1302 km
Railway exposed	4.3% or 40 km	6.7% or 62 km	8.8% or 82 km
Household accommodation at $232 per person (2)	$41 760 000	$63 336 000	$86 304 000
Household cleanup at $4472 per house	$100 620 000	$214 208 800	$384 592 000
Physical damage to houses at $25 970 per house	$584 325 000	$1 243 963 000	$2 233 420 000
Total cost of impact(3)	$726 705 000	$1 521 507 800	$2 704 316 000

Notes for Table A1:

(1) The data are derived from PMSA. It is the number of addresses, which is used as an approximation of building numbers.

(2) House exposure costs are assessed as $232 per person for accommodation, $4472 per house for cleanup and $25 970 per house for damage (see Footnote 11).

(3) The total cost does not include the cost as a result of exposed commercial buildings, roads and railways in the table.

Calculation 2: Exposure and costs for 1-in-100-year storm tide today, 2030 and 2070

The estimation in Table A2 is made by interpolation based on Table A1. It shows that the cost is about $1.1 billion for 1-in-100 event today, which rises to $1.3 billion by 2030 and $1.5 billion by 2070, assuming by that by then planning controls have been implemented to avoid *any new* development in areas subject to flooding.

Table A2: Exposure and cost for a 1-in-100 year storm tide today, 2030 and 2070 with sea level rise but no extra population and development at risk.

	Today's population 2.5 m event 1-in-100-year today	Today's population 2.7m event 1-in-100-year by 2030	Today's population 3.0 m event 1-in-100-year by 2070
Established area exposed (km^2)	42	48	57
Total population	2 700 000	2 700 000	2 700 000
Population exposed	8.4% or 226 500	9.1% or 245 100	10.1% or 273 000
Total buildings (1)	1 650 000	1 650 000	1 650 000
Total residential houses(1)	1 392 000	1 392 000	1 392 000
Residential houses exposed	2.5% or 35 200	2.9% or 40 280	3.4% or 47 900
Total commercial buildings(1)	97 000	97 000	97 000
Commercial buildings exposed	2.3% or 2272	2.6% or 2542	3% or 2 947
Roads exposed	1.5% or 563 km	1.7% or 641 km	2.1% or 759 km
Railway exposed	5.5% or 51 km	6.0% or 55 km	6.7% or 62 km
Household accommodation at $232 per person(2)	$52 548 000	$56 863 200	$63 336 000
Household cleanup at $4472 per house	$157 414 400	$180 132 160	$214 208 800
Physical damage to houses at $25 970 per house	$914 144 000	$1 046 071 600	$1 243 963 000
Total cost of impact(3)	$1 124 106 400	$1 283 066 960	$1 521 507 800

Notes for Table A2, A3, A4 and A5:

(1) The data is derived from PMSA. It is the number of addresses, which is used as an approximation of building numbers.

(2) House exposure costs are assessed as $232 per person for accommodation, $4472 per house for cleanup and $25 970 per house for damage (see Footnote 11).

(3) The total cost does not include the cost as a result of exposed commercial buildings, roads and railways in the table.

Calculation 3: Exposure and costs for 1-in-500-year storm tide today, 2030 and 2070

The estimation in Table iii is made by interpolation based on Table i. It shows that the cost is about $1.8 billion for a 1-in-500-year event today, and rises to $2.0 billion by 2030 and $2.3 billion by 2070, assuming by that by then planning controls have been implemented to avoid *any new* development in areas subject to flooding.

Table A3: Exposure and cost for 1-in-500-year storm tide today, 2030 and 2070 with sea level rise but no extra population and development at risk.

	Today's population 3.2 m event 1-in-500-year today	Today's population 3.4 m event 1-in-500-year by 2030	Today's population 3.7 m event 1-in-500-year by 2070
Established area exposed (km^2)	65	73	85
Total population	2 700 000	2 700 000	2 700 000
Population exposed	10.8% or 292 800	11.6% or 312 600	12.7% or 342 300
Total buildings (1)	1 650 000	1 650 000	1 650 000
Total residential houses(1)	1 392 000	1 392 000	1 392 000
Residential houses exposed	4.0% or 55 520	4.5% or 63 140	5.4% or 74 570
Total commercial buildings(1)	97 000	97 000	97 000
Commercial buildings exposed	3.6% or 3476	4.1% or 4005	4.9% or 4800
Roads exposed	2.3% or 868 km	2.6% or 976 km	3.1% or 1 139 km
Railway exposed	7.1% or 66 km	7.5% or 70 km	8.2% or 76 km
Household accommodation at $232 per person (2)	$67 929 600	$72 523 200	$79 413 600
Household cleanup at $4472 per house	$248 285 440	$282 362 080	$333 477 040
Physical damage to houses at $25 970 per house	$1 441 854 400	$1 639 745 800	$1 936 582 900
Total cost of impact(3)	$1 758 069 440	$1 994 631 080	$2 349 473 540

Calculation 4: Exposure and costs for 1-in-100-year storm tide with higher population and today's pattern of development

This Table shows that the cost increases to $2.0 billion by 2030 with 0.2 m sea level rise, when population increase is included and building development is assumed to continue to follow today's patterns (as in the current projections of the PSMA). The 2 m and 3 m storm tide events are plausible events, utilised for interpolation to estimate a 2.7 m (or 1-in-100-year) event in 2030.

Table A4: Exposure and cost for 1-in-100 storm tide by 2030 with sea level rise, projected population growth and building development

	2030 population 2 m event	2030 population 2.7 m event 1-in-100-year by 2030	2030 population 3 m event 1-in-100-year by 2070
Established area exposed (km^2)	28	48	57
Total population	4 400 000	4 400 000	4 400 000
Population exposed	6.7% or 293 333	9.1% or 399 422	10.1% or 444 889
Total residential houses (1)	2 127 000	2 127 000	2 127 000
Residential houses exposed	1.6% or 34 380	2.9% or 61 549	3.4% or 73 192
Household accommodation at $232 per person (2)	$68 053 333	$92 665 956	$103 214 222
Household cleanup at $4472 per house	$153 749 095	$275 245 046	$327 314 740
Physical damage to houses at $25 970 per house	$892 858 675	$1 598 415 441	$1 900 796 912
Total cost of impact (3)	$1 114 661 103	$1 966 326 442	$2 331 325 874

Calculation 5: Exposure and cost for 1-in-100-year storm tide in 2030 with different rates of population and building growth

This Table shows that if we maintain the same rate population and building development growth from 2030 – 2070, or half this after 2030, the costs will rise to \$3.9 billion and \$2.7 billion, respectively.

Table A5: Exposure and cost for 1-in-100 year storm tide by 2070 with sea level rise, when and population growth and building development maintains the same rate or half the rate of growth from 2030 to 2070.

	2070 population 3 m event	2070 population 3 m event
	1-in-100-year by 2070	1-in-100-year by 2070
	Same rate of growth to 2070	Half rate of growth from 2030 to 2070
	Population growth = 80 952 per year	Population growth = 40 476 per year
	Building growth = 35 000 per year	Building growth = 17 500 per year
Established area exposed (km^2)	57	57
Total population	7 638 095	5 169 048
Population exposed	10.1% or 772 296	10.1% or 522 648
Total residential houses (1)	3 527 000	3 527 000
Residential houses exposed	3.4% or 121 367	3.4% or 84 634
Household accommodation at \$232 per person (2)	\$179 172 741	\$121 254 370
Household cleanup at \$4472 per house	\$542 754 625	\$378 481 712
Physical damage to houses at \$25 970 per house	\$3 151 909 124	\$2 197 936 062
Total cost of impact (3)	\$3 873 836 490	\$2 697 672 145

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